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HERNÁN GONZALO ORDEN
MARTA ROJO ARCE

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R-EVOLUCIONANDO EL TRANSPORTE

Burgos
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R-Evolucionando el Transporte

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R-EVOLUCIONANDO EL TRANSPORTE

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PRESENTACIÓN

Tras varias ediciones por diferentes ciudades y universidades españolas, el XIV Congreso de Ingeniería del Transporte (CIT 2021) recae en Burgos (España) en 2021. El CIT 2021 forma parte de una serie de congresos que se inició en Sevilla (1993), y tiene periodicidad bianual desde Madrid (1996), promovido por el Foro de Ingeniería de los Transportes (FIT). En el caso del año 2020, debido a la crisis del COVID-19, se pospuso la XIV edición al año 2021, que finalmente se realiza en modalidad online.

La organización de XIV Congreso de Ingeniería del Transporte ha estado a cargo del Grupo de Investigación en Logística e Ingeniería del Transporte de la Universidad de Burgos. Más de 210 ponencias han sido aceptadas para ser presentadas en el mismo, y se recogen en estas Actas.

Queremos agradecer a los ponentes el esfuerzo realizado para preparar sus trabajos y vídeos, y presentarlos durante las sesiones técnicas de este Congreso. En segundo lugar, agradecemos al FIT la confianza depositada para organizar este Congreso. Gracias a la Universidad de Burgos y en particular a la Escuela Politécnica Superior por su inestimable colaboración. Queremos también extender nuestro agradecimiento a las personas que nos han ayudado en la organización, con especial mención a los miembros de la Junta Directa del FIT: Andrés Monzón de Cáceres, Alfredo García García, Margarita Novales Ordax, Juan de Oña López, Ana Rivas Álvarez, Felipe Jiménez Alonso, Julián Sastre González, José María Díaz y Pérez de la Lastra y Daniel Álvarez Mántaras.

Nuestro agradecimiento a las personas que han ejercido el papel de Presidentes moderando las sesiones técnicas, y también a todos los miembros del Comité Científico que nos ayudaron en la tarea de revisión de ponencias. Y un último agradecimiento a nuestros compañeros de Área, con mención especial a Maria Nadia Aponte Sanjínez y a Alaitz Linares Unamunzaga.

Finalmente, gracias a todas las empresas e instituciones patrocinadoras y colaboradoras del Congreso, en especial a PTV Group.

Nuestro agradecimiento a:

- PTV Group
- Universidad de Burgos
- Aimsun
- Escuela Politécnica Superior
- Colegio de Ingenieros Técnicos de Obras Públicas
- Ineco
- Vía Libre
- Alsa
- Congreso Campus FIT 2020
- Ayuntamiento de Burgos
- Oficina de Congresos de Burgos

El Comité Organizador del CIT 2021

PRESENTATION

After various editions in some Spanish towns and Universities, the XIV Conference on Transport Engineering (CIT 2021) comes to Burgos (Spain) in 2021. The CIT Conference started in Sevilla (1993) and has a biannual frequency from Madrid (1996), promoted by the The Forum of transport engineering (FIT). In 2020, due to the Covid-19 pandemic, it was postponed into 2021, and it is finally developed in a virtual mode.

The organization of the XIV Conference on Transport Engineering has been in charge of the Researching Group in Logistics and Transport Engineering of the University of Burgos. More than 210 papers have been accepted to be presented in it, and are included in these Proceedings.

We want to thank the speakers for the effort made to prepare their papers and videos, and present them during the technical sessions of this Conference. Secondly, we thank the FIT for the trust they placed in us for organizing this Conference. Thanks to the University of Burgos and in particular to the Higher Polytechnic School for their invaluable collaboration. We also want to extend our gratitude to the people who have helped us in the organization, with special mention to the members of the FIT Board: Andrés Monzón de Cáceres, Alfredo García García, Margarita Novales Ordax, Juan de Oña López, Ana Rivas Álvarez, Felipe Jiménez Alonso, Julián Sastre González, José María Díaz y Pérez de la Lastra and Daniel Álvarez Mántaras.

Our gratitude to the people who have served as Presidents moderating the technical sessions, and also to all the members of the Scientific Committee who helped us in the task of reviewing the papers. And our last thanks to our Area mates, with special mention to Maria Nadia Aponte Sanjinez and Alaitz Linares Unamunzaga.

Finally, thanks to all the partners, companies and institutions that sponsor and collaborate with the Conference, especially to PTV Group.

Our acknowledgement to:

- PTV Group
- Universidad de Burgos
- Aimsun
- Escuela Politécnica Superior
- Colegio de Ingenieros Técnicos de Obras Públicas
- Ineco
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AEROPUERTOS
AIRPORTS

A DATA-DRIVEN APPROACH FOR DYNAMIC AND ADAPTIVE AIRCRAFT TRAJECTORY PREDICTION

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ABSTRACT

Traffic Prediction (TP) is a key element in Air Traffic Management (ATM), as it plays a fundamental role in adjusting capacity and available resources to current demand, as well as in helping detect and solve potential conflicts. Moreover, the future implementation of the Trajectory Based Operations (TBO) concept will impose on aircraft the compliance of very accurately arrival times over designated points. In this sense, an improvement in TP aims at enabling an efficient management of the expected increase in air traffic strategically, with tactical interventions only as a last resort. To achieve this objective, the ATM system needs tools to support traffic and trajectory management functions, such as strategic planning, trajectory negotiation and collaborative de-confliction. In all of these tasks, trajectory and traffic prediction represents a cornerstone. The problem of achieving an accurate and reliable trajectory and traffic prediction has been tackled through different methodologies, with different levels of complexity. There are two main aspects to be considered when assessing the most appropriate forecasting methodology: (a) time-horizon: depending on the timescale (anticipation before the day of operations), the level of uncertainty associated to the prediction will be different; and (b) input data: both the source and the quality of the input data (completeness, validity, accuracy, consistency, availability and timeliness) are key characteristics when assessing the viability of the prediction. This study develops a methodology for TP and traffic forecasting in a pre-tactical phase (one day to six days before the day of operations), when few or no flight plans are available.

This should be adjusted to different time scales (planning horizons), taking into account the level of predictability of each of them. We propose a data-driven, dynamic and adaptive TP framework, which can be accommodated to different Airspace Users' characteristics and strategies.

1. INTRODUCTION

To face the increasing air traffic demand, the future Air Traffic Management (ATM) system will rely on the Trajectory Based Operations (TBO) approach, which will require aircraft to follow an assigned 4D-trajectory (time-constrained trajectory) with high precision. TBO involves separating aircraft via strategic (long-term) trajectory definition, rather than the currently practicing tactical (short-term) conflict resolution. The main goal is to increase air traffic capacity by reducing the controllers' workload. Nevertheless, real time measures (over the trajectory) will be required to improve reliability, react to unplanned conditions and thus maintain the expected capacity.

The 4D-trajectory concept is based on the integration of time into the 3D aircraft trajectory, defining each point by position (latitude, longitude and flight level) and time. In the same way that there are restrictions associated with flight levels, the future operational framework foresees restrictions regarding time. It aims to ensure the flight is on a practically unrestricted, optimum trajectory for as long as possible in exchange for the aircraft being obliged to meet very accurately an arrival time over a designated point. In the context of TBO, Airspace Users (AUs) will agree a preferred trajectory with Air Navigation Service Providers (ANSPs) and airport operators (AOs). Aircraft and ground systems will exchange information regarding the trajectory and the expected airspace capacity, in order to foresee the ability to meet the assigned Controlled Time of Arrival (CTA).

The benefits of the 4D-trajectory approach on the ATM framework are: (a) improvement of air traffic operations reliability by increasing the overall traffic predictability; (b) optimal operations for airlines (aircraft using preferred routes and levels); (c) better service provided (due to ground-ground and air-ground interoperability) and fewer trajectory distortions; (d) potential absorption of delays; (e) enhanced safety with less controller workload (fewer conflicts, strategic management, information rich environment with data in advance); (f) reduction of costs (e.g. fuel and/or time); (g) increased airspace capacity; and (h) reduction of the environmental impact through reduction of emissions and noise.

To exploit these benefits accurate and reliable trajectory prediction (TP) is required. Enhanced traffic forecasts (which integrate uncertainty assessment and include different sources of relevant flight information) may enable improved demand-capacity balancing and conflict detection and resolution (CD&R) models. Moreover, new methodological approaches, as the exploitation of historical data by means of machine learning techniques is expected to boost TP performance.

In this context, this study has been able to develop a methodology framework for TP and traffic forecasting in a pre-tactical phase (from a few days to a few hours before the operations, when only a limited number of flight plans are available).

This has been adjusted to different time scales (planning horizons) supporting different operational scenarios, taking into account the level of predictability of each of them according to the available data. This step has resulted in an individual flight plan predictive model, which considers patterns in historical data to provide a pre-tactical prediction and incorporate “uncertainty” to Trajectory Prediction (as a probabilistic approach), incorporating also the possibility to self-calibrate with updated tactical data.

This way, we have not just obtained a specific implementation but a data-driven, dynamic and adaptive TP framework, suitable for further implementations. It is data-driven as the main study outcomes will be based on data analysis and interpretation, dynamic as can be adjusted to different planning horizons and adaptive as it can be enhanced iteratively with new tactical data. A fourth research objective of the study is for the TP framework to adapt to different Airspace Users’ characteristics and strategies. AUs will exhibit different strategies, as far as flight intentions and execution are concerned. The study has analysed and unravelled policies and features to apply the best TP for each AU according to observations.

We have validated the TP framework on a case study, including interviews to operational staff to understand the best way to apply such features. The proposed method aims to anticipate the needs of the ATM system; main applications of the model are related to reduction of complexity, demand-capacity balancing, conflict resolution, separation management, ANSP resource allocation.

The main results of the study are the specific implementation of the data driven analysis with Spanish data (the study also explores ECAC - European Civil Aviation Conference - area capabilities with existing datasets), the TP methodological framework and the mock-up comprising operational staff feedback.

2. BACKGROUND

2.1 Operational / technical context

Accurate and reliable trajectory prediction (TP) is a fundamental requirement to support trajectory-based operations (TBOs). Particularly, the mismatch between planned and flown trajectories (caused by operational uncertainties from airports, Air Traffic Control interventions, Airspace Users behaviour and changes in flight plan data) act as a driver for shortcomings in flow and capacity management (e.g. congestion and suboptimal decision making) and as a precursor for potential safety conflicts. Therefore, enhanced traffic forecasts (which integrate uncertainty assessment and include different sources of relevant flight information) may enable improved demand-capacity balancing and conflict detection and resolution (CD&R) models. Moreover, new methodological approaches, as the exploitation of historical data by means of machine-learning techniques is expected to boost TP performance.

2.2 Scope and objectives

Traffic prediction is a key element in Air Traffic Management (ATM), as it plays a fundamental role in adjusting capacity and available resources to current demand, as well as in helping detect and solve potential conflicts (Lymperopoulos & Lygeros, 2010). Moreover, the future implementation of the Trajectory Based Operations (TBO) concept will impose on aircraft the compliance of very accurately arrival times over designated points (SESAR, 2015; FAA, 2016). In this sense, an improvement in TP aims at enabling an efficient management of the expected increase in air traffic strategically, with tactical interventions only as a last resort. To achieve this objective, the ATM system needs tools to support traffic and trajectory management functions, such as strategic planning, trajectory negotiation and collaborative de-confliction. In all of these tasks, trajectory and traffic prediction represents a cornerstone (Rodríguez-Sanz et al., 2019).

The problem of achieving an accurate and reliable trajectory and traffic prediction has been tackled through different methodologies, with different levels of complexity (Alligier & Gianazza, 2015; Tastambekov et al., 2014; Wang et al., 2018; Wi et al., 2008; De Leege et al., 2013).

There are two main aspects to consider when assessing the most appropriate forecasting methodology:

- Time-horizon. Depending on the timescale (anticipation before the day of operations), the level of uncertainty associated to the prediction will be different.
- Input data. Both the source and the quality of the input data (completeness, validity, accuracy, consistency, availability and timeliness) are key characteristics when assessing the viability of the prediction.

The main target of the study is the development of a methodology for TP and traffic forecasting in a pre-tactical phase (from a few days to a few hours before the operations, when only a limited number of flight plans are available). This can be adjusted to different time scales (planning horizons), considering the level of predictability of each of them and the specific use case to where it should be applied. This initial step delivers a model that considers advanced tactical data to validate/enhance the previous pre-tactical prediction and incorporate "uncertainty" to Trajectory Prediction (as a probabilistic approach).

In this way, the study has obtained a data-driven, dynamic and adaptive TP framework: data-driven, as the main study outcomes is based on data analysis and interpretation, dynamic, as can be adjusted to different planning horizons, and adaptive, as it allows iterative enhancement with new tactical data.

Another objective of the study was, for the TP framework, to adapt to different Airspace Users' characteristics and strategies. Previous works showed that different AUs exhibit different strategies, as far as flight intentions and execution are concerned, affecting predictability, even at route level in some cases (SESAR P04.07.07, in EXE-04.07.07-VP-006 run in Barcelona ACC; statistical analyses carried out as part of the SESAR WpE project ELSA) (Gurtner et al., 2014; Gurtner et al., 2015). The implication is that different methodologies need to be used to develop the best TP for each AU.

3. LITERATURE REVIEW

The works developed around organization of airspace are globally focused in achieving an "ideal" airspace configuration, for this matter, dynamic sectorisation is considered with the corresponding problem of Demand-Capacity balancing. In a more in-depth analysis of the demand, the research is fixed in clustering techniques, improving the scope as well as the analysis of the data already available. Then, the trajectory prediction is enlarged by considering other type of data apart from the temporal and spatial, designated as contextual data.

From the point of view of clustering, several approaches can be stated. Clusters are formed from similar trajectories; this similarity trait requires an extensive analysis of origin/destination pairs, take-off patterns, weather deviations and any other type of data (De Leege et al., 2013). Considering a different approach, clusters are formed taking into account the relevant part of the trajectories, relevance is understood as a changing variable where markers to each of the route waypoints are assigned and added or discarded for each analysis (A Andrienko et al., 2017).

Contextual data can be chosen to cluster by relevance. Following this line, temporal characterization is thought to be of high importance (Enriquez, 2013), enabling the identification of salient traffic and temporal persistent flows. Temporal clustering has been implemented (Sidiropoulos et al., 2016) using a k-means algorithm, for the classification of arrivals and departures for Multi-Airport Systems. The final objective is to obtain a route that can be representative for each cluster, lowering the computational requirements.

In terms of the data available for clustering, Flight Plans (FP) are the most important resource and they are extremely dependent on the airline, consequently analysis of the behaviour of the airline have been developed (Calvo-Fernández & Cordero, 2013) obtaining patterns that can be posteriorly used for a more accurate prediction. This trait is measured with three indices: predictability, reliability and accuracy.

For further determination of the spatial-temporal state of the aircraft a variety of trajectory prediction methodologies have been developed that do not require any specific data of the performance of the aircraft, they do require aircraft state data, flight information, historical data or flight information from aircraft messaging. Environmental conditions are included in analysis (Stewart et al., 2015). In recent studies, the analysis and prediction is developed using Machine Learning techniques. Furthermore, in some references (Wanke et al., 2012) the trajectory (route terminology employed in the paper) is obtained from weighting a series of factors; concretely two groups of factors are considered: reaction (constraints to the route) and planned (changes in the route utilization). These factors are obtained using a regression model. In recent studies the analysis and prediction is developed using Machine Learning techniques (De Leege et al., 2013), the Hidden Markov Model is considered among several options.

An accuracy analysis is consistently associated to the trajectory prediction methods. The confidence level of the output is dependent on the quality of information extracted and varies depending on the phase of flight due to the difficulty of prediction for each of the phases (Gong & Mcnally, 2004), while in other studies (Wanke et al., 2004) a statistical model is used based on empirical observations and a Monte Carlo simulation is conducted. Other studies involve the use of a Distributional Robust Optimization formulation (Sidiropoulos et al., 2016), the uncertainty of the prediction is based on the drawing of information from different uncertain parameters by using probabilistic operations. To set the method in place, data is used from the Time Based Flow Management system obtaining this way the calibration.

For the demand-capacity balance instead of considering individual flights the approach is to consider a flow allowing independent flow routes, this is the Eulerian-Lagrangian (Rebollo et al., 2009) model where the optimization is solved using a Model Predictive Controller Technique minimizing the air and ground delay. Contrarily if individual flights are taken into account (which is typical for conflict resolution), interacting trajectories can be localized and modified in order to solve this problem, for this purpose collaborative reinforcement learning methods have been explored (Chen et al., 2016; Vouros et al., 2018). For the sector configuration, it is feasible to be obtained through a Branch and Bound algorithm choosing between the combinations available (Gianazza et al., 2009).

4. PREDICTIVE MODEL

4.1 Predictive model: High-resolution scenario analysis

The high-resolution analysis corresponds to operational data from Spanish Airspace extracted from the operational ATC platform (SACTA), including highly reliable data such as surveillance or every flight plan update.

In this initial phase of the analysis, a sample of relatively frequent flights (of relatively frequent airlines) in January, March and August 2018 is selected. Callsigns flying less than 10 times in a month and airlines with less than 200 flights in a month are discarded. These numbers are set accordingly to cumulative graphs.

Using this dataset, a clustering process is applied. The main “dissimilarity measure” used in the analysis is:

d = 1- (common wp / max wp), where:

- common wp: number of waypoints appearing in both the first and the last Flight Plan of each FPkey (last intended as last before estimated off-block time);
- max wp: maximum between the number of waypoints appearing in the first Flight Plan and the number of waypoints appearing in the last Flight Plan.

The histogram in Figure 1 represents the distribution of d in the different months. It is clear that 0 is the most common value and that the frequency of greater values rapidly decreases as the value increases: in particular, more than 70% of the Flight Plans do not show any difference in the first and the last path declared and that, in general, only 10% of the Flight Plans shares less than the 50% of waypoints between the first and last record before off-block time.

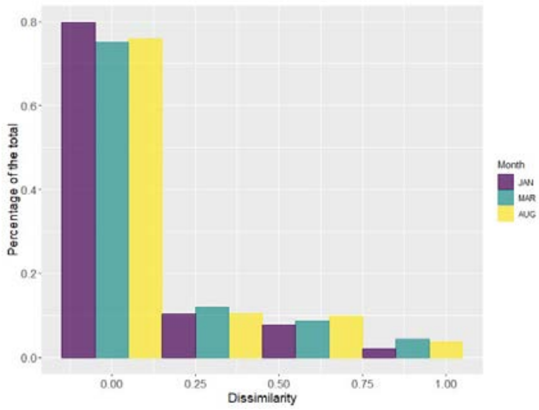


Figure 1: Histogram of the distribution of d in the different months analysed.

Furthermore, differences between months do not seem to be really relevant from this perspective. March and August behave almost identically, while in January there seem to be slightly smaller values of d.

The variable immediately associated to this d is a DeltaT variable defined as the difference between the expected off-block time of a flight and the record time of its first flight plan, in order to understand at what level of anticipation (before the beginning of departure operations) the flight plan was emitted.

As can be seen in Figure 2 (Dt is expressed in hours, and the categories are chosen as almost homogenous in size), d seems slightly or not dependent on the level of anticipation with which the flight plan is registered.
In fact, while the first histogram (less than 2 hours before EOBT – Estimated Off-Block Time) is different from the others, there is apparently no pattern in the following ones. The fact that the “< 2” section is composed essentially of observation with d=0 can be also because in many cases the first and last flight plan coincide. However, the graph remains meaningful as it shows that flight plans recorded in that time slot are almost surely reliable.

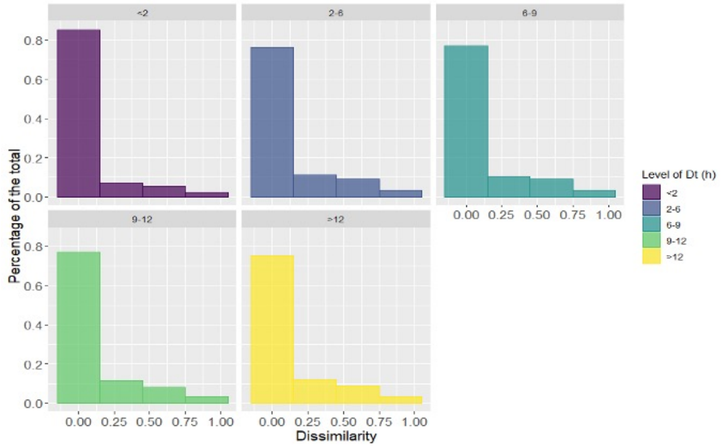


Figure 2: Representation of DeltaT (Dt) for different anticipations in the reception of the flight plan.

Another variable which seems not linked to the dissimilarity is the involvement in weather phenomena. The same comparison was performed distinguishing different weather conditions, in all the three months, leading to the same conclusions. Furthermore, no stable pattern is found also for aircraft type.

The distribution of d is also analysed for airlines, airports and routes. To associate a representative value of d to a group of flights, one possible choice is to use the average value of the variable in the group. The distribution of d is very asymmetrical and consequently the average is mainly determined by the highest values, possibly leading to a non-representative estimation. Because the median is 0 for every airline and airport (in fact, the 70% percentile of d is 0 for almost every subgroup), a possible choice is to consider another quantile; the most effective in discriminating the airlines and airports is found to be the 80% percentile.

The following graphs represent airlines in three groups (European Legacy, European Low Cost and Non-European). These graphs report the 80% percentile essentially for two reasons:

- This value is assumed by d, while this is not true for the mean.
- It has an "operational" meaning being x the quantile, it can be said that the 80% of data relative to the group assumes values smaller than x.

Furthermore, in Figure 3, Figure 4 and Figure 5, the size of every group is indicated.

Please be aware that these numbers indicate the occurrences in the selected samples (so, for example, infrequent flights are discarded) so they are just approximations of the real number of flights.

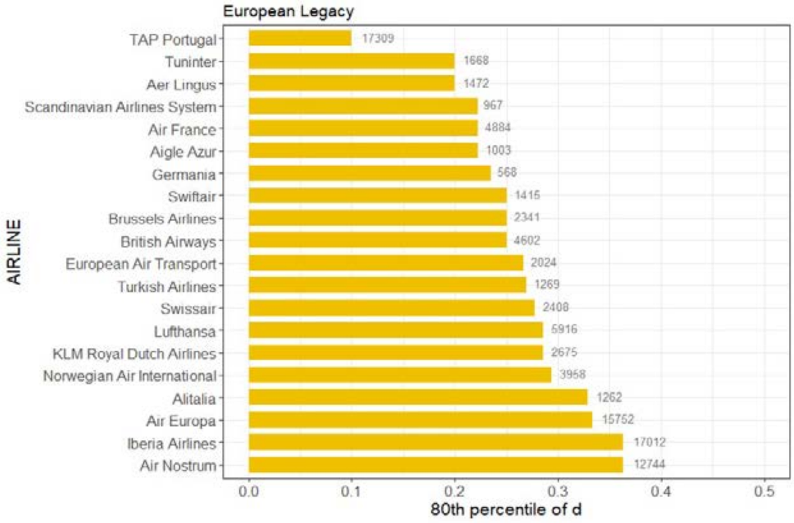


Figure 3: Representation of the 80th percentile for the Group of “European Legacy” airlines.

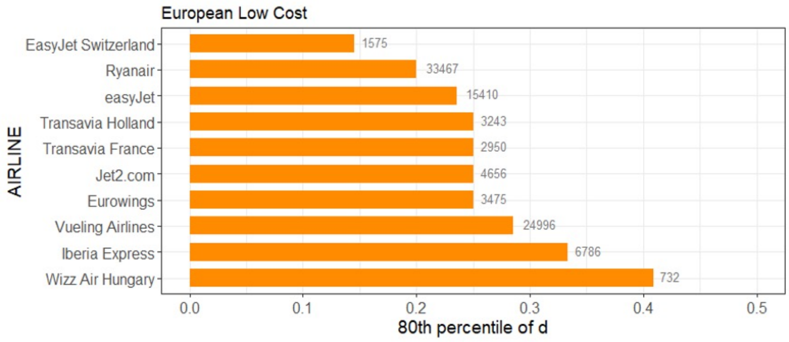


Figure 4: Representation of the 80th percentile for the Group of “European Low Cost” airlines.

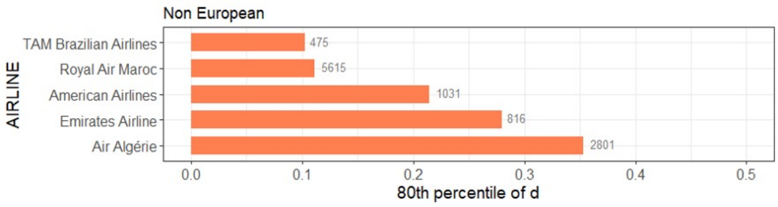


Figure 5: Representation of the 80th percentile for the Group of “Non-European” airlines.

Looking at the graphs above, there seems not to be great differences between the three groups (legacy, low cost, non-EU airlines); the major differences are, in fact, within each group.

The role of airports, instead, seems more decisive: departures from non-EU airports show lower values of d and departures from Madrid show much “less reliable” behaviours than the other frequent airports.

Arrivals, on the other hand, behave differently: non-EU airports show more variable values of d and often also higher values. This distribution is also reflected in the ranking of routes (e.g., flights departing from Madrid have higher d-values than flights arriving in Madrid).
Moreover, the Reliability time has been analysed. It is possible to estimate, for each flight number but also for each airline, the average time in which the flight plan became identical to the last one, plus a Confidence Interval based on the variance and size of data relative to that airline.

Figure 6 and Figure 7 are representative of the idea: the point is the average "reliable time" (sample mean), and the black line is the 95% probability interval of the mean.

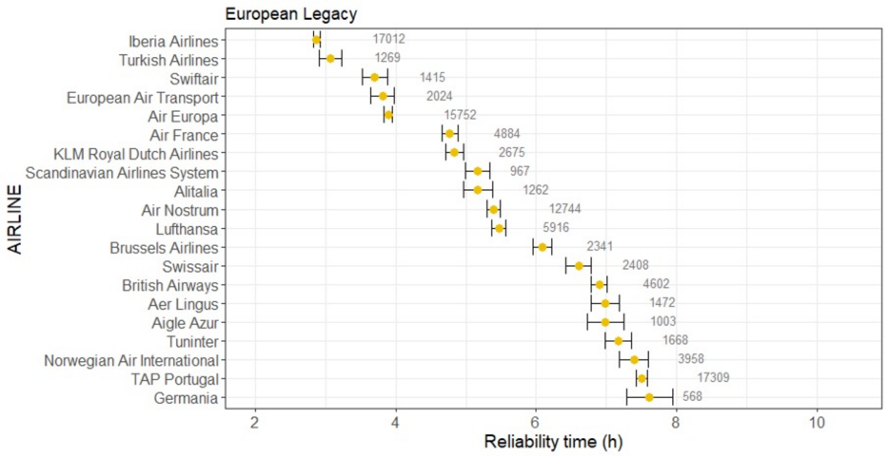


Figure 6: Reliability time for European Legacy Airlines.

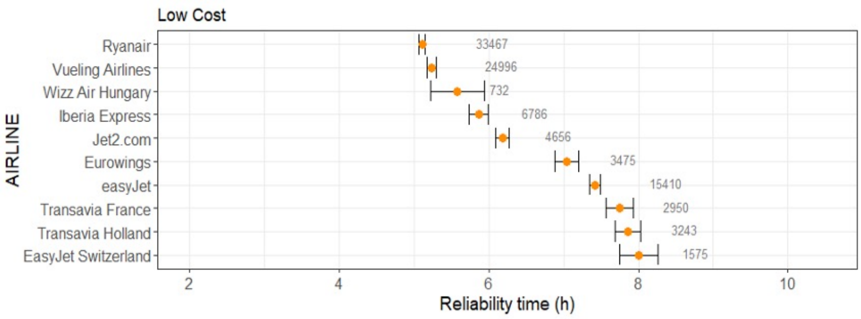


Figure 7: Reliability time for Low Cost Airlines.

Since the previous analysis indicates that the reliability of a flight plan depends essentially on the "intrinsic" properties of the flight and in some cases on the season, while the "contingencies" (e.g., weather, hour of the day, day of the week) play no or little role, the prediction presented here is only based on historical data; furthermore, this approach emphasizes the role of the companies' strategic reasoning.

The prediction is performed for different Δt's (where Δt is the difference between current time and off-block time): 8h, 4h, 2h, 1h.
For each Δt, the predictive methodology is the following:

- the current flight plan is compared with all the historical flight plans of the same flight (in this context, flight = callsign) at the same Δt, selecting all the past single flight's whose trajectories coincide with the current one.
- if the current flight plan is not the first one recorded that day, also the previous flight plans are compared with the corresponding past ones, discarding from the previously selected single flights all the ones that do not match.
- for all the selected single flights, the last-before-off-block-time planned trajectory is retrieved.
- the predicted trajectory is the most frequent one in this set.

In this case, this methodology is applied on two sets of data, different form the one used in first place for the dissimilarity measure:

- data from February 1st to May 31st, 2018 (in the following, denoted as spring)
- data from June 1st to September 30th, 2018 (in the following, denoted as summer)

and only to flights: classified as "Regular", flying at least 3 times a week, pertaining to the most frequent airlines, and with average levels of Δt sufficiently high.

To estimate the real usefulness of the prediction, its accuracy is compared with the one of the "default" prediction (i.e., the last trajectory is predicted to be the current one).

Accuracy is the percentage of trajectories that are correctly predicted for each flight (see Table 1 and Table 2).

SPRING	8h	4h	2h	1h
average *default* accuracy	76%	75%	82%	86%
average *prediction* accuracy	82%	82%	85%	87%

Table 1: Average Default and Predicted Accuracy in the different time horizons for the spring dataset analysed.

In spring the prediction is able, on average, to anticipate at Δt = 8 the accuracy that the default prediction has at time Δt = 2, so it reaches the same level of certainty 6 hours before.

SUMMER	8h	4h	2h	1h
average *default* accuracy	88%	76%	83%	88%
average *prediction* accuracy	92%	85%	87%	90%

Table 2: Average Default and Predicted Accuracy in the different time horizons for the summer dataset analysed.

It is important to remark the fact that the smallest accuracies appear in Δt = 4 and not in Δt = 8 can probably be explained with the fact that not all the flights considered record flight plans with the anticipation of Δt = 8 every day, so the values are computed on slightly different samples (and it can be reasonable to suppose that the sample relative to Δt = 8 is somehow more "reliable"). For this reason, Δt = 8 in these tables can be considered as a world apart.

Relative improvement in accuracy is computed for each callsign as follows:

(callsign prediction accuracy - callsign default accuracy) / callsign default accuracy

As could be expected, the relative improvement in accuracy is greater for and Δt = 4 than for the smallest Δt's, in both the seasons.

SPRING	8h	4h	2h	1h
average *relative improvement*	23%	29%	10%	6%

Table 3: Average Relative Improvement in the different time horizons for the spring dataset analysed.

SUMMER	8h	4h	2h	1h
average *relative improvement*	13%	59%	23%	13%

Table 4: Average Relative Improvement in the different time horizons for the summer dataset analysed.

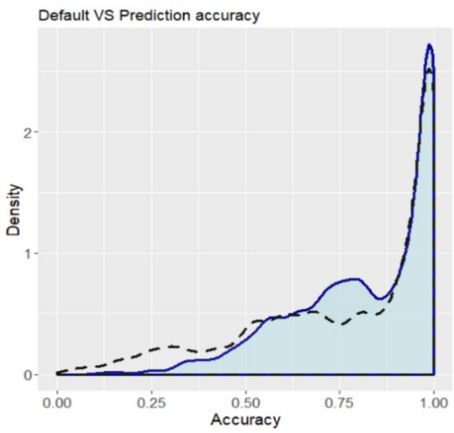


Figure 8: Comparison between default and predicted accuracy.

In Figure 8, *prediction accuracy* (in blue) and d*efault accuracy* (dashed line) at Δt = 8h in spring are represented (this representation is consistent with other Δt's and seasons). In view of this, three main considerations arise:

- the distribution of prediction accuracy is concentrated on highest values in general.
- the prediction accuracy has a negligible percentage of values lower of 0.5, so the biggest difference with the default accuracy is with regards to the lowest values.
- if values greater than 90% are concerned, the two densities appear almost overlapped.

So, the main conclusion seems to be that this *prediction* is particularly useful in enhancing accuracy for “very unpredictable” flights, while for very regular flights the *default choice* and the *prediction* are almost always the same.

This conclusion is confirmed by the correlation between the default accuracy and the relative increase due to the prediction, clearly represented in Figure 9 (Δt = 4h):

In the following, results about relative improvement are often reported only for Δt = 4h. The reason is that this Δt is computed on a larger sample than Δt = 8h, and at the same time the differences in relative improvement are more visible than for Δt = 2h and 1h.

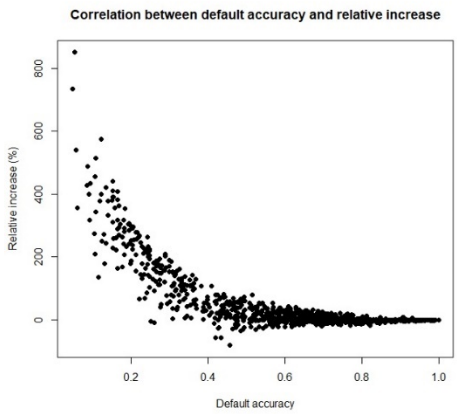
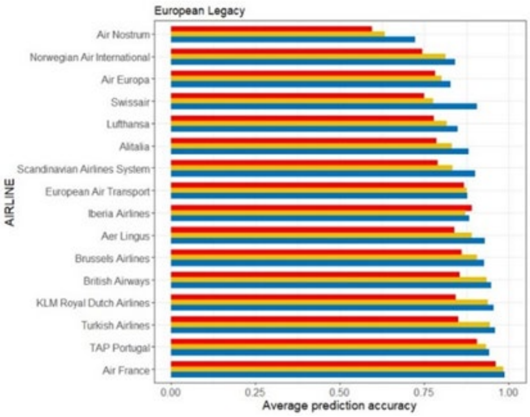


Figure 9: Correlation between default accuracy and relative improvement for the Δt = 4h time horizon.

From Figure 9, it is also possible to understand the global distribution of the relative increase: the most frequent value is 0 and, though there are some (very few) negative values (which means, cases in which the default prediction would suggest the right trajectory while our prediction fails), the general mean is “pushed up” by the many high values. The maximum is around 800%, which means there are flights for which the accuracy of our prediction is 8 times greater than the default (e.g., 0.1 of default accuracy and 0.8 of prediction accuracy).

Now, we have a look at how the *prediction accuracy* is distributed with regards to airlines. These graphs are referred to spring; summer graphs are not reported since there are no meaningful differences. For the comparison to be meaningful, Δt = 8h was not represented, for the previously explained reasons.



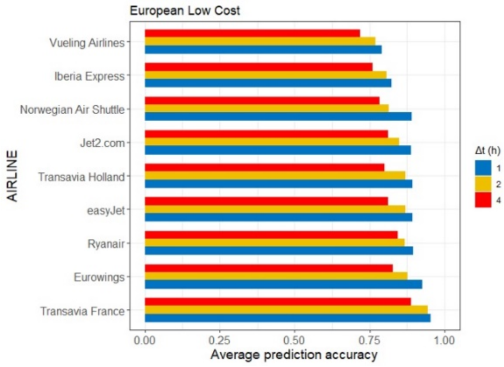


Figure 10 and 11: Average prediction accuracy for European Legacy and Low-Cost airlines.

Three main considerations arise:

- In most of the airlines the prediction accuracy increases as Δt decreases.
- There are some slight differences between airlines, but basically the prediction reaches a similar level of accuracy in for all the airlines, apparently without any bias.
- The level of accuracy is, on average, over 80% for the great majority of airlines.

What is probably of major interest is to evaluate the *average relative improvement* in accuracy for each airline. In fact, this value is informative: if it is high, it means that the unpredictability of that airline is “systematic enough” to become predictable, and so it is likely to be part of a strategy.

Graphs are relative to Δt = 4h, both seasons. The number of flights involved in the analysis is reported next to each bar. The horizontal axes have different scales in the two seasons since the relative improvement in summer has highest values. European airlines show a clear behaviour: Air Europa, Alitalia and Air Nostrum (legacy) and Vueling, Ryanair and Iberia Express (low cost) have significantly higher values than the others, in both seasons.

Also, the companies with the smallest values are consistent in the two seasons. The aforementioned airlines show the same behaviour also when we compare them with other airlines traveling on the same routes, as represented in Figure 11.

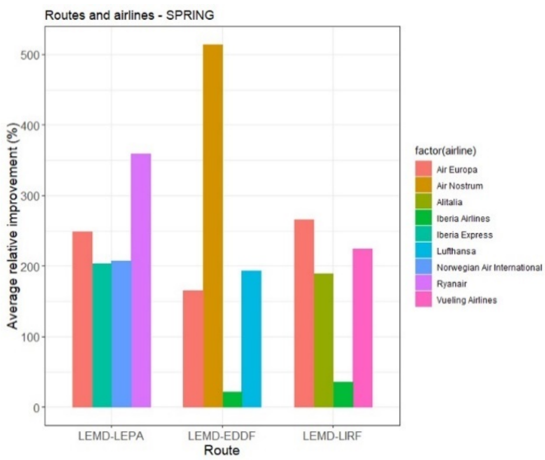


Figure 11: Comparison between airlines flying the same route in the spring period analysed.

By means of the previously described predictive model, it is possible to estimate the probability of change of every flight (given that the flight is a regular and frequent one). The following graph (Figure 12: Average probability of change of Lufthansa for Δt = 4h for different routes during the diurnal shift. is relative to the *diurnal shift* and it is referred to Δt = 4h. Callsigns with average probability of change less than 0.01 are not shown.

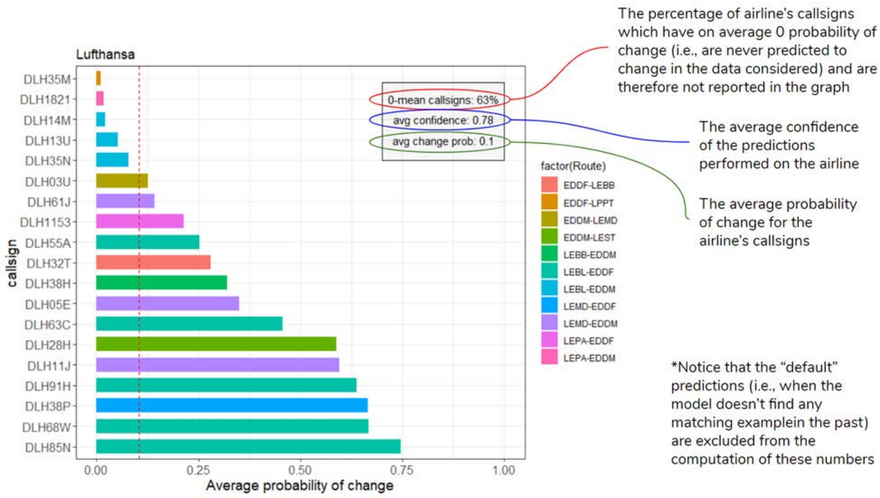


Figure 12: Average probability of change of Lufthansa for Δt = 4h for different routes during the diurnal shift.

Furthermore, the probability of change is not independent of the route; in Figure 13 and Figure 14, it is clear that the same airlines can behave in quite different ways on different routes, while on the same route, different airlines tend to behave in similar ways.

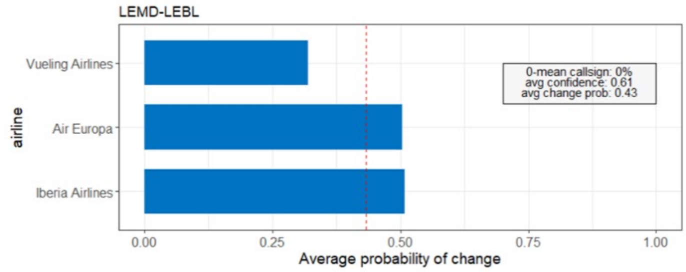


Figure 13: Average probability of change in the route LEMD-LEBL for the airlines: Vueling, Air Europa and Iberia.

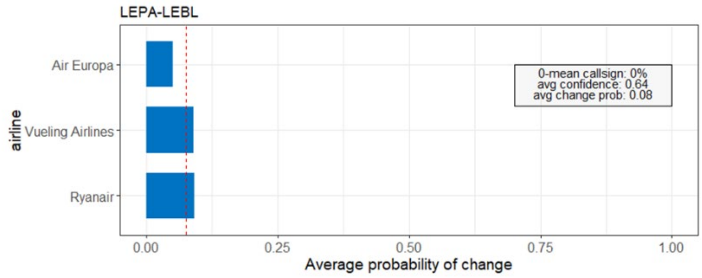


Figure 14: Average probability of change in the route LEPA-LEBL for the airlines: Vueling, Air Europa and Ryanair.

Another observation that deeper analyses suggest is that flights departing from some airports (especially the biggest ones) seem to have higher probability of change, e.g. LEMD.

4.2 Predictive model: Low-resolution scenario analysis

This scenario is referred to the ECAC (European Civil Aviation Conference) area, trying to apply similar analysis. Is to be noted that the European-wide data source (DDR – Demand Data Repository) is a determinant factor in what can be applied. The study has tried to illustrate the result by applying a similar approach to this scenario, for reference.

In order to render the low-resolution analysis comparable with the high-resolution one, we needed to find the correspondent definition of waypoints; to do so, we compared the trajectory description of DDR with the one in the data from the first scenario, whenever the same flights are involved (i.e., flights whose entire trajectory pertains to Spanish airspace).

Here is an example from the 1st of June 2018, a flight from Madrid to Valencia:

- high-resolution (spatial) trajectory description:
  MD14L; MD050; MD035; NANDO; MINGU; ABOSI; CLS; OPERA; VLCT
- low-resolution trajectory description:
  20180601142400:LEMD:NANDO1U:20:0:A:402820N0033339W::Y
  20180601142415::DCT:25:1:V:402759N0033304W:14:Y
  20180601142443::DCT:35:4:V:402657N0033121W:57:Y
  20180601142513:*MD50:NANDO1U:48:7:D:402554N0032937W::Y
  20180601142517::DCT:50:8:V:402538N0032900W:6:Y

20180601142600::DCT:70:13:V:402415N0032558W:38:Y
20180601142645::DCT:90:19:V:402237N0032219W:75:Y
20180601142709:*MD35:NANDO1U:100:23:D:402131N0031953W::Y
20180601142820::DCT:130:35:V:401902N0031206W:11:Y
….

This kind of behaviour is rather systematic, so to apply the model to the new scenario we used as waypoints the information in the second field of the variable. The low-resolution model was built by mimicking the high-resolution one, with the necessary adaptations. In fact, since in this scenario we only have one flight plan per day, the predicted trajectory is the most probable one given the flight plan of the day before.

The model, as in the high-resolution case, has two main functionalities: predict if the trajectory will change and predict the final trajectory (and its probability). The following results are relative to about 8000 flights (i.e., the ones flying every day) in June 2018.

The model was tested on the last week of the month; for each test day, all the preceding ones are used as training set. This assessment methodology is slightly different from the one adopted in the high-resolution scenario since in this case the order of days is absolutely not negligible.

For each flight, the predictive accuracy of the model was computed. The performance on low-resolution scenario is - quite predictably - lower than the high-resolution one. The main reason for this is the probability of change:

- In the high-resolution scenario, we compared the last-before-EOBT trajectory with the flight plan recorded 2h/4h/8h before, and in the vast majority of cases the input trajectory was already reliable, with a probability of change on average around 20%;
- in this low-resolution scenario, we compare today's trajectory with yesterday's one, and the probability of change is on average 55%.

Furthermore, this change rate (and therefore also the accuracy of the model) is distributed in quite an uneven fashion. Figure 15 shows the distribution of airlines' change rate, from which there are a huge amount of extreme values.

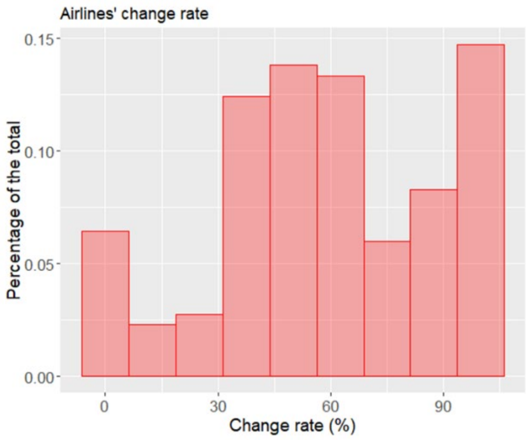


Figure 15: Airline's change rate.

For this reason, the median accuracy is considered, instead of the average one, since is more robust to extreme values:

- Median accuracy per flight of the model: 67%
- Median accuracy per flight without the model: 33%

As in the high-resolution case, we can retrieve some interesting information on airlines by looking at the distribution of the *average relative improvement per airline*. The median value is around 500% (e.g., if the probability of correctly predicting tomorrow's trajectories for an airline just trusting today's trajectories is 15%, on median thanks to the model it will be 75%). Also, in this case, values are actually very spread, and a central value cannot be representative.

Figure 16 shows the average relative improvement of some airlines. In general, all the values range between 0 and 3. Notice the x-axis is not expressed in percentage (e.g., 3 is 300%).

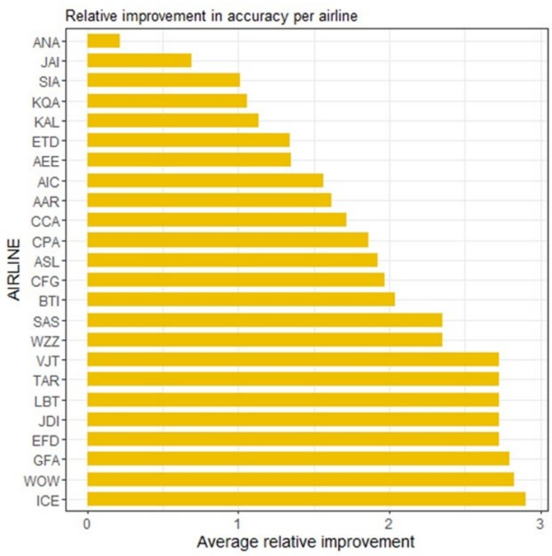


Figure 16: Average relative improvement of some airlines.

4.3. Use case application/Mock-up tool

The proposed model generates, for each individual scheduled flight of a given day, the prediction of the most likely flight plan (FP) submitted by the airspace user (AU) hours before the expected off-block time. The purpose of this model, when applied to one operational use case, is to provide the Network Manager (NM) and Air Navigation Service Providers (ANSPs) with additional information about the upcoming flights and a prediction of the demand of airspace that improves the current methods based on the FPs issued by the AUs and on historical data.

To validate the use case and expected benefits of the model, we interviewed potential target users, developed a static mock-up to demonstrate how the associated tool could be integrated in the current workflow, and eventually collected target users' feedback on the developed mock-up.

The process is summarised as follows:

1. Interviews to target users
2. Definition of user needs and requirements
3. Redesign of strategic planning, enhanced by the proposed model
4. Design of HMI (Human Machine Interface) mock-up
5. Analysis of data to be visualised into the HMI mock-up
6. Feedback from target users

5. RESULTS

5.1 Use case application/Mock-up tool results

The scheme in Figure 17 represents how the planning process of the NM could be modified to include the information generated by the model.

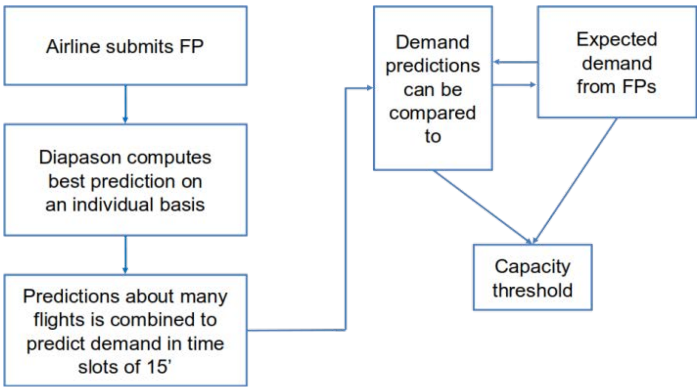


Figure 17: Schematic of the way the proposed tool predictions could be integrated in the planning process at NM level.

Every time an airline submits a FP hours before the EOBT, the proposed tool (called DIAPasON or Data-drIven approach for dynamic and Adaptive trajectory PredictiON) computes the best prediction of what the final FP will be.

While each prediction could be useful also on its own individually, the target users expressed a need of aggregate information, about all flights predicted to cross specific airspace sectors within a certain time interval. This prediction corresponds to the overall demand of traffic as a function of time in every given sector.

As soon as FPs become available, the predicted demand computed with our model can be compared to the expected demand calculated from the airline FPs. Both demands are to be compared with the capacity of the sectors at any given time of the day. The objective of the planning is to always keep the demand below the capacity threshold.

The main benefit occurs when the predicted and expected demands differ, and essentially when one of the two exceeds the capacity threshold. In this situation, the planner must choose between the model prediction and the expectation based on the FPs.

At this stage, the HMI mock-up is designed to display the flights exceeding the capacity threshold and for which there is a discrepancy between the model prediction and the expected FP.

As the model prediction comes with an indication of the prediction quality (in percentage), a different design option would be to decide a threshold over which only this prediction is considered.

To give a demonstration of how the model can be integrated in the tools for planning that are already in use at the pre-tactical level, we developed a static HMI mock-up, which was used to collect feedback from target users. The mock-up is meant to capture the benefit to current planning processes, focusing on the role a new tool might play. The look & feel simulates an interactive tool, and it was implemented using an off-the-shelf prototyping software (i.e. Figma).

To design the role and the mock-up look&feel, we first designed a storyboard, describing:

- User input
- System reaction
- HMI sketch

We took 6 months of data from 01/02/2018 until 30/09/2018, which include 26369 individual flights, with focus on the flights connecting the two main Spanish airports, LEMD and LEBL, with a limited number of European airports, LPPT, LFPG, EGLL, and LIRF. To understand the extent to which the model prediction differs from the FP data 4-8 hours before EOBT, we plotted the trajectories on maps, as illustrated in the following Figure 18.

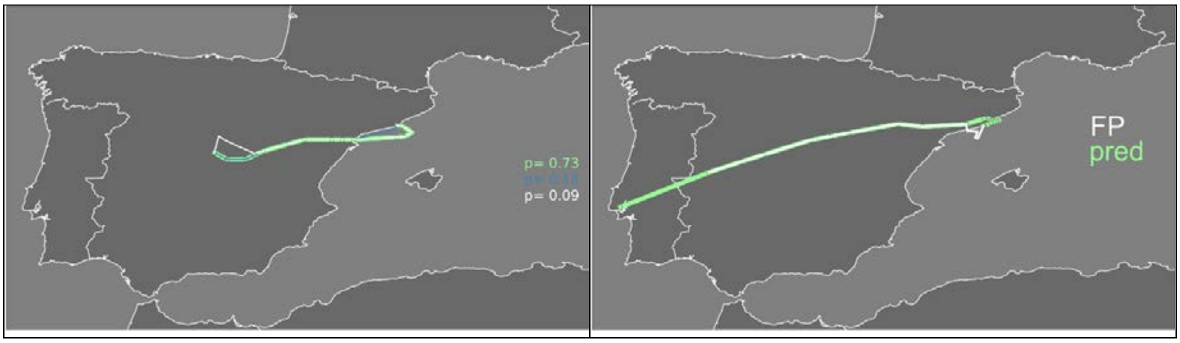


Figure 18: (left) flight #2328616 MAD - BCN on 20/06/2018 with 3 alternative predictions from the model with decreasing likelihood of being accurate. (right) submitted FP for flight #2326321 BCN - LIS on 02/02/2018 (white line with open circles) and corresponding predicted trajectory (green).

This illustrates how, compared to the FP submitted by the AUs 8 and 4 hours before EOBT, respectively, the model prediction at the same time points leads to a more accurate estimate of the last FP before operations. Figure 18 also depicts a problem encountered in the majority of the trajectories selected at this stage: in particular, despite being more accurate, the predictions of the model differ from the FP only in the regions immediately surrounding the TMAs (Terminal Manoeuvring Areas), while the two coincide in most of the en-route phase. This difference is only of limited benefit for the target users, as it might be related to local needs emerged at contingency level (an issue on a runway, a change in local weather conditions, etc.), and therefore as a follow up we choose a different approach to select the flights to visualise on the map.

In our revised approach, we focus on one week dataset (25 – 31 May 2018) and we select only flights that exhibit significant differences in the en-route waypoints Figure 19 and Figure 20 below show some of the results obtained with this selection criterion. For these flights, the model may enable a better demand prediction in en-route sectors.

Figure 19: FP (white) and model prediction (blue) 4 hours before EOBT for flight #3229838 LIRF – LEBL.

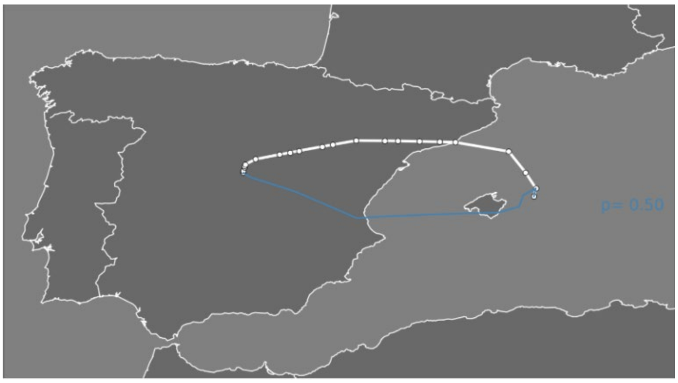


Figure 20: Same as Fig. 3 for flight #3229078 LEMD – LEMH.

The next step to develop the HMI mockup is to visualise the map of the Spanish en-route sectors of the Madrid, Barcelona and Sevilla ACCs (Area Control Centres). For these sectors, we study the occupancy demand and capacity as a function of time. In particular, we highlight in red the suffering sectors in which either the expected occupancy calculated with the FPs or the model-predicted occupancy (or both) exceed the declared threshold capacity of that sector at a given time. By selecting one such a sector, the user access to additional information, namely:

- The expected occupancy as a function of time compared to maximum capacity.
- The predicted occupancy as a function of time compared to maximum capacity.
- The list of flights expected to cross the sector in the time interval in which the demand exceeds the capacity.
- For these flights, the comparison of the trajectories in the FP and in the predictions, with their associated probability.

These data are meant to support the decision process of the target users at pre-tactical level as follows:

- By drawing attention on sectors that will be under stress in the course of the day.
- By enabling a more accurate estimate of the sectors’ occupancy than that obtained from the FPs.
- By showing how the sectors under stress may vary in the forecasts based on FPs and our model.
- By displaying the expected and predicted trajectories of flights that might overflow sectors close to the capacity limit.

A second round of interviews has been conducted among target users to obtain their feedback on the HMI mock-up (in terms of functionality), on the model, and on the way the information generated by the proposed model could be integrated in the existing tools currently adopted by air traffic controllers and the NM.

During the interviews, the HMI mock-up was presented to the target users and subsequently the following questions were asked to guide the discussion.

- What are your first impressions?
- What do you like/find useful in this tool?
- Would you change or add anything to the tool?

In general, the response was very positive. In the context of the development of an innovative tool to support the decision process at a pre-tactical level, the most relevant elements the interviewees appreciated include, among others:

- The graphical layout of the interface which resembles other tools currently adopted by Eurocontrol and ANSPs.
- The way the information is delivered was perceived as very clear.
- The actions that were mimicked in the HMI mock-up (such as the selection and visualisation of critical sectors or critical time intervals, the visualisation of individual flights, etc.) were perceived as intuitive to understand and to perform.
- The histograms with the aggregated data about the evolution of the sector occupancy in time were perceived as clear. The interviewees were very familiar with this way of conveying the information and they consider it fundamental to have a thorough view of how the demand of airspace will evolve in each sector. The possibility to directly compare between the expected and predicted air traffic load was considered very useful.
- The panel with the additional information about the reliability time of the airlines, i.e. the threshold in time after which, on average, a given airline is unlikely to change the FP, was found innovative and insightful.

The interviewed target users provided thorough advice on possible aspects to consider and explore in the further development of the tool:

- Attention should be paid to the possible reasons that trigger a change in FP: this could be related to the weather conditions, temporary needs of the company, regulations, and so on. The case of imposed regulations should be studied separately, as they force AUs to take a decision that normally they would not make. Therefore, it is interesting to isolate the situations in which the AUs actively take a decision from the cases in which they are subjected to a decision taken at ATM level.
- A useful information to include is the dynamical evolution of the sectorisation. This information would provide the users with elements to evaluate if the currently planned sectorisation is the best possible or if it is possible to adapt it to the forecasted traffic, for example merging two sectors that are both predicted with a limited load. It would be useful for the controller to visualise the consequences of this decision, namely by how much the traffic would increase on the merged sector, for how long the new configuration could be sustainable, etc.

- Target users consider useful to have the possibility to dynamically change the size of the time window at which to look at when studying the overall traffic load on a specific sector over time. In particular, at ATCO level it is common to visualise 20-minutes or 60-minutes slots. Sometimes, in particularly trafficked situations, it could be useful to visualise shorter time slots of 5-10 minutes.
- The interviewees confirmed that the tool is most useful in predicting variations in the en-route phase of the flights. This is because variations in the TMA are most often connected to local needs at airport level and consequently lack the regularity that is necessary to have reliable predictions.
- The future tool could integrate data-based advice to the users on how to react to a foreseen critical situation, for example by showing and comparing the impact of different decisions, such as: imposing a regulation on one or several flights, opening a new sector, collapsing two sectors, etc.
- The future tool should include the vertical dimension, which is considered a fundamental information to optimise the air space management.
- An intriguing development of the tool to improve its efficacy at airport/TMA level is to include the temporal dimension and a precise timing of the arrivals. This could help avoid congestion at airport level.

5.2 Predictive Model results

In this Section we present a summary of the validation performed to the predictive model.

The objective is to show the differences in occupancy counts per sectors between the real data in the planning phase and the output provided by our model.

It is important to note that for the validation of the model presented in this section, the time and altitude were estimated (so that we had a 4D trajectory), while in the results presented in section 3.1, it was only considered the 2D prediction of the waypoints.

The first step was to extract the information from the Network Manager in order to obtain the number of occupancy counts based on the information of the flight plan just before the EOBT (Estimated Off-Block Time) of the flight. The second step was to extract the output from our model using the same time windows, that is, fifteen minutes width sliding fifteen minutes, as showed in Figure 21.

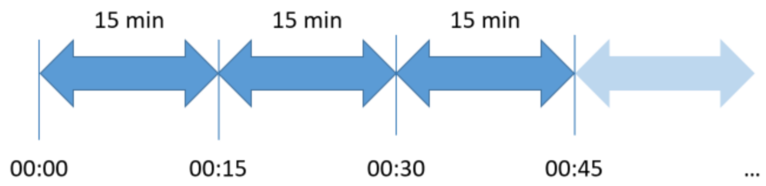


Figure 21. Distribution of times windows.

The third step was to compare the real data, flight plan before EOBT, with the computation of occupancy counts extracted from the algorithm. It is key to highlight that our model provides two different outputs: data that are just what would be predicted if the flight plans were completely reliable (and so the knowledge from the week before), and data with the prediction model. Both cases are provided in two different timestamps: eight and four hours before EOBT.

The comparison aforementioned was carried out for six different days from summer and winter season of 2018: 18th, 20th and 23rd of June, and 19th, 21st and 24th of November (Monday, Wednesday and Saturday), and for two different sectors: LECMTLL and LECMASU. A summary of the results are presented in Figure 22, Figure 23, Figure 24, Figure 25 and Figure 26 , where the light blue line is the real data, "fp" stands for flight plan (trusting in the reliability of the flight plan), "pred" corresponds to the output with the model, and DT4 and DT8 are the two different timestamps described.

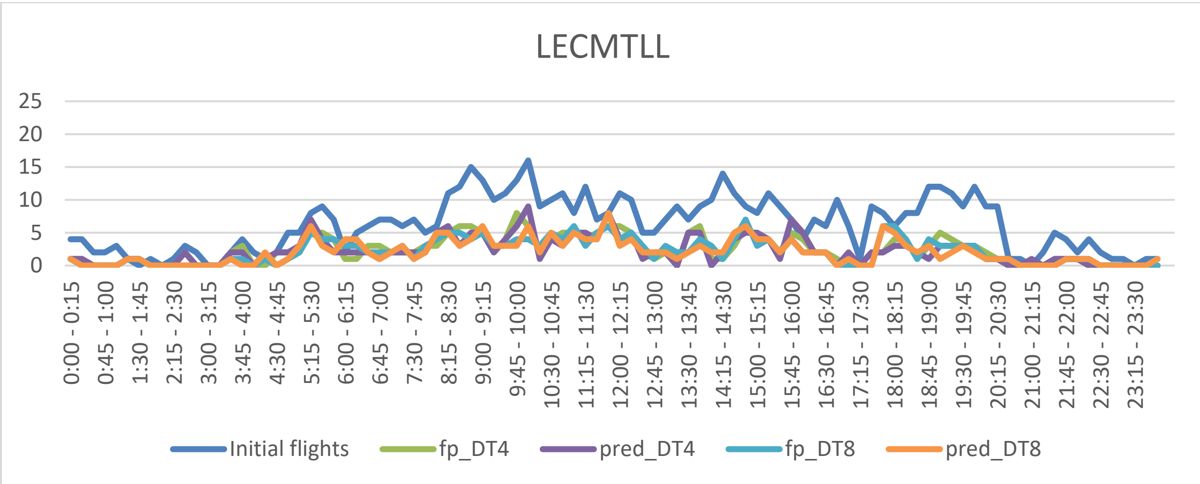


Figure 22. Comparison for 18th of June in LECMTLL sector.

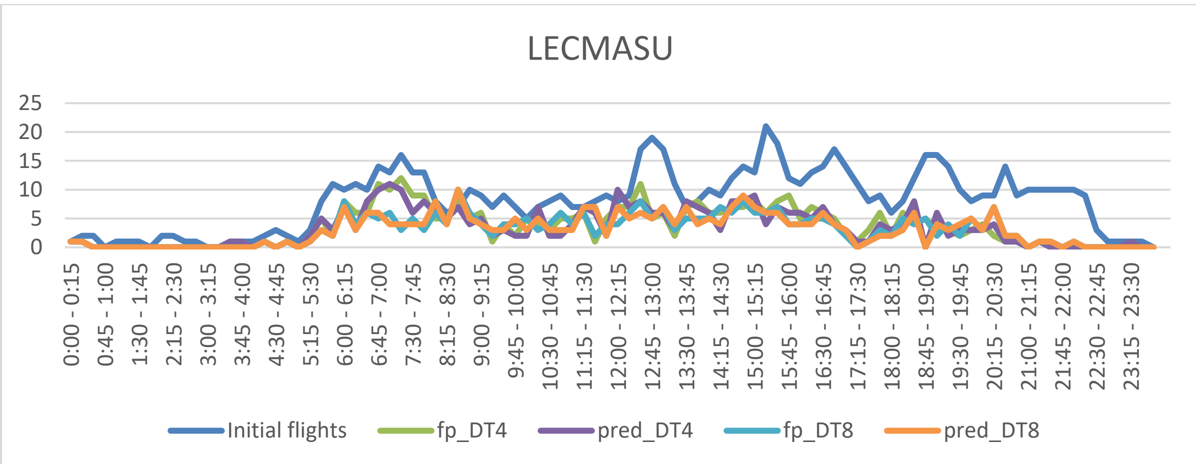


Figure 23. Comparison for 18th of June in LECMASU sector.

Figure 22 and Figure 23 show the comparison between the reality and the forecast for 18th of June 2018 and for two different sectors: LECMTLL and LECMASU.

In both cases, the trend of the occupancy counts is captured by the forecast, but it is interesting to underline that the behaviour of the prediction is better in the case of LECMASU than LECMTLL which is a sector with most of the flights in evolution, instead of in en-route phase, more typical for LECAMSU sector. Moreover, zooming in to a specific period, as seen in Figure 24 , it can be said that, in general, the prediction 4 hours before the EOBT is better than the one 8 hours before.

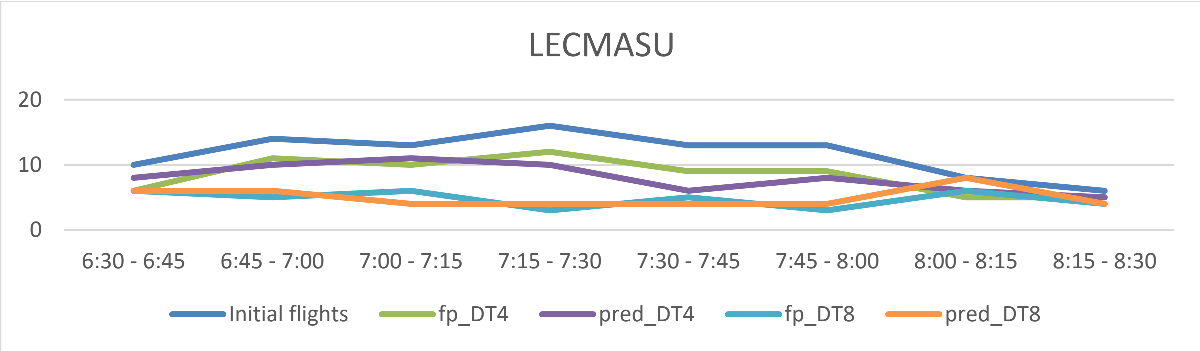


Figure 24. Comparison between DT4 and DT8.

Regarding the day of the week, there are no important differences, and the trend of the occupancy counts is also captured, as it can be seen in Figure 25.

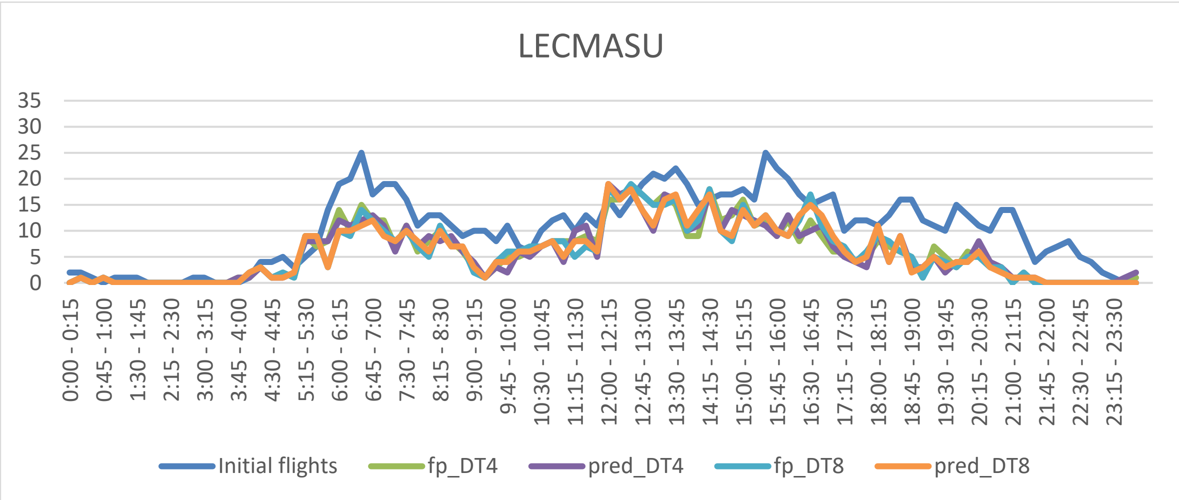


Figure 25. Comparison for 23rd of June in LECMASU sector.

However, for winter season the difference between forecast and reality is higher than in summer season, as it can be seen in Figure 26, which can be explained by the uncertainty induced by bad weather.

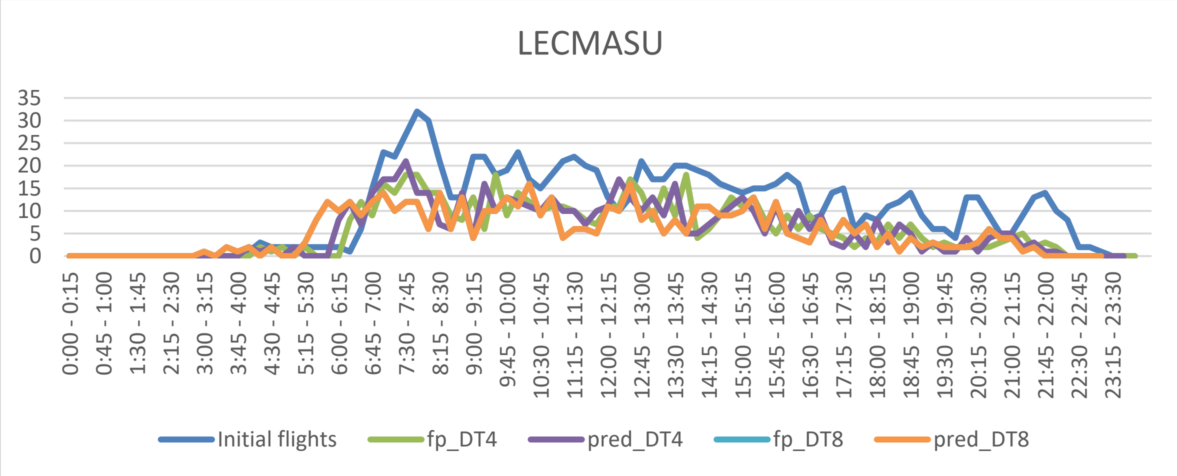


Figure 26. Comparison for 24th of November in LECMASU sector.

6. CONCLUSIONS

Our study focuses on the need of the ATM system to develop tools and methodologies that are able to support traffic and trajectory management functions. For these activities, trajectory and traffic prediction is key, in particular within the context of Trajectory-Based Operations (TBO).

While there are previous research addressing these matters, we present a different approach. In particular, the study aims at analysing patterns of flight plan evolution for individual flights, and extract patterns and feature which can be applied in a wide number of operational contexts where this information is available. The main result of the study is the development of a methodology for TP and traffic forecasting in a pre-tactical phase (from a few days to a few hours before the operations, when a only limited number of flight plans are available). This can be adjusted to different time scales (planning horizons), considering the level of predictability of each of them and the specific use case to where it should be applied. These results have been explored with support of operational staff to maximize the benefits in pre-tactical phase.

Hence, we aimed at developing a methodology for Trajectory Prediction and traffic forecasting in a pre-tactical time horizon (covering from one to six days prior to operation), period in which few flight plans are available.

As a result of the work conducted, the study has obtained a Trajectory Prediction framework with the following characteristics:

- Data-driven, as the methodology is based on data analysis and its interpretation.
- Dynamic, as it can be adjusted to different planning horizons.
- Adaptive, as it the methodology can be enhanced through the inclusion of new tactical data.

- Airspace User oriented, as the framework is adapted to the characteristics and strategies of different AUs.

Both the actual specific implementation based on operational Spanish data and the overall methodological framework allowing extension to any similar context of operations are considered sufficiently usable and having reached the targeted TRL4 maturity. In particular, the implementation for Spanish data is considered a candidate for inclusion in operational decision-making support tools.

The Trajectory Prediction Framework has been developed in both a high resolution and low-resolution scenario:

- For the high-resolution scenario, a predictive model was developed using actual high-quality operational data from the Spanish ANSP, ENAIRE.
  Results of the predictive model derived in the study were analysed in different time horizons to conclude that the lowest accuracy is found in $\Delta t = 4$ and not in $\Delta t = 8$. This can probably be explained with the fact that not all the considered flights submit flight plans with the anticipation of $\Delta t = 8$ every day, so the prediction accuracies for different Δt are computed on slightly different samples. The main outcome is that the model significantly enhances the prediction accuracy for "very variable" flights, while for very regular flights the default choice and the prediction are usually the same.
  The prediction accuracy of the model was also computed for different airlines, concluding that in most of the airlines the prediction accuracy increases as Δt decreases, being similar for mainly are airlines and over 80% in most of the cases.
- For the low-resolution scenario, the predictive model was developed using DDR data instead, to cover the ECAC area. In order to make this scenario comparable to the high-resolution one, the correspondence between both sources of data was identified. The model, as in the high-resolution case, has two main functionalities: predict if the trajectory will change, predict the final trajectory (and its probability). The performance on low-resolution scenario is - quite predictably - lower than the high-resolution one.

On the other hand, digging on the usability and feedback from operational TP end users, the purpose of this predictive model is to provide the NM and ANSPs with additional information about the upcoming flights and a prediction of the demand of airspace that improves the current methods based on the FPs issued by the AUs and on historical data.

For this reason a series of interviews with potential target users were conducted and a static mock-up to demonstrate how the proposed tool could be integrated in the current workflow was developed. The most relevant elements the interviewees appreciated include, among others:

- The graphical layout of the interface
- The way the information is delivered was perceived as very clear.
- The actions that were mimicked in the HMI mock-up were perceived as intuitive to understand and to perform.
- The histograms with the aggregated data about the evolution of the sector occupancy in time were perceived as clear.
- The panel with the additional information was found innovative and insightful.

7. FUTURE WORKS AND LEASSONS LEARNED

To continue with the work already done in our study, two main aspects need be addressed:

- A refinement of the predictive model itself to obtain better accuracy in the low-resolution scenario, though the use of more reliable data sources to cover ECAC area.
- A refinement of the tool to present the results of the predictive model. In this sense, target users interviewed, proposed the following:
  - ✓ Attention should be paid to the possible reasons that trigger a change in FP.
  - ✓ A useful information to include is the dynamical evolution of the sectorisation.
  - ✓ Target users consider useful to have the possibility to dynamically change the size of the time window at which to look at when studying the overall traffic load on a specific sector over time.
  - ✓ The interviewees confirmed that the tool is most useful in predicting variations in the en-route phase of the flights.
  - ✓ The future tool could integrate data-based advice to the users on how to react to a foreseen critical situation.
  - ✓ The future tool should include the vertical dimension, which is considered a fundamental information to optimise the air space management.
  - ✓ An intriguing development of the tool to improve its efficacy at airport/TMA level is to include the temporal dimension and a precise timing of the arrivals.

The first lesson learned in our study is related to the use of DDR data to perform data-driven analysis based on flight plan information, as this source of information has shown to not be useful in this purpose given the lack of data on the flight plan updates. For this reason, for further works on this field, different sources of information at ECAC level should be used to obtain more accurate results. The study was able to demonstrate the importance of having high-quality operational information, such as the dataset used in the high-resolution scenario.

However, initial expectations were that, even only in the high-resolution scenario, predictions of flight plan behaviour (planned trajectories) would imply a larger accuracy when apply to an actual scenario, such as those described in the results section. The potential of such information is observed in a non-constant way, despite a very wide set of factors for predictability was addressed. This implies that this approach for TP is not applicable to all cases as implemented in our model. The use case needs to be carefully chosen to extract a maximum benefit (i.e., specific time advance, or specific shifts to be applied). The possibility to consider not just individual flights factors but repeated patterns in aggregated demand is considered to be a potential enhancement, as it would incorporate “hidden” policies or behaviours of interest for global TP/demand forecast.

An additional lesson, not unknown but definitively highlighted in the study, is how positive the input from operational staff is when applying methodologies to actual operations. The operational staff guidance and vision brings a lot of practical value to projects with a certain maturity level, such as the proposed model and tool.

ACKNOWLEDGEMENTS

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EVALUATING AIRPORT AND AIRLINE SERVICE QUALITY: A STRUCTURAL EQUATION MODELING APPROACH

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ABSTRACT

A new scale for assessing traveler experience in air trips is proposed. Here, passenger experience is measured through travelers' perception of service quality, considering it as a chain of services. The new scale is called air travel service quality (ATSQ). It considers three service quality stages: departure airport service, airline service, and arrival airport service.

This research applies the ATSQ scale to examine service quality in domestic travels in a Colombian context. Given that traveler's experience plays a crucial role in determining passenger satisfaction, a structural equation model was applied to examine the relationship between service quality stages, customer satisfaction, and behavioral intentions. Adding the passengers' perception of the arrival airport to the integrated service quality measurement is considering one of the main contributions of this study. The finding of this research confirmed that all three stages of air travel service have a significant, positive effect on passenger satisfaction. The scale found in this research should provide useful information for developing effective operational and marketing strategies for the air travel market. In this way, airports and airlines could better understand how traveler's perception of service quality may affect each choice related to which departure airport, airline, and arrival airport combination to choose from.

1. INTRODUCTION

In the air transportation industry, airlines and airports enjoy high revenues when traveler satisfaction increases because when travelers are satisfied, they are more likely to repeat their purchase. Airports and airlines recognize the necessity of studying traveler's satisfaction and identifying service quality indicators for improving the travel experience (Bogicevic, Yang, Bilgihan, & Bujisic, 2013). Some studies of airlines and the airport industry have found a significant relationship between perceived service quality and passengers' satisfaction (Park, 2010; Hussain, Al Nasser & Hussain, 2014; Al-Refaie et al., 2014; Prentice & Kadan, 2019).

Therefore, in the air transportation market, traveler's satisfaction plays an essential role in assessing service quality and its influence on loyalty (Park, Robertson, & Wu, 2005).

Different instruments have been developed to assess service quality. Parasuraman et al. (1988) proposed a model to measure service quality that included five dimensions known as tangibles, reliability, responsiveness, assurance, and empathy. The instrument was called the SERVQUAL scale. Cronin & Taylor (1992) instead developed the SERVPERF scale, which measures service quality based on customer's perceptions. Cronin & Taylor (1994) found that the SERVPERF instrument explains more of the overall variance in the measure of service quality than the SERVQUAL scale.

Bezerra & Gomes (2015)suggested that future works should be focused on integrated service quality, by including dimensions related to airline and airport service quality because they share a significant area of overlap. Airports act as the first and last contact point for air travelers, and Kirk et al. (2014) found that negative airport experience can influence future travel plans. Ekiz, Hussain, & Bavik (2006) tried to integrate service quality in two stages and developed a new instrument called AIRQUAL scale. This instrument measures airline service quality perception, by including a dimension related to the departure airport. AIRQUAL identified five dimensions of service quality: airline tangibles, terminal tangibles, personnel, empathy, and image. AIRQUAL scale has been widely applied to national and international travels (Nadiri et al., 2008; Suki, 2014; Ali, Lal Dey & Filieri, 2015; Alotaibi, 2015; Mohamed & Rani, 2016; Farooq et al., 2018).

Despite AIRQUAL applications in the air transportation industry, it might not be suitable for measuring overall traveler's experience through travel service quality measurement due to the different features of service quality related to the airline, departure airport, and arrival airport. This research attempts to extend previous works by incorporating traveler's experience with arrival airport into the perceived service quality measurement of the air travel.

This research contributes to the air travel experience literature in three aspects: first, by adding the traveler's perception of arrival airport to the integral service quality measurement. Second, by developing an assessment tool for evaluating traveler's experience in air travel, called here air travel service quality (ATSQ) instrument (Munoz, Laniado, & Córdoba, 2019). Finally, by investigating the relationship between service quality in its different service stages and satisfaction, as well as the effect of traveler's satisfaction on future intention.

2. HYPOTHESIS DEVELOPMENT

This study proposes a new instrument that measures air traveler's experience through passenger's perceptions of service quality of their recent air travel. The proposed theoretical model consists of dimensions related to the departure airport, airline, and arrival airport. This study proposes following six hypotheses:

H1: Perceived quality related to airline tangibles will have a significant positive effect on traveler´s satisfaction.
H2: Perceived quality related to airline staff will have a significant positive effect on traveler's satisfaction
H3: Perceived airline empathy will have a significant positive effect on traveler's satisfaction.
H4: Perceived quality related to the departure airport will have a significant positive effect on traveler's satisfaction.
H5: Perceived quality related to the arrival airport will have a significant positive effect on traveler´s satisfaction.
H6: Traveler's satisfaction will have a significant positive effect on brand loyalty.

3. RESEARCH INSTRUMENT AND DATA ANALYSIS

The objective of this study is to measure air traveler's experience through service quality perception, by focusing on the Colombian domestic flights. The survey questions were based on air traveler's service quality perceptions. The questionnaire was divided into five sections. The first and second sections contained demographic and the latest travel information, respectively. Third survey component had questions about service quality perception; some questions were based on the AIRQUAL scale (Ekiz, Hussain & Bavik, 2006).

The traveler's satisfaction model in air transportation was assessed, by using the structural equation modeling SEM with latent variables. The aim of constructing an SEM was to test whether the five dimensions of air transportation service quality have a significant influence on traveler's satisfaction. Besides, the supposition of whether traveler's satisfaction leads to traveler's loyalty was assessed.

The confirmatory factor analysis (CFA) was performed to confirm the measurement model and to assess the degree to which the measured variables represent the number of constructs. By using a maximum likelihood estimation method, 58 items were subjected to a CFA with a seven-factor measurement model. The results of the CFA in Table 1 show that composite reliability (CR) ranged from 0.85 to 0.97. These values were all greater than the recommended threshold of 0.70 suggested by Hair et al. (2014), implying that multiple items for each factor are internally consistent and reliable.

The average variance extracted (AVE) was used to assess convergent validity. AVE ranged from 0.53 to 0.82, exceeding the recommended threshold value of 0.5 (Hair et al.,2014), which means that more than one-half of the variances observed in the items were explained by their hypothesized constructs. Therefore, the data has good convergent validity.

Statements	**Composite reliability (CR)**	**Average Variance Extracted (AVE)**
Airline Tangibles	**0.95**	**0.76**
Airline Staff	**0.97**	**0.78**
Airline Empathy	**0.85**	**0.53**
Departure Airport Tangibles	**0.96**	**0.61**
Arrival Airport Tangibles	**0.96**	**0.66**
Satisfaction	**0.92**	**0.62**
Loyalty	**0.95**	**0.82**
Goodness-of-fit: $\chi 2/df = 2.7$, CFI = 0.9, RMSEA = 0.075		

Tabla 1 – Confirmatory factor analysis results

A detailed examination of Table 2 shows that airline tangibles (β=0.127; t-value=2.581; p<0.05) have a significant positive effect on traveler's satisfaction. Thus, hypothesis H1 is supported. Table 2 also reveals that airline staff (β=0.166; t-value=3.427; p<0.001) have a significant effect on traveler´s satisfaction, which means that H2 is supported. Similarly, the findings of this study also support H3, which proposes the significant influence of airline empathy (β=0.480; t-value=8.455; p<0.001) on traveler's satisfaction. Furthermore, a high perception of service quality related to departure airport tangibles has a significant positive effect on traveler's satisfaction (β=0.203; t-value=4.088; p<0.001), supporting hypothesis H4. It can also be noted that the arrival airport tangibles has a significant relationship with traveler satisfaction (β=0.237; t-value=4.818; p<0.001). Lastly, H6 hypothesized that there is a relationship between satisfaction and traveler loyalty. The results shown in Table 2 support this hypothesis (β=0.786; t-value=17.89; p<0.001).

Hypothesis	**Endogenous variable**	**Exogenous variable**	**Standardized estimate**	**t-value**	**Result**
H1	Satisfaction	Airline Tangibles	0.127	2.581**	Supported
H2	Satisfaction	Airline Staff	0.166	3.427*	Supported
H3	Satisfaction	Airline Empathy	0.480	8.455*	Supported
H4	Satisfaction	Departure Airport Tangibles	0.203	4.088*	Supported
H5	Satisfaction	Arrival Airport Tangibles	0.237	4.818*	Supported
H6	Loyalty	Satisfaction	0.786	17.890*	Supported
*Notes: *p<0.001; **p<0.05*					

Tabla 2 – Standardized estimates of the air travel experience model

4. DISCUSSION AND CONCLUSION

Empirical outputs via SEM demonstrated that service quality perception is a multidimensional construct, which includes service quality of departure airport, airline service quality, and service quality of arrival airport. The scale developed here is both reliable and valid. Therefore, this study contributes to the literature on air traveler's experience assessment through the validation of the ATSQ instrument (Munoz et al., 2019). This research extends on the current air traveler's experience literature to examine the effect of service quality on traveler's satisfaction and, in turn, the relationship between traveler's satisfaction and traveler's behavioral intention.

All the hypotheses formulated in this study were tested. One of the main results is that traveler's satisfaction is affected by service quality dimensions, here called airline tangibles, airline staff, airline empathy, departure airport tangibles, and arrival airport tangibles. The results of this paper indicate that departure airport tangibles, arrival airport tangibles, and airline empathy factors are the most influential constructs in terms of traveler's satisfaction. In this regard, this research finding coincides with previous studies (Nadiri et al., 2008; Mohamed and Rani, 2016; Farooq et al., 2018) due to fact that the departure airport tangibles significantly affect traveler's satisfaction.

The present study also supports previous empirical findings, where the traveler's satisfaction is an important prerequisite of traveler's loyalty (Gures et al., 2014; Hussain et al., 2014; Leong et al., 2015; Kos Koklic et al., 2017). Therefore, this study contributes to traveler's loyalty literature due to the fact that loyalty is characterized by repurchase intention and word-of-mouth communications. Hence, airline and airport management should try to keep service quality at a high level in order to increase traveler's satisfaction.

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BICICLETAS Y PEATONES
BICYCLES AND PEDESTRIANS

AFECCIÓN DE LA PRESENCIA DE CICLISTAS EN CARRETERAS CONVENCIONALES ESTRECHAS. ADAPTACIÓN DE UN MODELO DE MICROSIMULACIÓN

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RESUMEN

La presencia de ciclistas circulando individualmente o en grupo es un fenómeno habitual en las carreteras convencionales españolas. El uso compartido de estas carreteras por bicicletas y vehículos motorizados implica su interacción, pudiendo modificar la seguridad y la funcionalidad de las vías. Este efecto puede ser mayor en carreteras convencionales estrechas, donde las bicicletas deben circular por el carril, y los motorizados realizan una invasión mayor del carril opuesto durante el adelantamiento, implicando maniobras potencialmente peligrosas y una mayor duración del adelantamiento.

La microsimulación del tráfico es una excelente herramienta para analizar la funcionalidad del tráfico y la seguridad en carreteras convencionales, pero los modelos actuales no consideran a los ciclistas en este ámbito, y mucho menos su interacción con los motorizados.

En este estudio, a partir de observaciones del fenómeno, se ha adaptado un modelo, que ya consideraba vehículos motorizados en carreteras convencionales, a la circulación de bicicletas y a la interacción entre estos dos usuarios. El modelo ha sido calibrado y validado con datos reales recogidos mediante bicicletas instrumentadas y observaciones naturalísticas en una carretera convencional estrecha considerando 7 configuraciones distintas de grupos de ciclistas, variando el número de ciclistas y su configuración en línea o paralelo. La calibración se ha realizado en dos pasos, el primero a nivel microscópico con datos de adelantamientos, y el segundo, a nivel macroscópico con datos de medidas de desempeño del tramo. La duración del adelantamiento se ha considerado una variable clave para calibrar la longitud equivalente de cada grupo de ciclistas.

Los resultados confirman la reducción en la funcionalidad causada por la presencia de ciclistas, y apuntan a que se necesitan nuevas medidas de desempeño y/o la reformulación de las existentes, de modo que incorporen el efecto del tráfico ciclista sobre la funcionalidad del tráfico y la seguridad en estas carreteras.

1. INTRODUCCIÓN

La circulación de ciclistas por carreteras convencionales es un fenómeno frecuente en la actualidad. La gran mayoría de ciclistas que se observan por carretera son ciclistas deportivos que circulan de manera individual o bien forman parte de un grupo. En 2019 el número de ciclistas y clubes federados en España fue de 74768 y de 3878 respectivamente (Ministerio de Cultura y Deporte, 2020). Al mismo tiempo que ha aumentado el número de ciclistas en las carreteras también lo ha hecho el número de accidentes con ciclistas involucrados. En 2019 se registraron en España 7837 accidentes con ciclistas implicados, aunque la mayor parte se produjo en vías urbanas (72%), en vías interurbanas se registró el 60% de las víctimas mortales. De hecho, en 2019 murieron 48 ciclistas en vías interurbanas, 5 más que en 2018 (Dirección General de Tráfico, 2019). Estos datos apuntan a la necesidad de investigar las interacciones entre ciclistas y vehículos motorizados en estas vías, y a definir medidas que aumenten su seguridad.

Las carreteras convencionales suponen el 90% de la red de carreteras en España (Dirección General de Tráfico, 2019). Estas carreteras han sido diseñadas teniendo en cuenta solamente a los vehículos motorizados, y la mayoría de ellas no dispone de arcenes suficientemente anchos ni de ninguna infraestructura diseñada para la circulación de ciclistas. En la Diputació de València un 68% de las carreteras convencionales disponen de arcén inexistente o impracticable, presentando un ancho de vía menor de 7 m (Ministerio de Fomento, 2019), y muchas de ellas presentan una elevada presencia ciclista. Un estudio realizado por la Universitat de València, junto con las fundaciones Ponle Freno y AXA, a partir de datos de accidentes con ciclistas entre 2008 y 2013 en España facilitados por la Dirección General de Tráfico, concluyó que el 78% de los accidentes se produjeron en carreteras con arcén inexistente o impracticable (Universitat de València, 2016), demostrando que muchas de las carreteras en las que interaccionan vehículos a motor y bicicletas son secundarias, con arcén estrecho o nulo. En este tipo de carreteras el adelantamiento a ciclistas supone una mayor invasión del sentido opuesto y más maniobras iniciadas desde el seguimiento, pudiendo crear situaciones más peligrosas.

En España la circulación de ciclistas y su interacción con los vehículos a motor viene regulada por el Reglamento General de Circulación (Ministerio del Interior, 2003). En este Reglamento se permite la circulación de las bicicletas por el arcén o por el lado derecho de la calzada cuando el arcén es intransitable, y se les permite circular como máximo dos en paralelo si existe suficiente visibilidad. También se regula el adelantamiento a ciclistas exigiendo una distancia mínima de 1,5 metros.

El uso compartido de las carreteras por bicicletas y vehículos motorizados implica su interacción, pudiendo modificar no solamente la seguridad, sino también la funcionalidad del tráfico en estas vías. En España la funcionalidad del tráfico se determina mediante la metodología del Highway Capacity Manual (HCM) (Transportation Research Board, 2016).

El HCM determina el nivel de servicio que ofrece una carretera basándose en tres medidas de desempeño: el porcentaje de tiempo en cola, la velocidad media de recorrido del tramo y la velocidad en flujo libre. Para carreteras estrechas con una intensidad de tráfico motorizado relativamente baja, el porcentaje de tiempo en cola es la principal medida de desempeño que caracteriza la funcionalidad del tráfico. Sin embargo, la metodología descrita en el HCM solamente tiene en cuenta a los vehículos motorizados. En carreteras convencionales la presencia de ciclistas supone un obstáculo para los vehículos a motor, debido a la diferencia de velocidades que existe entre ellos, siendo la posibilidad de adelantamiento esencial para no penalizar la funcionalidad del tráfico. En vías estrechas el adelantamiento requiere la prácticamente total ocupación del sentido opuesto, y en muchos casos obliga a realizar un seguimiento del grupo de ciclistas previo a su adelantamiento. Esto implica que tanto el deseo, como la posibilidad de adelantamiento a bicicletas, sean mayores que entre vehículos motorizados, para una misma carretera. Por tanto, es necesario analizar en detalle la interacción entre bicicletas y vehículos motorizados en estas vías para evaluar el efecto de la presencia de tráfico ciclista tanto en la seguridad como en la funcionalidad del tráfico.

En los últimos años se han realizado numerosos estudios sobre la interacción de bicicletas y vehículos motorizados en entorno interurbano. La mayoría de ellos están enfocados a la seguridad durante el adelantamiento, centrándose en el análisis de la separación lateral y la velocidad durante la maniobra de adelantamiento y el tipo de maniobra realizada, como los realizados por Llorca et al. (2017), Bianchi Piccinini et al. (2018) y Farah et al. (2019).

Recientemente un estudio realizado por Feizi et al (2021) recogió datos de separaciones laterales utilizando una bicicleta instrumentada en distintos tipos de carreteras de Estados Unidos; una de sus conclusiones fue que en carreteras anchas con arcenes las separaciones laterales eran mayores. En España la circulación de grupos de ciclistas es una realidad que debe de tenerse en cuenta. Sin embargo, pocos estudios han considerado la circulación de ciclistas en grupos, solamente García et al. (2019) y López et al. (2020) realizaron un estudio considerando grupos de hasta 3 y 10 ciclistas respectivamente. En el presente estudio se consideran grupos de ciclistas circulando en línea y en paralelo.

A partir de observaciones en campo se pueden obtener medidas que permiten caracterizar la seguridad y la funcionalidad del tráfico en carreteras convencionales. Sin embargo, las observaciones no cubren todo el rango de demandas de tráfico existentes, y no es posible obtener algunas medidas de desempeño mediante observación directa del fenómeno. La microsimulación del tráfico es una herramienta que permite simular escenarios geométricos y de tráfico diferentes a los observados, y obtener medidas de desempeño difícilmente medibles en campo como el tiempo de demora acumulada de los vehículos. En la actualidad existen diferentes programas de simulación del tráfico, pero ninguno de ellos permite simular la interacción entre bicicletas y vehículos a motor en entornos interurbanos. En este estudio se ha utilizado el sofware de simulación de tráfico Aimsun Next (Aimsun, 2020).

Aimsun Next dispone de un módulo que permite simular adelantamientos entre vehículos motorizados en carreteras convencionales desarrollado por Llorca et al. (2015), y que fue calibrado y validado con observaciones en campo. En este estudio se pretende incorporar a las bicicletas como un nuevo usuario en este modelo, con sus respectivas características, considerando la interacción con los vehículos motorizados y la circulación de grupos en línea y en paralelo.

El adelantamiento a grupos ciclistas presenta algunas particularidades que deben adaptarse al modelo existente para vehículos motorizados. El modelo debe de representar la realidad, considerando las interacciones entre motorizados pero incorporando a las bicicletas, por tanto, los parámetros que rigen las interacciones entre motorizados deben adaptarse sin variar el comportamiento entre ellos.

Las principales limitaciones del modelo actual son la imposibilidad de simular la invasión parcial del carril opuesto durante el adelantamiento y la no consideración de anchos de vía ni de vehículos. Para superar estas limitaciones se ha modificado el modelo, calibrando las longitudes equivalentes de los grupos de bicicletas de manera que las duraciones de los adelantamientos coincidan con las observadas, incorporando así el efecto de invasiones parciales del carril opuesto, y la configuración del grupo de ciclistas.

Se consideran diferentes longitudes para grupos circulando en línea o en paralelo, considerando el diferente ancho de cada grupo de ciclistas.

Este estudio es la continuación de Moll et al. (2021), donde se calibró y validó el modelo considerando ciclistas; sin embargo, solo fueron analizados ciclistas circulando en paralelo. Dado que la presencia de grupos ciclistas en línea también es muy habitual, este estudio se centra en la influencia de esta configuración y en la comparativa de las mismas con el objetivo de analizar la seguridad y la funcionalidad del tráfico en estas vías.

2. OBJETIVOS E HIPÓTESIS

El objetivo principal de esta investigación es analizar el efecto que tiene la presencia de tráfico ciclista en la seguridad y la funcionalidad del tráfico en carreteras convencionales mediante el uso de un microsimulador de tráfico, considerando a los grupos de ciclistas circulando en línea y en paralelo. Para ello se desarrollaron dos metodologías de tomas de datos en campo que permitieron obtener los datos necesarios para adaptar, calibrar y validar un modelo de microsimulación de tráfico que incorpore a estos usuarios, su comportamiento y sus interacciones.

Las hipótesis de partida consideradas son las siguientes:
La presencia de ciclistas reduce la velocidad media de recorrido de los vehículos motorizados.

- A mayor número de ciclistas que forman el grupo mayor será su afección sobre la funcionalidad y la seguridad.
- Cuando los ciclistas circulan en línea su afección es mayor que cuando lo hacen en paralelo.
- El uso de microsimulación del tráfico permite obtener medidas de desempeño difícilmente medibles en campo.

3. METODOLOGÍA

Para llevar a cabo este estudio se han diseñado y realizado dos tipos de tomas de datos reales en campo; por una parte, se han instrumentado bicicletas con la finalidad de obtener datos relativos a la maniobra de adelantamiento a nivel microscópico, y por otra, se han realizado tomas de datos en la entrada y salida del tramo de estudio para obtener medidas de desempeño a nivel macroscópico.

Una vez recogidos y analizados todos los datos, tanto a nivel microscópico como macroscópico, se modela el fenómeno en el microsimulador de tráfico, y se calibra y valida con los datos observados en campo, considerando la circulación de los grupos de ciclistas en línea y en paralelo.

Con el modelo de microsimulación se obtendrán las medidas de desempeño consideradas en el HCM y otras que caractericen el efecto de la presencia de ciclistas, y se verificará la validez del modelo para simular carreteras convencionales estrechas con tráfico motorizado y ciclista.

3.1 Tramo de estudio

El tramo de estudio está situado en el sur de València, en la carretera CV-502, entre los PK1+315 y PK3+500. En este tramo se realizaron diversos aforos y se comprobó una elevada presencia de tráfico ciclista, tanto en días laborables como festivos, ya que se trata de un tramo habitual en los recorridos de los clubes ciclistas. La Fig. 1 muestra la ubicación del tramo y sus características geométricas.

Fig. 1 - Localización y características del tramo de estudio.

Se trata de un tramo de carretera convencional sin arcén, con un ancho de carril de 3.5 m, una IMD de 3544 veh/día y un porcentaje de vehículos pesados de 2.07% (Diputació de València, 2020). El tramo de estudio discurre paralelo a la playa, y la pendiente es prácticamente nula en todo el tramo.

La longitud del tramo es de 2185 m, y la velocidad límite es de 70 km/h. Se trata de un tramo homogéneo, sin entradas ni salidas intermedias de vehículos. Para poder modelar el tramo en el simulador de tráfico se ha realizado un estudio determinando las características geométricas del tramo, tales como líneas continuas, velocidades límite y señalización viaria.

Estos datos se han tomado en los dos sentidos de circulación, y son necesarios para incorporar el tramo en el simulador de tráfico correctamente.

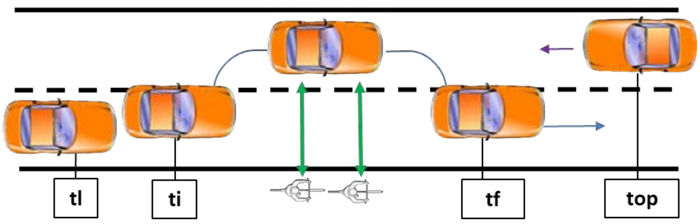
3.2 Datos a nivel microscópico

Para modelar correctamente las interacciones entre vehículos motorizados y ciclistas es necesario conocer en detalle la maniobra de adelantamiento, ya que esta es la interacción más importante que se produce entre ellos. Para estudiar esta maniobra se ha diseñado una metodología de toma de datos basada en la circulación, por el tramo de estudio, de bicicletas instrumentadas que permitan registrar datos durante las maniobras de adelantamiento. La instrumentación detallada de las bicicletas puede consultarse en Moll et al. (2021), y puede verse en la Fig. 2.

Los ciclistas recorrieron el tramo en las siete configuraciones de grupo mostradas en la Fig. 2. Los ciclistas que participaron en las pruebas tenían experiencia en el ciclismo de carretera, y circularon libremente manteniendo la configuración del grupo indicada. Para la realización de las pruebas los ciclistas llevaron ropa deportiva adecuada y casco, ya que su uso en obligatorio en carretera.

Fig. 2 - Bicicleta instrumentada y configuraciones estudiadas.

En la reducción de los datos registrados con las bicicletas instrumentadas se obtuvo la línea temporal de cada adelantamiento. Se define la duración del adelantamiento como el tiempo desde que el vehículo inicia la maniobra hasta que la termina regresando a su posición natural en el carril de circulación, en la Fig. 3 corresponde con tf-ti. La duración del adelantamiento es la principal variable utilizada para calibrar las maniobras de adelantamiento a nivel microscópico.



tl: tiempo de llegada a las bicicletas; ti: tiempo de inicio de la maniobra; tf: tiempo fin de la maniobra; top: tiempo en que se observa el opuesto.

Fig. 3 - Línea temporal de la maniobra de adelantamiento.

3.3 Datos a nivel macroscópico

La metodología de toma de datos a nivel macroscópico o de sección consiste en realizar grabaciones desde una posición estática a la entrada y salida del tramo, con la finalidad de registrar en estos puntos el tiempo de paso de cada usuario y su tipología. En el caso de agrupaciones de ciclistas también se registra el número de ciclistas que componen el grupo y su configuración en línea o en paralelo. Todas estas grabaciones se realizaron con videocámaras de alta definición colocadas de forma estratégica de manera que se consiguieron grabaciones en las que se distingue perfectamente las variables de estudio sin ser advertidas por los usuarios, no afectando así a su comportamiento. La Fig. 4 muestra la metodología utilizada y las variables registradas en estas tomas de datos.

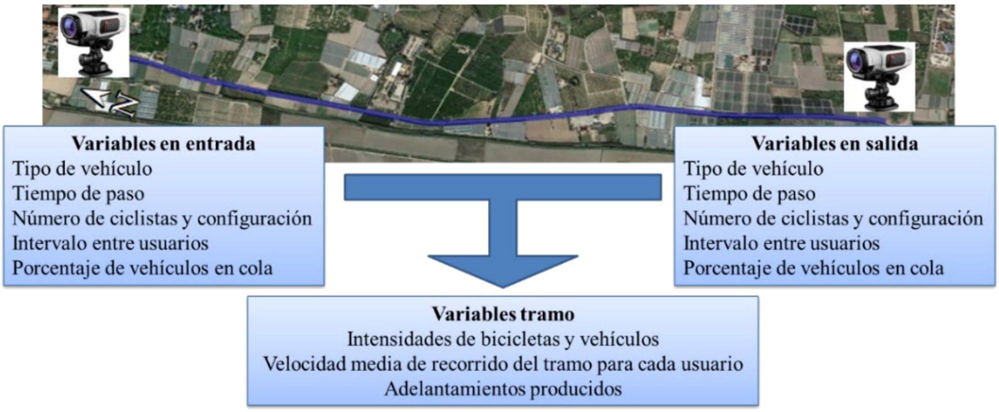


Fig. 4 - Toma de datos y variables registradas a nivel macroscópico en el tramo de estudio.

La reducción de datos se realizó mediante el software de procesamiento de vídeos Kinovea, obteniéndose las siguientes variables:

- El tiempo de recorrido del tramo de cada usuario.
- La velocidad media de recorrido de cada usuario.
- Intervalos de tiempo entre usuarios en entrada y salida.
- Porcentaje de usuarios en cola a la entrada y a la salida del tramo. Se considera que un vehículo circula en cola si el intervalo con su predecesor es menor de 3 s, siguiendo el criterio del HCM (Transportation Research Board, 2016).

A partir de estos datos se calcularon las intensidades en periodos de 15 minutos, tanto de bicicletas como de vehículos motorizados. Estas intensidades se calcularon con ventanas deslizantes de 5 minutos, y para cada valor se obtuvo la intensidad horaria equivalente. Para las bicicletas se tuvo en cuenta su agrupamiento, registrando el número de ciclistas que formaban el grupo y su configuración en línea o en paralelo. Estas intensidades horarias equivalentes proporcionaron los escenarios de tráfico necesarios para calibrar y validar el modelo de microsimulación.

3.4 Modelo de microsimulación

En este estudio se utilizó el software Aimsun Next, en su versión Aimsun Next 20. Esta versión incorpora una mejora que permite adelantar a vehículos más lentos incluso con línea continua (Aimsun, 2020), esta novedad permite representar la realidad más fielmente, ya que la normativa española permite adelantar a bicicletas en línea continua si existe suficiente visibilidad según el Reglamento General de Circulación (Ministerio del Interior, 2003).

Aimsun Next dispone de un módulo de adelantamiento en carreteras convencionales desarrollado por Llorca et al. (2015). En este estudio se adapta el modelo existente a la circulación de bicicletas y motorizados y a su interacción, y se calibra y valida con datos observados. La metodología de desarrollo del modelo de microsimulación, y la calibración y validación se puede consultar en Moll et al. (2021).

4. RESULTADOS Y DISCUSIÓN

4.1 Resultados de la toma de datos a nivel microscópico

Mediante la metodología de toma de datos a nivel microscópico se han recopilado un número elevado de variables relacionadas con la maniobra de adelantamiento entre vehículos a motor y bicicletas. Para calibrar el modelo de microsimulación solamente se utilizaron los datos de las duraciones de la maniobra de adelantamiento a los diferentes grupos de ciclistas que recorrieron el tramo en las configuraciones indicadas.

En la Tabla 1 se recogen los datos registrados de velocidades del vehículo adelantante, separaciones laterales y duraciones del adelantamiento a los distintos grupos de ciclistas. Se observa que los resultados de las velocidades del vehículo adelantante durante el adelantamiento fueron similares para todas las configuraciones de ciclistas estudiadas. En cuanto a las separaciones laterales durante el adelantamiento, cuando los ciclistas circularon en línea se registraron separaciones mayores, y en todos los casos, las separaciones laterales medias respetaron la distancia mínima exigida de 1.5 metros.

Configuración	Observaciones		Velocidad (km/h)		Separación (m)		Duración (s)	
	N	%	Media	Desv.	Media	Desv.	Media	Desv.
Individual (1)	37	16%	65.60	15.66	1.88	0.455	5.65	1.65
2 en línea (2L)	41	18%	66.39	19.35	1.78	0.461	6.71	2.11
2 en paralelo (2P)	42	19%	62.48	13.94	1.60	0.458	6.17	1.99
4 en línea (4L)	36	16%	68.46	13.55	1.91	0.42	8.58	2.22
4 en paralelo (4P)	31	14%	63.03	14.84	1.67	0.32	6.84	2.00
10 en línea (10L)	16	7%	62.06	9.72	1.99	0.39	9.44	2.22
10 en paralelo (10P)	22	10%	64.68	12.75	1.83	0.51	7.59	1.97
Total	225	100%	64.85	14.91	1.79	0.45	7.03	2.30

Tabla 1 - Número de adelantamientos registrados y datos de velocidad del adelantante, separación lateral y duración del adelantamiento según configuración del grupo de ciclistas adelantado.

4.2 Resultados de la toma de datos a nivel macroscópico

Se tomaron datos a la entrada y salida del tramo un día laborable por la mañana, iniciando a las 9:15 y con una duración poco mayor de 3 horas. Los datos se redujeron y analizaron en los dos sentidos de circulación. En la Fig. 9 se muestran las bicicletas y los vehículos motorizados ligeros acumulados registrados en cada sentido de circulación durante el periodo de toma de datos.

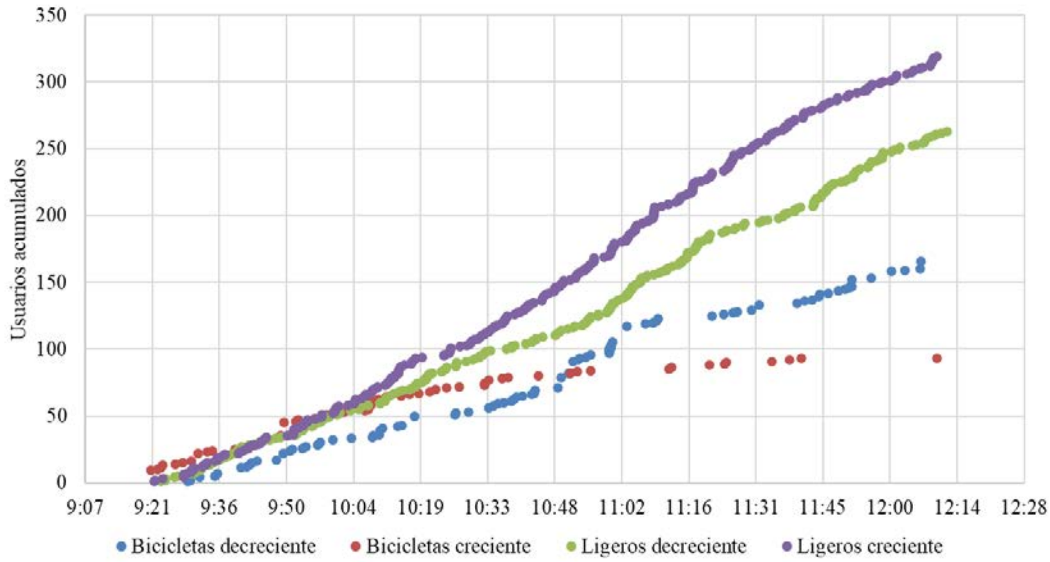


Fig. 9 - Bicicletas y ligeros acumulados registrados durante el periodo de estudio en cada sentido.

A partir de estas observaciones se decidió realizar el estudio en el sentido decreciente del tramo, ya que fue el sentido con mayor número de ciclistas observados. Se obtuvieron los escenarios de tráfico horario equivalente, a partir de las observaciones cada 15 minutos (Fig. 10).

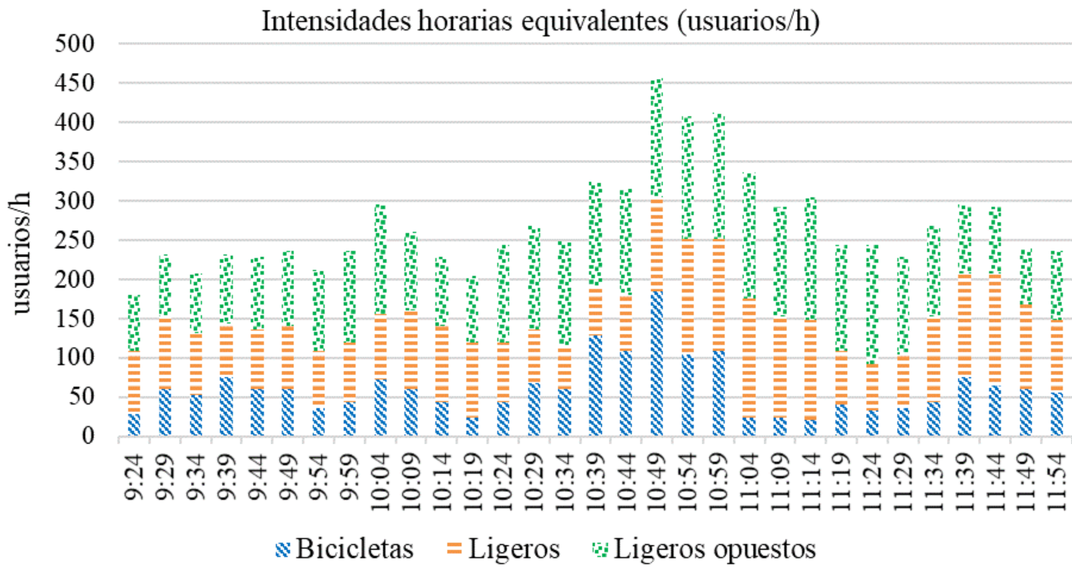


Fig. 10 - Intensidades horarias equivalentes de usuarios en sentido decreciente.

A partir de los datos observados en inicio y fin del tramo se obtuvieron las distribuciones de velocidades medias de recorrido de bicicletas y vehículos ligeros. Estos datos de velocidades son necesarios para definir las velocidades de los usuarios en Aimsun, y para calibrar y validar los resultados de las simulaciones.

Los datos de velocidades de bicicletas circulando individualmente y en pelotón se compararon mediante un análisis ANOVA y los resultados indicaron que no existe diferencia estadísticamente significativa entre las medias de las velocidades medias de recorrido de estos dos grupos ($F=0.09$, $p=0.7591$). Por tanto, a la hora de analizar las velocidades medias de recorrido de ciclistas individuales y en grupo, se consideran todos los datos conjuntamente, ya que todos ellos circulan a la misma velocidad.

La distribución de velocidades medias de recorrido de los ciclistas presentó un valor promedio de 29.52 km/h y una desviación de 4.45 km/h. Las velocidades de los ciclistas presentaron poca dispersión debido a que el tramo no presenta prácticamente pendiente, y los ciclistas observados eran semiprofesionales con una forma física desarrollada. Los 263 vehículos ligeros que se registraron presentaron una velocidad media de recorrido con un valor promedio de 62.08 km/h y una desviación de 8.21 km/h.

Se seleccionaron los escenarios para calibrar el modelo en Aimsun Next y para validarlo a partir de los datos de intensidades horarias observadas (Fig. 10). Para calibrar el modelo se utilizaron los escenarios de demanda máxima y mínima de bicicletas, y un tercer escenario de demanda media, con sus correspondientes demandas de ligeros en el mismo sentido de circulación y en sentido opuesto. Una vez calibrado el modelo se validó considerando cuatro escenarios de demanda diferentes a los utilizados en la calibración. Para calibrar y validar el modelo se consideraron los grupos de ciclistas circulando en línea y en paralelo.

Intensidades (usuarios/h)	Calmin	Calmed	Calmax	Val1	Val2	Val3	Val4
Ligeros	128	144	120	76	64	136	108
Ligeros opuestos	156	160	152	136	156	88	84
1	12	36	40	24	16	24	20
2P/2L	4	12	8	16	0	16	0
4P/4L	0	0	4	0	4	4	8
10P/10L	0	4	12	8	0	0	0
Total ciclistas	20	100	192	136	32	72	52

Tabla 2 - Escenarios de tráfico utilizados para calibración y validación (usuarios/h).

4.3 Resultados del modelo de microsimulación

4.3.1 Calibración del modelo

Se realizaron varios procesos de calibración del modelo, variando en cada uno de ellos los parámetros necesarios. En la Tabla 3 se muestran los resultados de los principales parámetros después del proceso de calibración. Se calibraron las longitudes de los grupos de ciclistas para conseguir las mismas duraciones de los adelantamientos obtenidas en las simulaciones y en las observaciones de campo. El resto de los parámetros del modelo se revisó con detalle, y se intentó variar mínimamente los valores originales para no afectar a la interacción entre motorizados, ya que en el modelo resultante los vehículos motorizados también deben de interaccionar entre sí de manera correcta.

Segmento					
	Diferencia de velocidades para adelantar en línea continua (km/h) = 20 km/h				
	Longitud tramos generación de colas (m) = 350 m				
Usuarios					
	Longitudes	Individual = 4 m;	2P = 6 m;	4P = 10 m;	10P = 16 m
	equivalentes (m):		2L = 11 m;	4L = 28 m;	10L = 35 m
	Velocidad máxima deseada Ligeros = media 78 km/h (Desv. 10 km/h)				
	Velocidad máxima deseada bicicletas = media 30 km/h (Desv. 2 km/h)				
Experimento					
	Demora entre adelantamientos simultáneos (s) = 0 s				
	Número de adelantamientos simultáneos permitidos = 5				
	Rango máximo en la cola para desear adelantar = 2				
	Umbral de tiempo hasta fin de tramo (s) = 5 s				

Tabla 3 - Valores de los principales parámetros calibrados.

El proceso de calibración se inició analizando los datos a nivel microscópico obtenidos de las maniobras de adelantamiento a los diferentes grupos de ciclistas en el simulador.

En esta fase se calibraron las longitudes equivalentes de cada grupo de ciclistas mostradas en la Tabla 3, de manera que no existieran diferencias estadísticamente significativas entre las duraciones de los adelantamientos obtenidas en los escenarios de calibración y las observadas en campo. Los resultados de la prueba ANOVA mostrados en la Tabla 4 muestran que para todos los casos el *p-valor* es mayor de 0.05, por tanto, las medias de los valores simulados y observados de las duraciones no presentaron diferencias estadísticamente significativas con un nivel de confianza del 95%. Para cada escenario de calibración se comparó una a una las distribuciones de duraciones obtenidas de las simulaciones con las observadas para cada grupo de ciclistas mediante la prueba de Kologorov-Smirnov (K-S). En total se realizaron 15 pruebas K-S, solamente para un ciclista individual se obtuvieron valores de $p < 0.05$, indicando en todos los otros casos que no existía una diferencia estadísticamente significativa entre las dos distribuciones comparadas con un nivel de confianza del 95%.

Grupos de ciclistas	Calmin			Calmed			Calmax			Resultados ANOVA	
	N	Media	Desv.	N	Media	Desv.	N	Media	Desv.	F	*p*-valor
1	148	5.88	1.46	192	5.74	1.57	190	5.56	1.54	1.22	0.303
2L	45	6.89	1.82	35	6.34	1.81	41	6.71	2.11	0.51	0.673
2P	45	6.18	1.93	81	6.20	1.64	73	6.06	1.55	0.10	0.961
4L	-	-	-	-	-	-	51	8.31	2.15	0.32	0.571
4P	-	-	-	-	-	-	40	6.65	1.66	0.19	0.665
10L	-	-	-	51	9.25	2.29	86	9.30	2.19	0.04	0.960
10P	-	-	-	69	7.31	1.73	103	7.14	1.62	0.71	0.495

Tabla 4 - Resultados estadísticos de las duraciones de los adelantamientos (s) según la configuración del grupo de ciclistas.

En la segunda parte de la calibración se obtuvieron los valores de los parámetros que minimizaban las diferencias entre los valores observados y simulados de las variables a nivel macroscópico. Se calibraron las velocidades medias de recorrido, los intervalos de tiempo entre usuarios y el porcentaje de vehículos en cola a la entrada y salida del tramo para los tres escenarios. Los resultados del proceso de calibración a nivel macroscópico pueden consultarse en Moll et al. (2021).

A la vista de los resultados del proceso de calibración, se considera que el modelo está calibrado y funciona correctamente, tanto a nivel microscópico, observando las maniobras de adelantamiento en detalle, como a nivel macroscópico o de sección.

4.3.2 Validación del modelo

El modelo se validó en cuatro escenarios de tráfico diferentes a los utilizados en la calibración, y mostrados en la Tabla 2. El proceso de validación se realizó a nivel macroscópico, comparando los resultados de las simulaciones con las observaciones en campo de las velocidades medias de recorrido, y el intervalo de tiempo entre vehículos y los porcentajes de vehículos en cola a la entrada y salida del tramo.
El proceso de validación y los resultados obtenidos se pueden consultar en Moll et al. (2021).

Después de los procesos de calibración y validación, el modelo está listo para ser utilizado para calcular las variables necesarias para analizar la afección que el tráfico ciclista puede tener sobre la seguridad y la funcionalidad del tráfico en carreteras convencionales estrechas considerando los grupos de ciclistas circulando en línea y en paralelo.

4.4 Análisis de la seguridad y la funcionalidad del tráfico

En este apartado se analizan los resultados de las simulaciones de los tres escenarios utilizados para calibrar el modelo de microsimulación. Estos tres escenarios han sido simulados considerando a los grupos de ciclistas circulando en línea y en paralelo.

A partir de las observaciones en campo realizadas mediante las bicicletas instrumentadas se obtuvieron las distribuciones de las duraciones del adelantamiento considerando diferentes agrupaciones de ciclistas. En la Fig. 11 se puede observar como la tendencia fue que a mayor número de ciclistas formando el grupo, se registraron mayores duraciones, y para grupos formados por el mismo número de ciclistas se registraron mayores duraciones cuando circulaban en línea que cuando lo hicieron en paralelo. Mayores duraciones del adelantamiento implican mayores tiempos en el carril opuesto, generando un mayor riesgo de exposición a colisión frontal con los vehículos opuestos.

En el tramo de carretera convencional estrecha donde se desarrolló el estudio, la mayoría de los grupos ciclistas observados circulaban en paralelo, esta configuración presentó duraciones menores del adelantamiento y por tanto una menor exposición al riesgo para los conductores. Estas observaciones difieren de la opinión de los conductores que realizaron las encuestas del estudio realizado por López et al., 2019, donde la mayoría de los conductores encuestados prefirieron que los ciclistas circulen en línea.

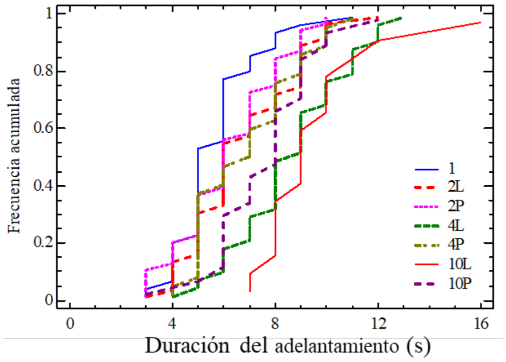


Fig. 11 - Distribuciones de las duraciones del adelantamiento (s) a los diferentes grupos de ciclistas obtenidas en campo.

En la Fig. 12 se muestran las distribuciones de velocidades medias de recorrido de los vehículos ligeros resultantes de las simulaciones de los seis escenarios de calibración.

Se observa que la velocidad media de recorrido del tramo se redujo a medida que aumentaba la demanda de ciclistas. Se realizó la prueba de Kruskal-Wallis para comparar las medianas de las distribuciones, ya que los datos no provienen de distribuciones normales, los resultados mostraron que existe una diferencia estadísticamente significativa entre las medianas con un nivel de confianza del 95%. Sin embargo, las medianas y las distribuciones de las velocidades considerando los escenarios de demanda máxima y media no mostraron diferencias estadísticamente significativas con una significancia del 5%. Esto indica que, a partir de un cierto nivel de tráfico ciclista cercano a la demanda media observada, el efecto sobre la velocidad media de recorrido de los vehículos ligeros es menor, a medida que aumenta el volumen de ciclistas. Las medianas entre línea y paralelo no presentaron diferencias estadísticamente significativas en la prueba de Bonferroni para los tres escenarios de tráfico.

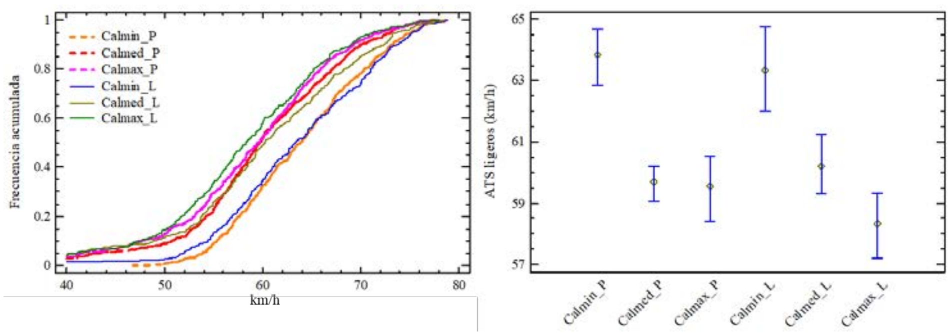


Fig. 12 - Distribuciones de las velocidades medias de recorrido de los vehículos ligeros (km/h) (izquierda) y medianas e intervalos del 95% de confianza (derecha) obtenidas en las simulaciones de los escenarios de calibración.

Otra variable que sirve para caracterizar la seguridad y la funcionalidad del tráfico es el número de adelantamientos realizados por vehículo en el tramo. En la Fig. 13 izquierda se pueden observar las distribuciones del número medio de adelantamientos por vehículo obtenidos de las 15 simulaciones para los seis escenarios simulados. Es evidente que a mayor volumen de ciclistas circulando en el tramo se realizan más maniobras de adelantamiento.

Los resultados de la prueba ANOVA constataron las diferencias entre las medias de los escenarios simulados ($F=116.65$, $p<0.05$). Sin embargo, para los escenarios simulados, no se observaron diferencias estadísticamente significativas entre las medias de los adelantamientos registrados considerando las configuraciones de los grupos de ciclistas en línea y en paralelo (Fig. 13 derecha).

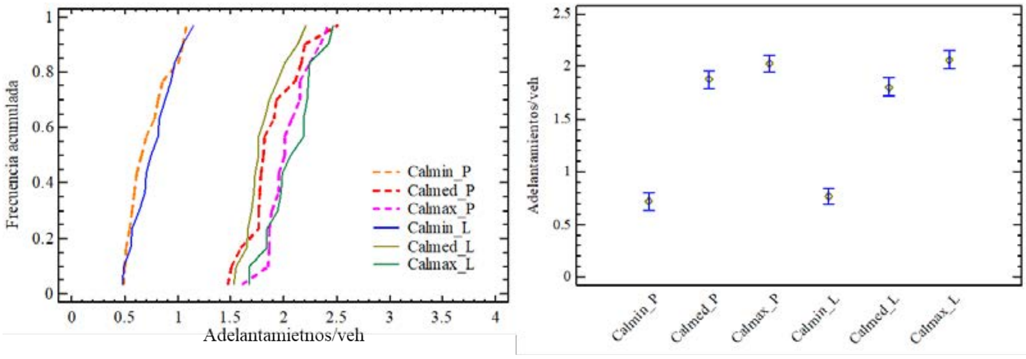


Fig. 13 - Distribuciones de los adelantamientos realizados por vehículo (izquierda) y media e intervalos LSD de Fisher (derecha) obtenidos en las simulaciones de los escenarios de calibración para los grupos circulando en línea y en paralelo.

En la Fig. 14 se han representado los valores del tiempo de demora acumulada de los vehículos ligeros obtenidos en las 15 replicaciones de cada escenario de calibración. Se puede observar como el tiempo de demora aumentó al incrementar el tráfico ciclista.

También se observa que, al aumentar la demanda de ciclistas, el tiempo de demora presentó una mayor dispersión. Esta mayor dispersión se debe a que al simular escenarios con una elevada demanda ciclista existen vehículos que se encuentran con más ciclistas y otros con menos, y su tiempo de demora depende del número de ciclistas con los que interaccione. La prueba ANOVA ($F=63.37$, $p<0.05$) indicó que las medias de las seis distribuciones de tiempo de demora presentaron diferencias estadísticamente significativas con un nivel del 5% de significación. Cuando los grupos circularon en línea, la media del tiempo de demora de los vehículos motorizados no presentó diferencias estadísticamente significativas respecto a la configuración en paralelo, sin embargo, los valores de la demora media y las dispersiones fueron ligeramente mayores para las configuraciones en línea debido a la mayor longitud de los grupos (Fig. 14 derecha). Esta diferencia, a pesar de no ser significativa en los escenarios simulados, va aumentando a medida que aumenta la demanda ciclista, poniendo de manifiesto que la configuración del grupo de ciclistas tiene mayor importancia cuando el tráfico es elevado.

El tiempo de demora acumulada de los vehículos ligeros es una variable difícil de medir en campo, en este estudio se ha obtenido mediante el uso del modelo de microsimulación, poniendo en valor el uso de esta metodología para obtener variables que pueden caracterizar la seguridad y la funcionalidad del tráfico.

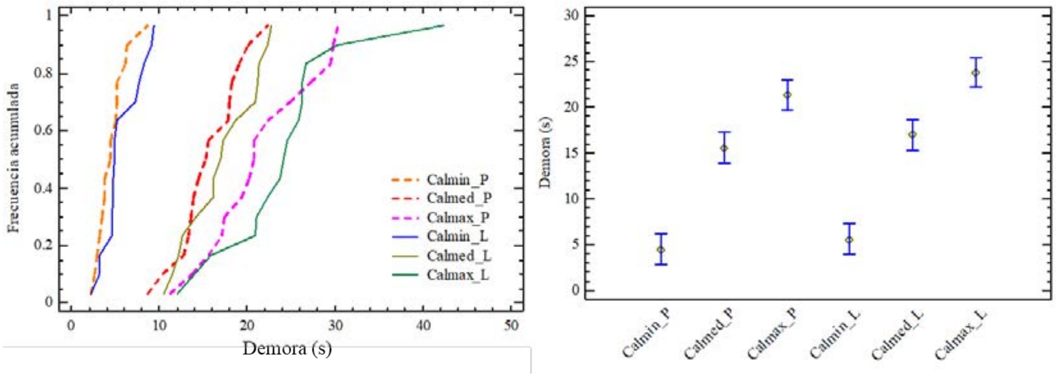


Fig. 14 - Distribuciones de las demoras acumuladas (izquierda) y media e intervalos LSD de Fisher (derecha) obtenidos en las simulaciones de los escenarios de calibración para los grupos circulando en línea y en paralelo.

Otra medida de desempeño analizada en este estudio fue el porcentaje de vehículos en cola (VC) a la entrada y a la salida del tramo de estudio. Esta variable se calculó en los escenarios considerando la demanda mínima, media y máxima de ciclistas registrados. En la Tabla 7 se pueden observar los valores calculados del porcentaje de vehículos en cola. Para cada escenario, la variación entre el inicio y el final del tramo no es muy significativa, presentando valores muy similares en los dos puntos para los tres escenarios analizados. Si se observa la variación entre escenarios, sí se aprecian más diferencias.

El escenario con demanda mínima de bicicletas presentó valores del porcentaje de vehículos en cola menores, cercanos al 20%, mientras que los escenarios con demandas media y máxima presentaron valores más elevados alrededor del 30%.

Por tanto, la presencia de tráfico ciclista aumentó el valor del porcentaje de vehículos en cola en carreteras convencionales estrechas. Los resultados obtenidos considerando a los grupos de ciclistas circulando en línea y en paralelo fueron muy similares, no presentando diferencias estadísticamente significativas entre las dos configuraciones.

	Inicio del tramo	Fin del tramo
Escenario	VC Sim.	VC Sim.
Calmin	18.80%	19.10%
Calmed	32.40%	28.20%
Calmax	29.40%	28.90%

Tabla 5 - Resultados estadísticos para el porcentaje de vehículos en cola (VC) en los escenarios de calibración.

Las diferencias entre las configuraciones en línea y en paralelo de los grupos de ciclistas en los niveles de tráfico analizados no fueron significativas para ninguna de las variables analizadas. Sin embargo, la configuración en la que circulan los grupos tiene más influencia sobre el tiempo de demora a medida que aumenta el volumen de ciclistas en el tramo. Como líneas futuras de investigación se propone simular escenarios de tráfico diseñados aumentando tanto la demanda ciclista como motorizada.

5. CONCLUSIONES

La presencia de ciclistas en carreteras convencionales no solamente afecta a la seguridad en estas vías, sino también a la funcionalidad del tráfico. Esta afección es especialmente acusada en carreteras convencionales estrechas, con arcén nulo o impracticable, donde los ciclistas deben de circular por el carril y los vehículos realizan adelantamientos con una mayor invasión del sentido opuesto y una mayor duración.

En este estudio se han tomado datos de campo en un tramo de carretera convencional sin arcén mediante dos metodologías distintas. Por una parte, se han recogido datos a nivel microscópico utilizando bicicletas instrumentadas. Se ha observado que la circulación de ciclistas por el tramo ha aumentado el número de maniobras de adelantamiento necesarias generando un mayor riesgo de colisión frontal con los opuestos y de alcance con las bicicletas. Uno de los principales resultados han sido las duraciones de los adelantamientos a los diferentes grupos de ciclistas considerados en el experimento. Estas duraciones fueron mayores a medida que había más ciclistas en el grupo, y en cuanto a su configuración, para un grupo formado por el mismo número de ciclistas, la duración del adelantamiento fue mayor cuando circulaban en línea que cuando lo hacían en paralelo.

La segunda metodología utilizada consistió en realizar grabaciones naturalísticas en los extremos del tramo de estudio, obteniendo los diferentes escenarios de tráfico utilizados para calibrar y validar el modelo de microsimulación, y para analizar la funcionalidad.

A partir de las observaciones en campo, se ha adaptado, calibrado y validado un modelo de microsimulación del tráfico que permite simular adelantamientos en carreteras convencionales, de manera que se represente el comportamiento de vehículos motorizados, bicicletas, y sus interacciones. Se ha utilizado el programa Aimsun Next 20. En el modelo de microsimulación se han calibrado las longitudes equivalentes de cada grupo de ciclistas para obtener duraciones de los adelantamientos similares a las observadas, representando así la invasión parcial del carril opuesto y la configuración del grupo de ciclistas. El uso de modelos de microsimulación del tráfico, debidamente calibrados y validados, permite estudiar el efecto de los ciclistas sobre determinadas medidas de desempeño que caracterizan la seguridad y la funcionalidad del tráfico. También permite obtener algunas medidas difíciles de registrar en campo, como el tiempo de demora acumulada de los vehículos ligeros.

Se han simulado seis escenarios considerando la demanda de ciclistas mínima, media y máxima observadas y considerando los grupos circulando en línea y en paralelo. Los resultados obtenidos muestran que al aumentar el volumen de ciclistas la velocidad media de recorrido de los vehículos ligeros disminuye, y el número de adelantamientos realizados por vehículo y el tiempo de demora acumulada aumentan.

El aumento de la presencia de ciclistas también aumentó el porcentaje de usuarios en cola en los extremos del tramo. Para los niveles de tráfico analizados en este estudio no se observaron diferencias estadísticamente significativas entre las configuraciones en línea y en paralelo de los grupos de ciclistas para ninguna de las variables analizadas. Sin embargo, al aumentar el volumen de tráfico, tanto ciclista como motorizado, puede que la configuración de los grupos si influya en los resultados, debido a la mayor longitud de los grupos al circular en línea. Este estudio se propone como futura línea de investigación.

La microsimulación del tráfico es una herramienta que puede ser explotada con diferentes fines, pudiendo simular medidas y escenarios obteniendo resultados de una manera rápida y económica. Uno de estos fines es la simulación de escenarios variando la demanda, tanto de motorizados como de ciclistas, y analizar cómo afecta a las diferentes medidas de desempeño esta variación. Por otra parte, se puede estudiar el efecto de medidas tomadas sobre el tráfico o la propia carretera, como reducciones de la velocidad límite o la incorporación de apartaderos que faciliten la maniobra de adelantamiento a los ciclistas. El uso de la microsimulación del tráfico puede ayudar a las Administraciones a integrar a las bicicletas y a los vehículos motorizados en las carreteras de una manera más segura y eficiente.

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ANÁLISIS DE LA DEMANDA Y DISEÑO DE ESTRATEGIAS DE PROMOCIÓN DEL USO DE LA BICICLETA EN SEVILLA

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RESUMEN

El Plan Director de la Bicicleta aprobado en 2007 para Sevilla, consiguió impulsar el uso de la misma hasta alcanzar un 6% de reparto modal. En el Programa de la Bicicleta Sevilla 2020 el Ayuntamiento se propuso como objetivo alcanzar al menos un 15% de reparto modal en 2020 en este modo. Para alcanzar esa cifra, es necesaria la promoción, con actuaciones no solo sobre la infraestructura, sino también con medidas de concienciación e información, con el fin de transmitir la idea de la bicicleta como un modelo eficiente y moderno, que puede mejorar la habitabilidad de la ciudad y la calidad de vida de sus ciudadanos. Este trabajo pretende aportar dicha visión por medio del mapa esquemático Metro-Bici, presentado en un formato similar al de un modelo de líneas del modo de transporte público (metro), con el fin de hacer más atractiva la idea de la bicicleta como modo de transporte.

Para su diseño, se han actualizado los datos de movilidad disponibles de tal forma que se consigan obtener volúmenes de demanda parecidos a los observados en las diferentes vías que conforman la infraestructura de la bicicleta, mediante un proceso de optimización y ajuste. A esto le ha seguido un posterior análisis de la demanda para concluir con un mapa esquemático de la red de bicicleta, en el que se define un conjunto de líneas, sintetizando las rutas principales obtenidas, presentando la bicicleta como un modo de transporte moderno y eficiente. Con la creación de estas líneas no solo se aspira atraer a la población hacia el modo de transporte en estudio, sino que también pretende identificar y jerarquizar corredores en función de su demanda con el fin de priorizar las posibles futuras actuaciones sobre la infraestructura.

1. INTRODUCCIÓN

Para conseguir mejorar el modo de transporte de la bicicleta es necesario analizar por un lado el comportamiento actual de sus usuarios y casi más importante, las causas que motivan el rechazo de los usuarios de los otros modos a usarla como modo de transporte para sus desplazamientos. Para ello, se han realizado una serie de encuestas que permiten identificar al tipo de usuario que hacen uso de esta infraestructura y a su vez, se decide encuestar a peatones con el fin de determinar si éstos utilizan la bicicleta asiduamente, y en caso negativo conocer el motivo.

Las encuestas de las que se dispone han sido realizadas por varias promociones del Máster en Ingeniería de Caminos, Canales y Puertos al cursar la asignatura de Planificación del Transporte de la Universidad de Sevilla, siendo la distribución del número de encuestas la siguiente:

- 555 encuestas a usuarios de bicicleta realizadas en el curso 2016/17.
- 350 encuestas a usuarios de bicicleta realizadas en el curso 2018/19.
- 293 encuestas a peatones realizadas en el curso 2018/19.

El cuestionario de las encuestas dirigidas a los usuarios en bicicleta se basa en el modelo propio de encuestas de SIBUS, 2015, con el objeto de contrastar el perfil de los usuarios y validar las encuestas.

Las modificaciones realizadas sobre las encuestas originales buscan la eliminación de los posibles sesgos que pudieran darse, así como destacar información relevante como la duración de los viajes, los pares Origen-Destino, e incluso se incluye un apartado de mejora de la infraestructura asociada a la bicicleta en Sevilla.

En cuanto a la encuesta de peatones, se busca obtener la frecuencia de uso de bicicleta, así como los motivos de su no uso si corresponde.

En García Sánchez, 2019 se presentan los modelos de encuestas utilizados y los resultados pormenorizados del análisis de las encuestas, presentando aquí las conclusiones de dicho análisis:

- Del proceso de encuestación a peatones se extrae que el 10% de los encuestados afirma no saber utilizar la bicicleta existiendo una relación estadísticamente significativa con el sexo, pues casi el 75% de estos eran mujeres. Esto puede influir en el hecho de que en el proceso de encuestación a usuarios de bicicleta tan solo el 35% eran mujeres.

- La edad es otro factor importante a comparar con otras variables, como por ejemplo el tipo de bicicleta, las cuales presentan una relación estadísticamente significativa, por lo tanto, los grupos de edad más jóvenes presentan mayor proporción de uso de la bicicleta de alquiler. En el caso de analizar los tiempos de viajes en función de la edad, se obtiene una significación estadística, de tal forma que a medida que avanza la edad, los tiempos de viajes por lo general tienden a ser superiores.

- Siguiendo con la dinámica anterior, se analizan los tiempos de viajes donde se observa como los viajes realizados con bicicleta de alquiler son relativamente más cortos, obteniendo una asociación significativa entre el tipo de bicicleta empleada y el tiempo de trayecto.

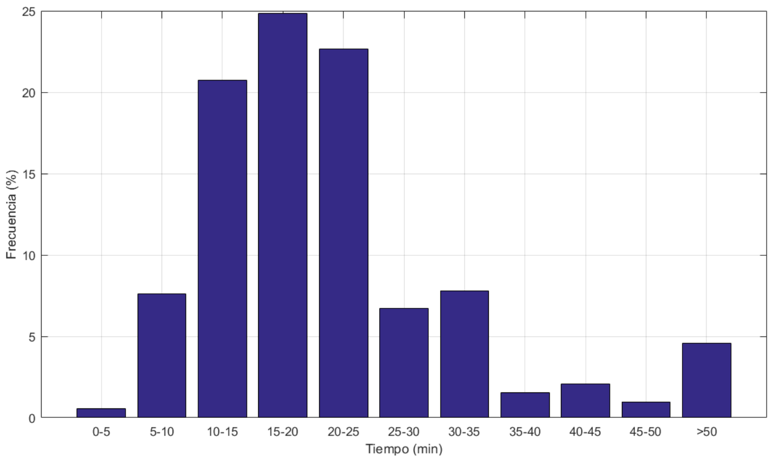


Figura 1. Histograma de viajes en distancia (km) extraído de encuestas

- De todo el proceso de encuestación cabe destacar la importancia, dada su implicación en el proceso de ajuste de la matriz, de:
  - Histograma unitario de viajes en distancias, mostrado en la Figura 1.
  - El motivo de viajes de los encuestados, donde el 75% de los viajes recogidos eran por movilidad obligada

2. PROPUESTA DE POLÍTICA DE PROMOCIÓN DE LA BICICLETA

Son de sobra conocidos algunos aspectos positivos del uso de la bicicleta, no solo para el usuario, sino también para la ciudad, así como ciertos inconvenientes que puedan derivar en rechazo a este modo de transporte, y, por tanto, los que habrá que trabajar para hacer más llamativa la bicicleta.

En cuanto al individuo, PROBICI,2010, el uso de la bicicleta aporta como ventajas:

- Autonomía, flexibilidad y accesibilidad: a diferencia del transporte público, la bicicleta está disponible en cualquier momento, ofrece un servicio puerta a puerta y no está sujeta a horarios ni rutas fijas. El individuo que la utilice goza de una libertad similar a la que ofrece el transporte privado.

- Fiabilidad y económica: dado que el sistema de transporte asociado a la bicicleta no está congestionado, los tiempos de viajes se mantienen y son fácilmente predecibles, a diferencia del transporte privado. Además, esta requiere una menor inversión no sólo inicial, sino también de mantenimiento frente al automóvil.

- Eficacia: en distancias cortas, la bicicleta es más competitiva que el transporte público o privado.

- Para viajes menores de los 2 km la bicicleta presenta mayor competitividad que el automóvil, siendo un factor primordial el aparcamiento disponible. Para distancias menores que la presentada, los tiempos de viajes en ambos modos son parecidos, presentando la bicicleta mayor eficiencia a la hora de aparcar dada su ligereza y pequeñas dimensiones con respecto al automóvil.

- Para viajes menores de los 5 km, la bicicleta es más competitiva que el transporte público, pues como se ha comentado esta presenta mayor autonomía y flexibilidad. Para distancias mayores, el transporte público presenta ventajas, siendo lo óptimo la intermodalidad (situación win-win o de ganancia mutua).

Analizando las encuestas realizadas, en particular el histograma en distancias mostrado en la Figura 1, aproximadamente el 25% de los viajes están por debajo de los 3 km y el 54% de los viajes menor de los 5 km de distancia, mostrando eficiencia hasta los 7km de distancia.

Conociendo que la mitad de los trayectos urbanos en vehículo privado en España están por debajo de los 5 km, se puede establecer la bicicleta como una buena opción para realizar estos trayectos.

A pesar de estas ventajas, también se encuentran inconvenientes que general rechazo al uso de la bicicleta. Teniendo en cuenta diferente bibliografía, PROBICI, 2010 Civinet, 2015 y las encuestas realizadas a peatones, las razones que llevan a un individuo a no optar por este modo son:

- Condiciones climáticas
- Pendientes pronunciadas en el trayecto
- Incomodidad a la hora del transporte de mercancía o niños
- Preocupación por el robo

La bicicleta, no solo presenta beneficios para el usuario que la utiliza, sino que también presenta ventajas para el resto de la población, y, por tanto, para la ciudad, si y solo si esta es capaz de aumentar su reparto modal atacando al de los vehículos motorizados, es decir, solo si se da una transferencia de demanda de vehículos privados a la bicicleta.

Estas son:

- Menor tasa de sedentarismo, lo que conlleva un aumento de la salud de la población.
- Menos contaminación (de agua, suelo y atmosférica) y ruido, lo que aumenta el bienestar social.

- Humanización, pues facilita el contacto interpersonal
- Mayor seguridad vial, pues se reduce el tráfico motorizado.
- Mayor disponibilidad de recursos al reducir el consumo de petróleo.
- Menor impacto sobre el territorio y mayor eficiencia, pues la bicicleta requiere menor ocupación del suelo urbano, además de menor mantenimiento, menor inversión inicial y apenas requiere gastos policiales, lo que conlleva a su vez un ahorro económico.

De aquí se extrae que la bicicleta es un modo de transporte bastante favorable y necesario teniendo en cuenta las situaciones desfavorables debido al tráfico motorizado que se están alcanzando en algunas ciudades españolas.

2.1 Promoción de la bicicleta: mapa esquemático

En esta comunicación se presenta una propuesta concreta para la promoción de la bicicleta, particularizada para la ciudad de Sevilla pero extensible para cualquier otra ciudad: la generación de un mapa esquemático de la red bici, con un diseño atrayente que presenta la bicicleta como un modo *moderno* y *eficiente*. Con este plano se pretende por un lado presentar una imagen del transporte en bicicleta como una opción moderna, de ahí su semejanza en el diseño a un plano de líneas de un sistema metro urbano. Por otro lado, se quiere mostrar que es un modo eficiente, que conecta los puntos más importantes de la ciudad en un tiempo competitivo con el de los otros modos.

Para la realización del plano, se contemplan las siguientes fases:

- *Determinación de puntos de interés*. Establecer puntos de interés en un mapa guía de líneas, ayuda a los usuarios a localizar rápidamente su destino. Estos puntos o lugares de interés se refieren a estaciones de metro, estación de autobuses y cercanías, los cuales permiten la intermodalidad, zonas de gran interés turístico y centros comerciales (para incentivar el uso de la bicicleta para viajes no obligados), siendo muy importante la localización del servicio de bicicleta pública más cercano a dichos puntos.

- *Elección de arcos principales.* En la realización del mapa esquemático es necesario estipular una serie de arcos principales, así como la localización de grandes centroides de atracción y generación.

Esta necesidad reside en el deber de establecer un conjunto de líneas del modo de transporte de la bicicleta con el fin de hacer atractivo el uso de la misma por medio de líneas simples y directas uniendo los principales orígenes destinos. Para conseguir esto, se seleccionan aquellos arcos que presenten mayor volumen de usuarios, el cual se ha obtenido gracias a la asignación realizada en el apartado 4.4, que serían aquellos arcos con un volumen mayor a 4900 usuarios Estos arcos deben formar parte de las líneas principales a desarrollar en el siguiente apartado, ayudándose a su vez de otras líneas de menor volumen.

- *Elección de las líneas o rutas principales.* El proceso de creación de las líneas principales de desplazamiento en bicicleta se ha realizado por medio de un estudio simplificado de la demanda asociada a cada par. Para ello, ha sido necesario desarrollar la modelización completa de la demanda de los usuarios, así como el modelo de red de los carriles bici de la ciudad de Sevilla. En el apartado 3 se resume la macrosimulación desarrollada.

3. MACROSIMULACIÓN DEL MODO DE TRANSPORTE BICICLETA EN SEVILLA

Para poder realizar la macrosimulación del modo de transporte “bicicleta” en Sevilla, uno de los datos previos más importante es la matriz Origen-Destino, que muestra el volumen de usuarios que viajan entre cada par de Origen y Destino.

En este apartado, se presenta la matriz OD en la que se basa el presente trabajo y el proceso de ajuste de la misma con el fin de obtener resultados que muestren la realidad de la forma más fidedigna posible.

3.1 Matriz OD base

La matriz OD de la que se parte es la matriz de movilidad global de Sevilla (EDM07), la cual agrupa todos los viajes de los diferentes modos de transporte que se dan en la ciudad en un día medio, basado en la encuesta de movilidad llevada a cabo en 2007.

Dado que esta matriz recoge todos los modos es necesario extraer de la misma la correspondiente a las bicicletas. El reparto de bicicleta estimada en el 2010 es del 6%, Ayto. de Sevilla, 2010. A falta de información para una mejor distribución, puede suponerse como matriz OD de partida para el modo bicicleta la resultante de imponer un reparto modal uniforme en todas las zonas de transporte, obteniéndose:

$$T_{bici} = 0.06 \cdot T_{global} \qquad (1)$$

Pero las hipótesis planteadas anteriormente presentan una deficiencia principal, aparte del desfase temporal de la misma, y es que la matriz global representa viajes realizados en otros modos como es el privado y el transporte público, que presentan características muy diferentes a los realizados en bicicleta. Un usuario que utiliza la bicicleta está condicionado por el tiempo de viaje, trayectos demasiado largos pierden interés, como se puede observar en el histograma de viajes en distancia extraído de las encuestas.

Esto significa que el reparto modal del modo en estudio no se produce de la misma forma que el transporte público o el privado.

La matriz global se estimó hace más de 10 años, y se ha observado como en general ha aumentado el número total de viajes en bicicleta desde el estudio de movilidad de 2010 que establece el reparto de la bicicleta en un 6%; por ello, se decide actualizar la matriz para que el número total de viajes sea representativo del actual.

3.2 Ajuste de la Matriz OD

3.2.1 Elección del criterio de ajuste de la matriz

Para modificar la matriz, se opta por implementar un método de ajuste de matriz, incluyendo información adicional de conteos de tráfico en arcos de la red y una serie de restricciones.

El objetivo de este proceso es disminuir la discrepancia con los volúmenes observados mientras se controla la distorsión de la matriz.

Como criterio de optimalidad en el proceso de ajuste de la matriz, se utiliza el de la máxima entropía o de mínima información, donde se busca extraer una matriz de viajes nueva a partir de una base. Bajo este criterio la función de distancia utilizada para medir la diferencia, tanto entre los aforos y los volúmenes modelados como entre la matriz resultante y la previa, es la función de entropía relativa, Van Zuylen y Willumsen, 1980 , Cascetta, 1980.

A lo largo del proceso de estimación de la demanda, se establece la hipótesis de que el mecanismo que utilizan los usuarios para escoger ruta es el minimizar su coste generalizado (que en el modo de transporte de la bicicleta básicamente se basa en la distancia de los recorridos). Esto es debido a que el fenómeno de la congestión todavía no es apreciable, y se supone que no tienen incidencia en la selección de ruta.

Por otro lado, la aplicación de máxima entropía tiene en cuenta una matriz de referencia, y el problema formulado tiene múltiples soluciones, siendo importante para el resultado final la solución inicial de partida. Se considera que los aforos no son fuentes de información creíble, puesto que se establece que estos no contienen suficiente información para la estimación, por ello, una buena decisión sería incluirlo en la función objetivo, puesto que los flujos en el modelo incluidos como restricción son de obligado cumplimiento:

$$Minimizar\ Z(\boldsymbol{g},\boldsymbol{v}) = \gamma_1 \sum_{p\in\boldsymbol{\mathcal{P}}} \left(g_p \left(log\left(\frac{g_p}{\bar{g}_p}\right) - 1 \right) \right) + \gamma_2 \sum_{a\in\bar{\boldsymbol{\mathcal{A}}}} \left(v_a \left(log\left(\frac{v_a}{\bar{v}_a}\right) - 1 \right) \right) \quad (2)$$

siendo g la matriz Origen-Destino con el flujo viajes para cada par origen-destino ordenada en formato vectorial, $\boldsymbol{v}$ el vector de flujos o volúmenes en los arcos, $\boldsymbol{\mathcal{P}}$ y $\bar{\boldsymbol{\mathcal{A}}}$ los conjuntos de pares Origen-Destino y de arcos aforados en la red, respectivamente.

A pesar de lo anterior, y dado el reducido número de puntos de aforo de los que se dispone, se deciden incluir como restricción por simplicidad.

$$Minimizar_{T,v}\, Z = \sum_{p\in\boldsymbol{\mathcal{P}}} g_p \left(log\left(\frac{g_p}{\overline{g_p}}\right) - 1 \right) \tag{3}$$

donde g_p es el flujo de viajes correspondiente al par p de los O/D

3.2.2 Restricciones del ajuste

Para realizar el ajuste de la matriz, se decide incluir una serie de restricciones que permitan obtener una mejor distribución de los viajes totales estimados en la matriz OD. Una posible alternativa es imponer un modelo físico, como el modelo gravitatorio o el de radiación, para explicar la demanda de este modo de transporte, infiriendo los parámetros del modelo de modo que se ajusten lo más posible a los datos de la realidad. Sin embargo, estos modelos se definen por semejanza a fenómenos físicos que poco tienen que ver con los mecanismos que tienen los viajeros para decidir si realizan determinados viajes y qué modo utilizarían para ello. En este trabajo se opta por imponer una serie de condiciones matemáticas que debería verificar una matriz de demanda, que resuman la información real conocida del modo de transporte, evitando así formular una serie de hipótesis sobre el comportamiento de los usuarios difíciles de validar. El concepto de restricción está asociado a una condición de obligado cumplimiento, es por ello, que se debe discutir la conveniencia de incluir o no cada posible restricción en el proceso final de ajuste. La información disponible para la definición de este conjunto de restricciones es la siguiente:

- Aforos.
- Histograma unitario de distancia del trayecto.
- Población.
- Usos del suelo (Catastro).
- Empresas de >50 empleados.
- Universidades

3.2.2.1 Aforos

Se dispone de la información de 10 Eco-contadores localizados a lo largo de la red ciclista de Sevilla. Estos dispositivos cuentan, almacenan y transfieren permanentemente el número de ciclistas que circulan sobre ellos. Esta información es controlada por la Gerencia de Urbanismo de Sevilla. Hay información disponible en datos diarios y también en tramos horarios. Esta información es relevante para completar el ajuste de la matriz, apareciendo los datos de flujo conocidos en arcos en la función objetivo.

Para el ajuste de la matriz se utilizarán los datos de los eco-contadores disponibles en la Gerencia de Urbanismo de Sevilla pertenecientes a un día que sea representativo y lo suficientemente próximo a la fecha actual, una vez eliminados los registros pertenecientes a fines de semana y festivos, así como los pertenecientes a los meses de verano. se decide escoger la media de los valores como volumen aforado para cada uno de los eco-contadores de los que se dispone información. Dado que se buscan valores representativos, se deciden despreciar los días en los que se obtiene una bajada significativa de los volúmenes causados por ejemplo por la existencia de precipitaciones.

En cuanto a la formulación del ajuste de la matriz, la restricción asociada a los aforos será tal que relacione los pares origen-destino con el aforo, de tal forma que quede registrado todos los pares OD que transiten por cada uno de los aforos disponibles.

$$\boldsymbol{v} = \boldsymbol{\Gamma}^T \cdot \boldsymbol{g} \qquad \forall a \epsilon \overline{\boldsymbol{\mathcal{A}}} \tag{4}$$

Donde $\boldsymbol{g}$ es la matriz de viajes ordenada en formato vectorial, $\boldsymbol{v}$ es vector con los volúmenes de los aforados en los eco-contadores y Γ^T la matriz de incidencia que relaciona los Pares Origen-Destino con los arcos aforados, en la que el elemento Γ_p a es 1 si la ruta mínima del par p contiene el arco a, 0 en otro caso.

La asignación de rutas mínimas empleada conlleva una asignación de tráfico lineal, limitándose a un único cálculo de la matriz de incidencia Γ (aforos-pares OD, constante por no considerarse la congestión) y una multiplicación de matrices que equivale a la suma de los pares que utilizan un arco determinado.

3.2.2.2 Histograma de viajes

Con un número razonable de encuestas, sí puede extraerse información cualitativa y cuantitativa sobre la disponibilidad de los usuarios a realizar o no un determinado viaje atendiendo a una información transversal a todos los pares en función del coste generalizado, como puede ser la distancia o el tiempo de viaje, aunque no sean encuestas suficientes para estimar una matriz OD.

De la idea anterior se extrae el histograma distancia-frecuencia de viajes, el cual recoge el número de viajes realizados según el tiempo o distancia de viaje. Esta información es bastante valiosa, puesto que puedo afectar al reparto modal de tal forma que, dependiendo de la distancia de viajes, ese par OD puede ser más o menos atractivo para ser realizado en bicicleta u otro medio de transporte.

El histograma de viajes que se ha obtenido de las encuestas es el mostrado en la Figura 1.
Al definir los intervalos del histograma de viajes, se extrae de las encuestas la proporción de viajes observados pertenecientes a cada uno de estos intervalos; es decir, para cada intervalo b del conjunto de intervalos $\boldsymbol{\mathcal{B}}$ se obtiene una proporción P_b respecto al total de viajes realizados en bicicleta.

Por tanto se puede establecer una restricción en la que la suma de los viajes de aquellos pares incluidos en un intervalo dado, se corresponda al total de viajes correspondientes a dicho intervalo. Esta restricción se puede expresar de forma matricial sin más que definir la matriz de incidencia Δ histograma-pares Origen-Destino, Ortiz 2017, que relaciona los pares OD con su intervalo en el histograma.

$$\sum_{p \in P(b)} g_p = P_b \cdot T \qquad \forall b \epsilon \boldsymbol{\mathcal{B}} \tag{5}$$

$$\Delta_b \cdot \boldsymbol{g} = P_b \cdot T \qquad \forall b \epsilon \boldsymbol{\mathcal{B}} \tag{6}$$

Donde el subíndice en la matriz índica que se trata de la fila b. Esto significa que el modelo debe de cumplir que los viajes de la asignación para cada intervalo definido en el histograma deben coincidir con las proporciones obtenidas de las encuestas mostrada en el histograma, Figura 1.

3.2.2.3 Población

La población es un factor importante a la hora de generación de viajes, por ello, se decide introducir como restricción en el modelo de ajuste. Ante la ausencia de información para la obtención de modelo de Generación – Atracción, se decide asumir que los viajes generados por cada TAZ están proporcionalmente relacionados con su población.

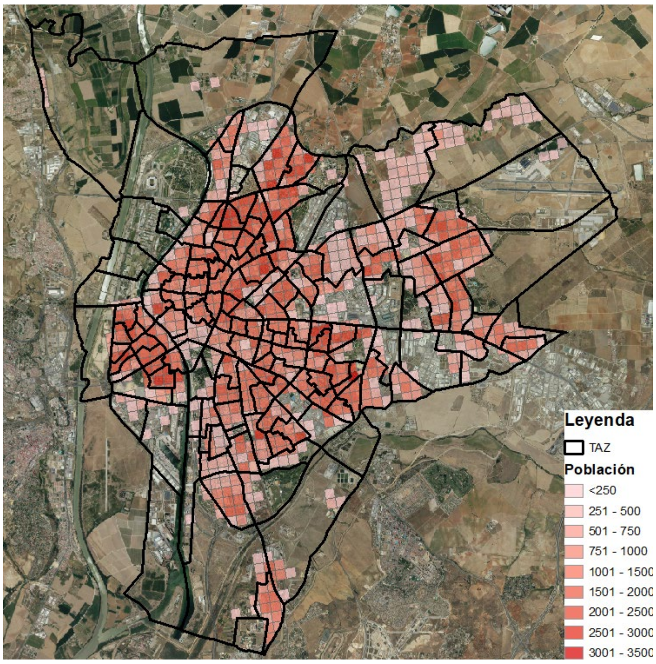


Figura 2. Distribución zonal de la Población 2017

Para imponer la restricción ha sido necesario contabilizar el total de la población y el % de población en cada una de las TAZs que intervienen en el modo de la bicicleta, Xpob. Se puede definir una matriz de incidencia **Θ** Orígenes - pares OD, que relaciona los pares OD con su origen, de tal forma:

$$\boldsymbol{\Theta} \cdot \boldsymbol{g} = \boldsymbol{X}_{pob} \cdot T \tag{7}$$

3.2.2.4 Número de empresas >50 empleados y Universidades

De las encuestas realizadas, se observa como uno de los principales motivos del uso de la bicicleta es el desplazamiento al trabajo, por lo que se decide introducir una restricción relacionada con el número de empresas y los asalariados de las mismas asociadas a cada TAZ. Los apartados anteriores trataban de actuar sobre la generación de viajes, pero en este caso, afectará a la atracción de los mismos. Con el número de empresas con más de 50 asalariados se busca relacionar el uso de la bicicleta con factores socioeconómicos.

Esta restricción se impone según los establecimientos que se encuentran dentro de cada una de estas TAZs, y, más tarde, se ponderan sus valores de atracción teniendo en cuenta los asalariados, obteniendo finalmente una proporción para cada TAZ.

En el ajuste, se impone la restricción por columnas, de tal forma que la atracción de viajes de una zona j sea proporcional a los establecimientos y el total de asalariados de la zona $\left(P_{emp,j} = \frac{A_j}{\sum A_k}\right)$, siendo P_{emp} la proporción, A el número de asalariados (o coeficiente de diferenciación) y j la TAZ en estudio.

$$\sum_{p/D(p)=j} g_p = P_{emp,j} \cdot T \qquad \forall j \epsilon \mathcal{D} \tag{8}$$

Siendo $\mathcal{D}$ el conjunto de destinos, que de nuevo coincide con $\boldsymbol{\mathcal{Z}}$ al considerar todas las zonas de transporte como posible Origen/Destino de viajes.

Para expresar esta restricción en formato matricial, se define la matriz de incidencia $\boldsymbol{\Phi}$ Destinos - pares OD, que relaciona los pares OD con sus destinos, de tal forma:

$$\Phi \cdot g = P_{emp} \cdot T \tag{9}$$

Como en el caso anterior, otro de los motivos principales que llevan al usuario a utilizar la bicicleta es por necesidad de desplazamiento hacia el centro de estudio, por tanto, se decide afectar la atracción de viajes con la inclusión de las diferentes facultades y centros universitarios existentes en Sevilla. Se extraen las diferentes facultades existentes en Sevilla y se asocian a los centroides que definen el modelo. Dada su similitud con la restricción anterior, y a fin de simplificar el ajuste de la matriz, se decide introducir la información de las universidades en la restricción de atracción que versa sobre los asalariados de las empresas de más de 50 empleados.

3.2.3 Algoritmo de ajuste

El proceso de ajuste que finalmente se propone se define en la expresión (10). Consiste en un problema de optimización en el que se minimiza una función objetivo que mide la distancia con respecto a una matriz previa $\bar{g}$ y las restricciones anteriormente comentadas.

La función de distancia finalmente adoptada para la función objetivo es la de la entropía relativa, que como puede verse sin más que desarrollar en serie en torno la matriz previa, es una función intermedia entre el error absoluto y el relativo. A este sistema es necesario incluir una última restricción en la cual se establece la obligatoriedad de que todos los volúmenes entre cada par OD sea positivo ($g \geq 0$), pues no tiene sentido físico un flujo de viajeros negativo. Con esta configuración, y dado que las restricciones impuestas son todas lineales, puede utilizarse como algoritmo de resolución el algoritmo de equilibrado iterativo, Bregman, 1967. Finalmente, se obtiene la siguiente formulación basada en la minimización de la función objetivo, sujeta a las restricciones anteriormente mencionadas:

$$Minimizar_{T,v}\ Z = \sum_{p \in P} g_p \left(log\left(\frac{g_p}{\bar{g}_p}\right) - 1 \right) \tag{10}$$

$s.a \quad \boldsymbol{v} = \boldsymbol{\Gamma}^T \cdot \boldsymbol{g} \quad \forall a \in \mathcal{A}$ Restricción Aforos

$\boldsymbol{\Delta}_b \cdot \boldsymbol{g} = P_b \cdot T$ Restricción Histograma

$\boldsymbol{\Theta} \cdot \boldsymbol{g} = \boldsymbol{X}_{pob} \cdot T$ Restricción Población

$\boldsymbol{\Phi} \cdot \boldsymbol{g} = \boldsymbol{P}_{emp} \cdot T$ Restricción Empresas

$g_p \geq 0 \quad \forall p \in \mathcal{P}$ Volúmenes reales

En la Figura se muestra la diferencia entre la matriz ajustada y la matriz base. Se destacan los valores de máxima diferencia, los cuales llegan hasta los 630 usuarios en algunos pares.

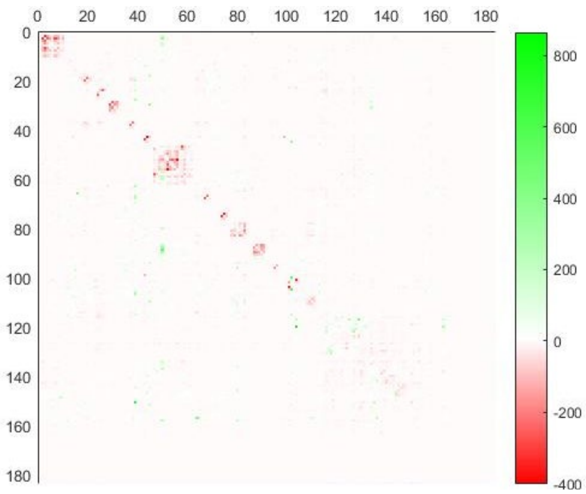
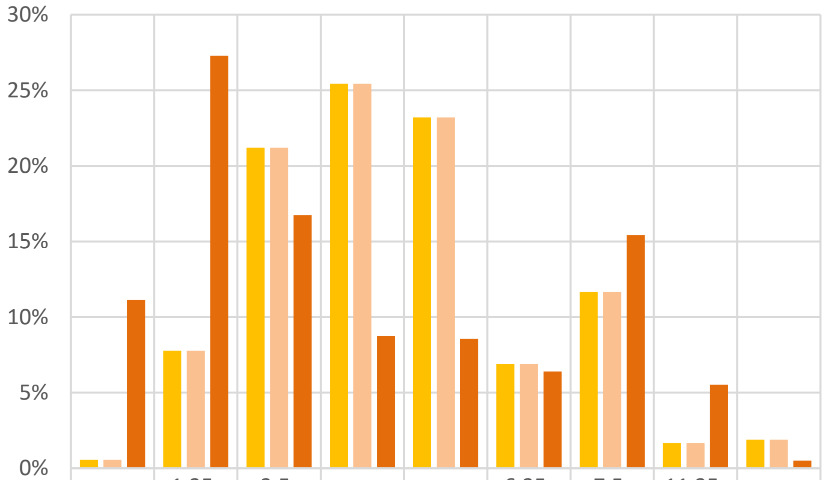


Figura 3. Diferencia entre matrices

En cuanto al histograma de viajes obtenidos, se aprecia como cumple perfectamente la restricción impuesta.



	0-1.25	1.25-2.5	2.5-3.75	3.75-5	5-6.25	6.25-7.5	7.5-11.25	11.25-15	15-30
Histograma encuesta	,555%	7,772%	21,207%	25,427%	23,206%	6,884%	11,658%	1,665%	1,888%
Histoframa Matriz Ajustada	,555%	7,772%	21,207%	25,427%	23,206%	6,884%	11,658%	1,665%	1,888%
Histograma Matriz 6% Actualizada	11,128%	27,277%	16,731%	8,732%	8,556%	6,398%	15,413%	5,525%	,501%

Figura 4. Histogramas extraídos de encuestas, de la matriz ajustada y la del 6% actualizada

4. DISEÑO DEL MAPA ESQUEMÁTICO.

Finalmente, esta tarea ha consistido en un proceso estético por el cual se busca llamar la atención de los potenciales usuarios de tal forma que vean la movilidad en bicicleta de una forma sencilla, con el fin de incitar al cambio de modo. Para conseguir esto se han llevado a cabo las siguientes acciones:

- Inclusión de los puntos de interés ya sea por medio de iconos o imágenes de sitios de interés turístico.
- Ubicación de estaciones Sevici cerca de los puntos de interés comentados.
- Identificación de las principales vías de tránsito, recogidas en la figura 5.
- Rectificación y esquematización del trazado.

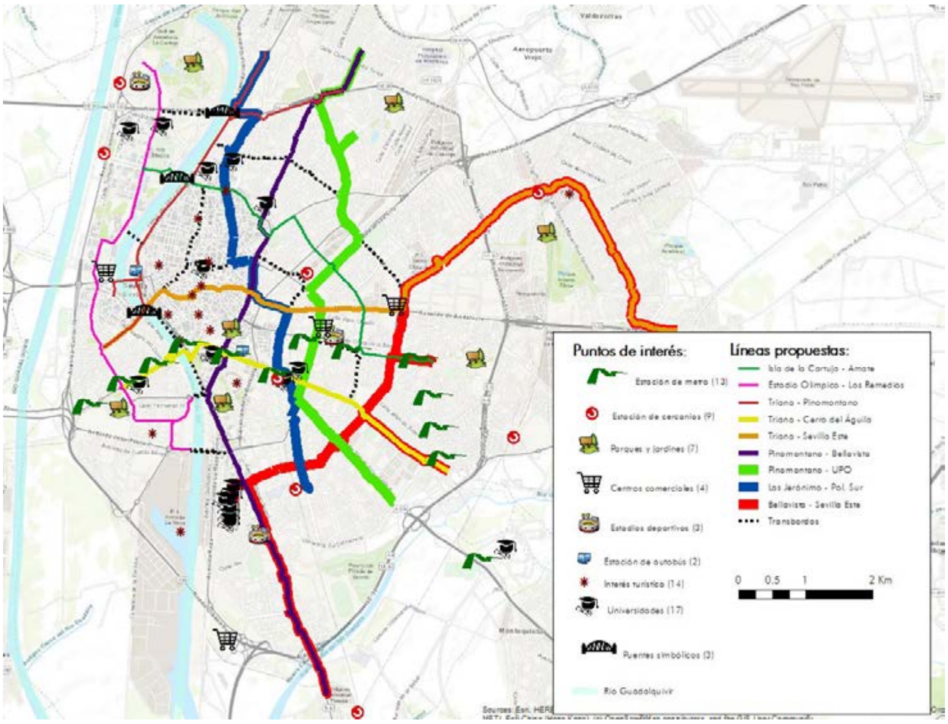


Figura 5. Trazado real de las líneas propuestas para incluir en el plano esquemático

Además, se decide no incluir información sobre el tiempo y distancia de recorrido asignado a cada uno de los arcos que componen las líneas, con el fin de evitar crear rechazo al individuo, pues la distancia y tiempo se relaciona con el esfuerzo físico que el individuo estima que debe realizar, y estos son las principales barreras que llevan a gran parte de la población a rechazar este modo de transporte. En la figura 6 se aprecia un recorte del plano resultante, diseñado a semejanza de un plano de Metro con recorridos idealizados como líneas rectas que unen los puntos de interés.

Figura 6. Fragmento del diseño final del plano esquemático de líneas de Metro-Bici Sevilla.

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ANALYSIS OF REAL EXPERIENCES USING DIFFERENT SIZED BIKE SHARING SCHEMES IN IRISH CITIES

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ABSTRACT

The first Irish public Bike Sharing Scheme (BSS) was launched in Dublin in 2009. Dublinbikes has been internationally recognised as one of the most successful bike-sharing rental schemes in the world. For this reason, among others, the cities of Cork, Limerick and Galway launched their own BSSs at the end of 2014.

The objective of this paper is to compare the performance of the four BSSs during the first two years of implementation in each Irish city according to endogenous factors, such as the physical design of the schemes, and exogenous factors, such as city size and population density. In terms of population, Limerick and Galway are small cities, Cork is a medium-sized city and Dublin is a large city. In consequence, the results cover the main relevant aspects of BSSs according to the size of the scheme, pointing out similarities and differences among BSS of different sizes. The main findings indicate that the number of daily rentals per bike is a good metric from the point of view of the transport operator. However, a higher density of bikes, stations and docking points does not imply greater usage, whereas the size of the deployment area could be a key factor in improving bike usage. Finally, a synopsis of the essential aspects to consider when designing a BSS deployment based on types of users in small cities is provided.

1. INTRODUCTION

The expansion of Bike Sharing Schemes (BSSs) across the world accelerated when the third generation of such schemes emerged. The third generation of BSSs refers to Information

Technology (IT)- based systems which apply computer technology tools to the operation of the schemes, such as electronic locks, telecommunications systems, smart cards, mobile phones or on-board computers. Moving around the city by bicycle has several advantages; for example, it reduces carbon footprints, reduces car use, provides a last-mile connector mode of transport or develops tourism. These are some of the main reasons why BSSs have grown exponentially around the world (see DeMaio, 2009; Shaheen & Guzman, 2011 or Midgley, 2011 for more detail).

Following this general trend, the first Irish public BSS (Dublinbikes) was launched in Dublin in 2009. Dublinbikes has been internationally recognised as one of the most successful bike-sharing rental schemes in the world, surpassing initial predictions and reaching one million journeys 11 months after its launch. Twenty months later, the two-million mark was attained (according to the reports of the Dublin BSS website: www.dublinbikes.ie). Besides the several advantages cited above, Dublinbike's success inspired the cities of Cork, Limerick, and Galway to launch their BSSs at the end of 2014. These four Irish cities: Dublin, Cork, Limerick and Galway, are the cities under study in this paper.

Recent works have addressed the multi-city scenario of BSSs. BSSs in European cities (for example, London, Barcelona, Paris or Dublin) and North-American cities (Denver, Chicago, Washington D.C. and Miami, among others) are compared to try to understand aspects such as the diffusion patterns of BSSs, considering the characteristics of cities and operator models, learning processes and future developments (see Parkes et al, 2013; Austwick et al, 2013; Sarkar et al, 2015). A global view of bike-sharing characteristics based on data analysed from 38 systems located in Europe, the Middle East, Asia, Australasia and America can be found in the research conducted by O'Brien et al (2014). In this study, the BSSs are characterised on a city level, comparing them in terms of system size, daily usage and compactness, to eventually build a hierarchy of cities sharing similar characteristics. Besides this, Chardon et al (2017) provide a comparison of 75 BSSs, mainly in Europe and North America, using the metric of trips per bike per day.

These studies have attempted to compare very different BSSs, and their main common results are; (i) BSSs are attractive and adaptable urban-mobility systems that are showing rapid development and expansion; (ii) there are a good number of quantitative factors characteristic to BSSs that are easily measurable, however, it is difficult to provide a benchmark to determine the success of BSSs, even when they have no explicit or measurable target; and (iii) the success of a BSS surviving over time depends on policy-makers' goals or other external inputs, such as inclusion within an effective public transport system.

In relation to the lack of a measurable target for some BSSs and their survival over time, this paper aims at pointing out similarities and differences arising from the different sizes of BSSs, mainly in small cities. It generates an open discussion about what the target users of a BSS should be according to the size of the city and its characteristics, in order to achieve a successful BSS that could be maintained over time. Moreover, whether BSS performance in one city could be extrapolated to another city with similar characteristics will be analysed.

Insights on these issues will be obtained from the study of real BSSs in the same country; Ireland. Specifically, the BSS of a large city, Dublin, during the 2009-2011 period; the BSS of a medium-sized city, Cork, during the 2015-2016 period and; the BSSs of two small cities, Limerick and Galway, during 2015-2016 will be analysed, corresponding to the first two years of their implementation in all the cases.

The paper compares how each BSS has performed according to the following differentiating factors: scheme size and density of bikes, stations and docking points (endogenous items) and city size and population density (exogenous items). These observed quantitative factors facilitate a simple comparison of many BSSs to understand each BSS in general terms. From this general perspective, it will be easier to conduct future detailed research.

This paper is structured as follows. Section 2 briefly describes the characteristics of the four Irish cities under study and their BSSs. In Section 3, data analyses focused on the density of bikes, stations and docking points of each BSS and their usage are shown, to finish with a discussion about the relevant issues found. Finally, in Section 4, some conclusions and possible future works are provided.

2. LITERATURE REVIEW AND CHARACTERISTICS OF THE BIKE SHARING SCHEMES STUDIED

2.1 Literature review

Several articles can be found about Irish BSSs; mainly about the Dublin BSS due to its success. For example, O'Neill and Caulfield (2012) analysed the mobility patterns of Dublinbikes during the first stage of the system, and Jiménez et al. (2016) focused on understanding the use of the bike stations according to user mobility patterns in 2015. Murphy and Usher (2015) studied the Dublin BSS from a social point of view, to find out the socioeconomic characteristics of the users, the impact of this mode of transport on modal choice and on driver awareness of cyclists. Caulfield (2014) investigates whether the pro-cycling policies (e.g., bicycle-purchasing schemes, reducing speed limits and the construction of segregated cycle lanes) to promote cycling applied by Dublin Council had an impact on cycling rates during the years after their implementation. Apart from these, this scheme has been researched from an economic point of view by Bullock et al (2017), whose paper places the benefits of BSSs in the economic context of private individual benefits and public good benefits, and they examine the relative value of these benefits and their impact on the spatial functioning of the city. Lawson et al (2013) have looked at the issue from a safety point of view, identifying and analysing the factors influencing cyclists' safety experiences in an urban, signalled multi-modal transportation network in their paper.

With regard to Cork, Limerick and Galway, a Technical Feasibility Study was conducted on the introduction BSSs in these regional cities, which is very useful for understanding the basis of these systems (Jacobs, 2011). Apart from this study, little more can be found about the BSSs of these three cities. Caulfield et al (2017) and McBain and Caulfield (2018) examine the trends of the bike-sharing scheme in the city of Cork, and an MNL Regression model is proposed to predict variations in the journey times of different bike trips based on spatial variables such as bike station location, distance from the city centre and type of services (shops, restaurants, public transport) along the route.

The effectiveness of the BSSs in Limerick and Galway based on station turnover ratios are described by Jiménez et al (2018). Regarding Galway BSS, Maher et al (2016) work with user surveys and stakeholder interviews to understand the beginning of the scheme (from January 2015 to September 2015); and O'Regan et al (2016) analyse the use of a smartphone application to collect rich trip and mode share data from the Limerick BSS to propose a methodology based on current feasibility studies to expand the existing schemes to other neighbourhoods.

Little research can be found related to BSSs developed in small cities. From a multi-city scenario, Audikana et al. (2017) study the Swiss experience with small BSSs spread across different cities to find out about the opportunities and challenges of BSSs in small cities. Among their different conclusions, the authors point out that more research is needed to ensure levels of success similar to medium-sized and large cities, and that partnership, communication and accountability are critical aspects to achieving successful small BSSs.

Thus, the findings of this paper could help to improve BSS performance in small cities, which usually enjoy ease of pedestrian and cycle movement.

2.2 Characteristics of the Irish bike-sharing schemes studied

The main characteristics of each Irish BSS (Dublin, Cork, Limerick and Galway) are described in this section.

Dublinbikes, is a public bicycle rental scheme which has operated in Dublin city since September 2009. At its launch, the scheme used 450 bicycles with 40 stations spread across Dublin city centre. Its acceptance was very positive during the first months. Therefore, in 2010, a mini-extension was made with 4 stations and 100 more bikes. Thus, during its first stage, Dublin Bikes consisted of 44 bicycle stations and 550 bicycles, with an estimated deployment area of 8.75 km^2; approximately 7.5% of the total area of the city (see Figure 1a). The subsequent extensions counted on up to 101 bike stations and 1,500 bikes (www.dublinbikes.ie), which increased this scheme to 20 km^2; about 17% of the total metropolitan area. In order to compare results at the same level as other cities; that is, after two years of the BSS implementation, the data collected from Dublin are related to the year 2011, considering the data of the first period of the scheme.

Figure 1b shows the deployment area of the scheme, the location of the 44 bike stations, the third-level campus located in the area, i.e., Trinity College Dublin, and the defined attraction area of the city. The attraction area includes numerous banks, offices, shopping centres, museums, tourist attractions, restaurants, cafés, clubs, hotels, pedestrian areas and green areas. That is to say, the attraction area has been defined by the high density of services offered. Most of the bike stations are located within the attraction area. They give access to businesses, shops, restaurants, tourist attractions and services, except the northern part of the system, which serves a more residential area.

The deployment area of 2.5 km per 3.5 km provides an appropriate distance to cross the city by bicycle with an average travel time of 12 minutes.

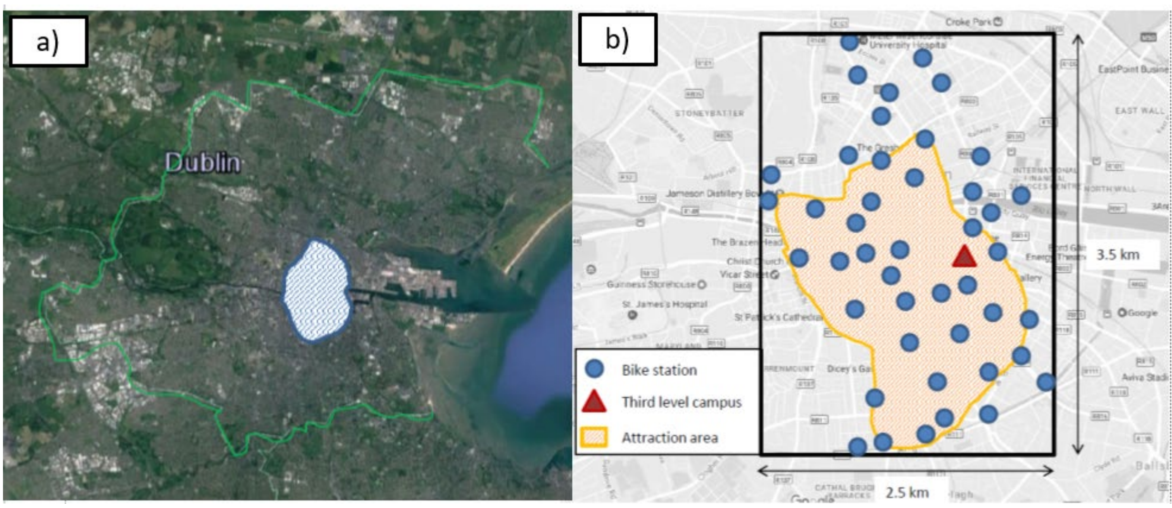

Fig. 1 – a) Dublinbikes deployment area in 2011. b) Detail of Dublinbikes extension in 2011. Source: Google maps. Digital globe 2016.

Cork's *Coca-Cola Zero Bikes* has operated in the city since December 2014. At its launch, the scheme used 330 bicycles with 31 stations spread across Cork city centre. It is estimated that the area occupied by this scheme is 2.5 km^2; approximately 6.5% of the total area of the city (Figure 2a), which is very similar to the first stage of the Dublin BSS.

Figure 2b shows the deployment area of the scheme in the main part of the Cork city centre (on the island between the two river channels), the location of the 31 bike stations and the third-level campus located in the southwestern part of the area, University College Cork. Most of the bike stations are located within the attraction area. Therefore, they give access to businesses, shops, restaurants, tourist attractions and services, but the scheme is enlarged to the Northeast to give access to the train station, and to the Southwest to cover the university, typically associated with higher BSS demand. The extension of this deployment area of 2.5 km per 1 km also provides the appropriate distance to cross the city by bicycle with an average travel time of 7 minutes; probably shorter distances than the Dublin scheme, but still efficient for bicycles.

Fig. 2 – a) Cork Bikes extension in 2016. b) Detail of Cork Bikes extension in 2016. Source: Google maps. Digital globe 2016.

Limerick's *Coca-Cola Zero Bikes* has operated in the city since December 2014, like the Cork BSS. The scheme uses 215 bicycles with 22 stations spread across Limerick city centre.

It is estimated that the area occupied by this scheme is 3 km^2; approximately 10% of the total area of the city, and the largest area of the four Irish cities at the beginning of their BSS implementation (Figure 3a). The deployment area of the Limerick scheme, the city centre, is shown in Figure 3b, together with the location of the 22 bike stations. Most of the bike stations are located within the attraction area. They give access to businesses, shops, restaurants and tourist attractions, although the scheme has some bike stations near to residential neighbourhoods in the East and Southwest. The extension of this deployment area of 1.5 km per 2 km is within the limit of an appropriate distance to go by bicycle. This means that to ride 2 km across the city takes 8 minutes with an average speed of 15 km/h (comfortable speed), whereas walking these 2 km across the city takes 24 min (average speed of 5 km/h for pedestrians). Generally, half an hour is the maximum time commuters will consider walking. Thus, it can be said that a distance of 2 km is the lower limit for the use of bicycles because distances lower than 2 km are also comfortable to walk, and people would not have to change their mode of transport. Note that this BSS does not cover the demand of the University of Limerick, located about 6 km from the city centre towards the East.

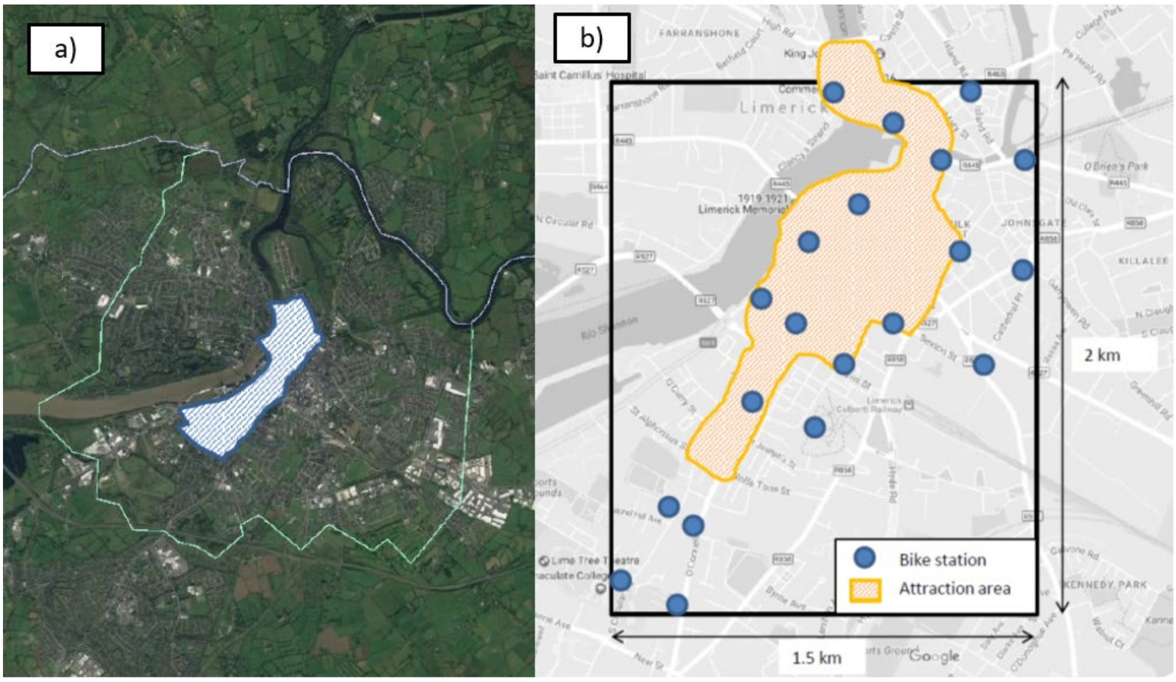

Fig. 3 – a) Limerick Bikes extension in 2016. b) Detail of Limerick Bikes extension in 2016. Source: Google maps. Digital globe 2016.

Galway's *Coca-Cola Zero Bikes* has also operated in the city since November 2014. The scheme uses 195 bicycles with 15 stations spread across Galway city centre. It is estimated that the area occupied by this scheme is 1.2 km^2; approximately 2% of the total area of the city, the lowest value among the four cities (Figure 4a). The deployment area of the Galway scheme, as well as the city centre, is shown in Figure 4b, together with the location of the 15 bike stations. Most of the bike stations are located within the attraction area. This means they give access to businesses, shops, restaurants and tourist attractions. Related to the third-level campus, the location of a bike station near the Galway Technical Institute (lower left corner) and the lack of them near the National University of Ireland - Galway (upper left red point in Figure 4b) stand out because universities are a source of potential bike-sharing users. On the other hand, the extension of this deployment area of 1 km per 1.2 km is also remarkable because the possible distance covered by bicycle (an average travel time of 5 min from extreme to extreme) can also be done by walking; thus, people might not be encouraged to use bicycles in the same way as in Limerick.

Note that in these specific cities, university campuses are relevant to understanding current and future BSS usage because (i) the scheme is used by students, faculty and staff members to access the university, (most of them combine bicycles with the train if they live in the outskirts), (ii) the bike stations related to these universities become part of the general scheme of the city, (iii) the universities are tourist attractions, especially in Dublin and Cork, and (iv) the students living on university campuses use bikes to move around the city.

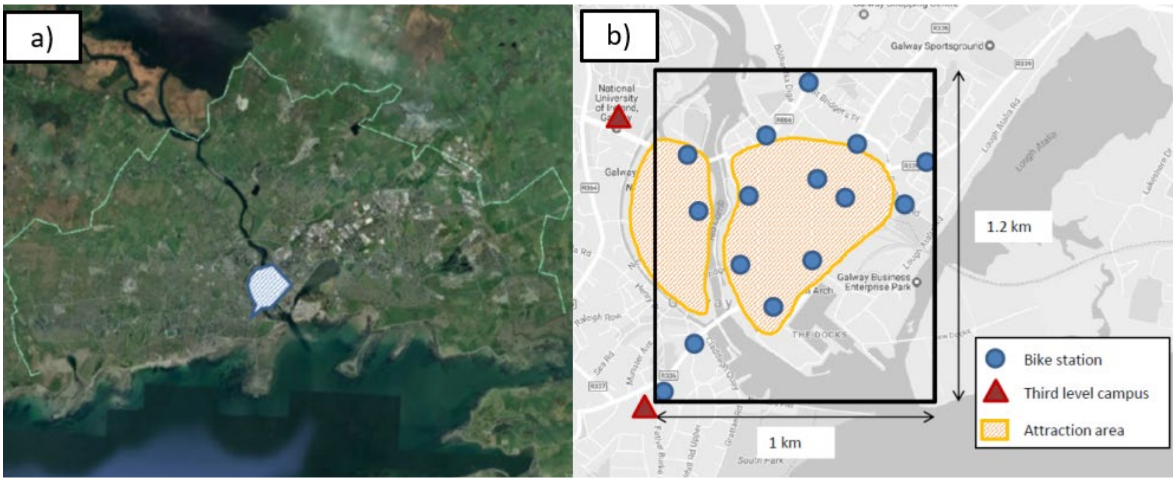

Fig. 4 – a) Galway Bikes extension in 2016. b) Detail of Galway Bikes extension in 2016. Source: Google maps. Digital globe 2016.

Table 1 provides data about population density, potential BSS users (considering that citizens between 20 and 39 years old are the main target group for bicycle usage on a daily basis), the area of the city occupied by the scheme and the number of bikes, stations and docking points of each BSS for each city. From this table two aspects are highlighted: (i) Dublin, Cork and Limerick have greater population density than Galway, and (ii) the percentage of the city area with bike stations during the first stage in all the cities could be considered to be similar, except for Galway. Galway has a low value with 2.4% of the area with bike stations; 5 points below the percentage of the first stage of *Dublinbikes*, and 8 points below the Limerick BSS. Both issues are important because they could affect the usage of the system in each city.

	Dublin 2011	Cork 2016	Limerick 2016	Galway 2016
Population (inhabitants)	527, 612	125, 657	94, 192	78, 888
Area of the city (km^2)	116.58	38.59	28.38	50.00
Population density (inh/km^2)	4, 526	3, 256	3, 319	1, 578
Main potential BSS users (20-39 years old)	208, 489	44, 561	26, 033	30, 693
% main potential BSS users over the total population	39	35	28	39
Area of the city with bike stations (km^2)	8.75	2.50	3.00	1.20
% area of the city with the bike stations over all area	7.51	6.48	10.57	2.4
BSS basic data				
Number of bikes	550	330	215	195
Number of stations	44	31	22	15
Number of docking points	1, 145	574	406	250

Table 1 –Basic demographic data and number of bikes, bike stations and docking points for each Irish city studied. Data source: Census 2011 and 2016 of Ireland and Northern Ireland. Central Statistics Office. *Dublinbikes. Coca Cola Zero bikes*.

3. DATA ANALYSIS

3.1. Research context

This paper focuses on a multi-city scenario (most of them small to medium-sized) within a country to identify similarities and differences among the different sizes of BSSs. Also, the role of BSS target users in relation to a city's size and its characteristics are investigated to see what makes a BSS successful over time. Moreover, the question about whether the BSS performance of a consolidated scheme, such as *Dublinbikes*, could be extrapolated to other schemes with similar characteristics except city size, will be analysed.

To achieve these objectives, the European research study, Optimising Bike Sharing in European Cities – A Handbook (OBIS, Büttner et al 2011) has been taken as a reference. Its main objective is to encourage the implementation and optimisation of BSSs all over Europe and worldwide. This project collects relevant information about more than 50 BSSs from different European countries. Data are analysed and the results presented according to city size, providing a good overview and guidance for cities with similar conditions.

Therefore, according to their population and the definition of the OBIS project, Limerick and Galway are small cities because their population is between 20,000 and 100,000 inhabitants, Cork is a medium-sized city because its population is between 100,000 and 500,000 inhabitants and Dublin is a large city with a population greater than 500,000 inhabitants (Table 1).

Furthermore, the OBIS document gathers factors influencing BSSs, which are divided into endogenous and exogenous factors. This classification is used as the guide to select the factors analysed in this paper.

Regarding endogenous factors, only the physical design of the schemes (size and density) is analysed because it is the main differentiating factor among the BSSs involved. The rest of the endogenous items are similar for the four BSSs. All the services are available all year round, 7 days a week, from 5 am to 00.30 am, though a bike can be returned to available stands at any time of day or night.

They all offer two types of registration; annual subscription and 3-Day subscription for occasional short-term use or for visitors to the cities. Thus, all stations are equipped for Annual Card and 3-Day Ticket users because the hardware and technology consist of card-based access in each station. The first 30 minutes of each hire is free. For longer hires, a charge is applied.

With reference to exogenous factors, city size is the most relevant. The other exogenous factors such as climate, topology, economy and policy exhibit secondary importance. In fact, climate is not a key factor because the weather is similar in all four cities.

They have a mild oceanic climate with abundant rainfall and a lack of extreme temperatures. Thus, the use of bicycles is typical of warm cities with regular use all year and a slight fall in winter and summer (according to the description of the OBIS document). In relation to general geographical factors, all the cities have a main river and/or river channels, they are not hilly, the bikes are integrated into the traffic flow (except in Dublin, where there are a few segregated cycle lanes), and the core of the bicycle scheme is located in the main attraction area of the city (with several businesses, restaurants, shops, tourist attractions and services).

Thus, the cities depart from a similar starting point in terms of local conditions. However, the size of the deployment area and its extension into residential areas or university campuses are different in each city, and these will be the aspects to compare and explain.

In particular, the density of the bikes, stations and docking points of each BSS related to the population, the entire city area and the city area with bike stations, together with other ratios regarding the docking points are analysed. These figures provide a general view of the scale of bicycle-sharing network coverage (relatively dense), allowing comparison with average European values (according to the OBIS document), which are helpful in understanding the possible relationship between BSS coverage scale and the usage and development of the schemes. With regard to BSS usage, the data are divided according to the type of user (annual or occasional).

An estimation of the degree of success of a BBS will depend on the point of view of the stakeholders. In this case, the point of view is the transport company's, based on the usage and efficiency of the systems, which is understood as the number of daily rentals per bike.

The aggregated data used in this study allows for the estimation of the degree of success from this perspective. The larger the values, the more successful the system is. This criterion is widely used because it is an easily comparable measure. Besides, it is of interest to identify possible patterns in the usage data of the first years of BSS implementation in the four cities and to find specific characteristics of BSSs in small cities.

3.2. Dataset description

The dataset has been obtained by open sources and previously published manuscripts. The data related to Dublinbikes are obtained through the reports available on its website (www.dublinbikes.ie), and in the cases of Cork, Limerick and Galway BSSs, from the reports available on the common website (www.bikeshare.ie). In addition, the provided data from Caulfield et al (2017) and McBain and Caulfield (2018) are consulted to complete Cork bike information, whereas for the BSSs of Limerick and Galway, data from Jiménez et al (2018) are also used.

The proposed approach is not data intensive. Thus, it is easily scalable by adding new cities, and allows a good picture of the main BBS characteristics without overwhelming the analyst with an overly extensive list of indicators.

3.3. BSS infrastructure

In order to compare the four BSSs, the density of bikes, stations and docking points of each BSS are calculated. Table 2 provides the main results in relation to the density of each bike, station and docking point over the population, over the entire area of the city and over the deployment area of the scheme. The ratios regarding docking points based on the figures of Table 1 are also analysed.

	Dublin 2011	Cork 2016	Limerick 2016	Galway 2016
Bike/station/ docking point density over population				
Number of bikes / 10, 000 inhabitants	10	26	23	25
Number of stations / 10, 000 inhabitants	0.8	2.5	2.3	1.9
Number of docking points / 10, 000 inhabitants	22	46	43	32
Bike/station/ docking point density over the whole city area				
Bike density (unit/km^2)	4.72	8.55	7.58	3.9
Station density (unit/km^2)	0.38	0.80	0.78	0.30
Docking point density (unit/km^2)	9.82	14.87	14.31	5.00
Bike/station/ docking point density over the city area with bike stations				
Bike density (unit/km^2)	62.86	132.00	71.67	162.50
Station density (unit/km^2)	5.03	12.40	7.33	12.50
Docking point density (unit/km^2)	130.86	229.60	135.33	208.33
Ratios regarding docking points				
Number of docking points / bike	2.1	1.7	1.9	1.3
Average number of docking points / station	26	18	18	17
Standard deviation of docking points / station	5.5	6.6	4.5	3.8

Table 2 –Scheme size and density of bikes/stations/docking points of BSSs for each Irish city studied.

In relation to the density of bike/station/docking points over the population, the Cork, Limerick and Galway BSSs (the medium-sized and the two small-sized, respectively) have approximately double the value than the Dublin BSS This means that they provide more physical components per inhabitants. The figures of these three cities are also higher than the average values indicated in the BSS key figures of the OBIS sample (14.8 bikes per 10,000 inhabitants and 1.5 stations per 10,000 inhabitants), whereas Dublinbikes is below these references.

When comparing the schemes according to city area or the deployment area of the BSSs, two aspects are highlighted. The first one is that Cork and Limerick’s ratios of bike/station/docking point density over the entire city area stand out above the rest, and the second one is that the ratios of bike/station/docking point density over the deployment area of the BSSs are similar between Cork and Galway, and, in turn, higher than Dublin and Limerick’s.

Ratios of docking points show that each bike has roughly two docking points. However, the ratio in Galway is close to one; the minimum value required to be able to operate. However, it corresponds to the figure in the OBIS document (1.2) for this item in small cities.

Concerning the capacity of the stations, the Dublin bike stations are bigger than the bike stations in the other cities; that is, they have more docking points. Interestingly, the capacity data are opposed to the sample given in the OBIS project, where results show an average of 9.5 docking points per station for large cities and 23.5 and 22.9 docking points per station for medium-sized and small cities, respectively.

3.4. BSS usage

Regarding the usage data shown in Table 3, three aspects are highlighted.

The first feature is the large number of trips in Dublin; four times greater than Cork, thirty-five times greater than Limerick and almost seventy-seven times greater than Galway. This figure is closely related to the number of users; that is, there are four times more users in Dublin than in Cork, and about twenty times more than in Limerick and Galway.

The second aspect to point out is the share of annual and occasional users. Dublin and Galway BSSs have a large number of tourists since occasional users are 40% of the total. However, the Limerick BSS has high annual user demand, with these users making up 90% of the total. Similarly, regarding the total number of trips during the two first years of implementation, the average number of daily trips is greater in Dublin, and this value decreases according to the size of the BSS.

The third point to highlight is related to the daily rental ratio per bike. Specifically, the low values in Limerick and Galway show practically no daily use of bikes.

This indicates that the trips and users are insufficient to keep a steady level of usage throughout the year, and use is concentrated over several months in spring and autumn. Thus, neither of these systems are considered to be efficient in terms of the regular usage of the scheme.

	Dublin 2009-2011	Cork 2015-2016	Limerick 2015-2016	Galway 2015-2016
Total number of trips	2, 500, 000	518, 000	71, 595	32, 460
Total number of users	62, 000	N.A.	3, 230	2, 743
% Annual users	60	N.A.	90	64
% Occasional users	40	N.A.	10	36
Average daily trips	3, 425	710	98	44
Daily rental per bike	6.2	2.2	0.5	0.2
Average number of trips per user (all types of users)	40	N.A.	22	12

Table 3- Usage of each BSS studied. (N.A. – Not available)

3.5. Discussion

Dublinbikes, a large city scheme, has been well received by society. Proof of this is the second enlargement of the system in 2014. Some of the main reasons are (i) Dublin's high population density, 4,526 inh./km2 in 2011 (see Table 1), and (ii) the size of the deployment area of the BSS; that is, the extension area where the bike trips are efficient and can be combined with trips on foot and by car to access work or when enjoying leisure activities.

Additionally, other characteristics and practical measures such as the percentage of young population, cycling facilities, 30 km/h zones, communication campaigns and council favour, have supported its development. However, the values of the density of bikes, stations and docking points over the population and the entire city area are lower than the values of the other three cities and the reference values of the OBIS document.

Related to Cork, a medium-sized city, when comparing the data of trips and population with the data of trips and population in Dublin in 2011, the same proportion is shown. Thus, the same trend experienced by Dublin could be expected there. Some of the main reasons for achieving these numbers of trips and users could be the city's population density and the deployment area of the BSS. Indeed, this area is within the limit of efficient bike trips; that is, an area of 2.5 km^2 providing appropriate distances to cross the city by bicycle with an average travel time of 7 minutes (in an area smaller than 2.5-3.0 km^2, the possible routes are also appropriate for walking, and the impact of the scheme might be lower due to the low level of usage).

Usage is reinforced with the university connection, which provide an important group of system users. Note that neither Limerick nor Galway have bike stations near their university campuses.

The findings of this paper show that usage in Galway and Limerick is lower than in the other Irish schemes, with average daily bike rental near zero (Table 3). One possible strategy to increase this usage could be to expand the scheme.

This coverage growth could result in an upturn in usage numbers. Considering that both cities have small deployment areas in the schemes, a modal shift from pedestrians to cyclists is complicated. Moreover, a large group of potential demand, the staff and students of the universities, are outside of both BSSs. However, the cities have different characteristics.

Limerick has similar population density to Cork, whereas Galway has lower population density than the other cities. The type of users in each city is also different. This indicates that the development of each BSS for the short-term should be addressed from different perspectives according to the characteristics of each target group.

The main outcomes of the analysis based on real experiences could be summarised as follows:

- Only data from Dublinbikes could be partially comparable to the Cork scheme (medium-sized city), according to the ratio of number of trips and population, which have the same proportion. Moreover, deployment areas have a large enough extension to encourage bike usage, being close to the university.

- The number of daily rentals per bike is the most objective indicator of success in relation to usage from the perspective of the transport operator. Thus, the schemes of Dublin and Cork have good performance, whereas Limerick and Galway show a value below 1 (some bikes are unused each day).

- A higher density of bikes, stations or docking points does not imply greater usage; whereas the size of the deployment area could be a key factor in improving bike usage.

- BSS performance in small cities should not be compared with the BSSs of large cities by means of only quantitative data.

The identification of a successful BSS is indeed a difficult issue to solve because each city is conditioned by many aspects such as the characteristics of the surrounding area, the initial scenario of implementation and operational management. Moreover, the success of a system cannot be based only on a single ratio (e.g., number of daily rentals per bike) despite its good performance. In fact, the success of a BSS will depend on the desired goals of the council or the promoting body of the project in the short and long term and on the indirect benefits expected. That is, assessing whether a BSS is successful or not will depend on *what* and *who* it is for. Therefore, and according to the obtained results, the question to answer is how to improve the performance of BSSs in small cities. To answer this question, some considerations were analysed, from which Figure 5 emerges.

Figure 5 shows a synopsis of key aspects and recommended questions to consider before designing a BSS deployment or when improvements are desired after a few years of working. The identification of city characteristics from the point of view of the offer available is the first analysis to carry out; that is, to identify the attraction areas of the city such as business areas, third-level campuses, shopping areas, outdoor leisure and indoor zones and museums and areas of cultural activities. Next, the generation areas are also determined, such as residential and tourist accommodation areas, to consider that all attraction areas become generation areas when they are the origin of the trip.

Geographical barriers are also described to discover uncomfortable paths, inaccessible areas or critical points in bicycle trips. Space syntax would be a useful tool for this purpose. At the same time, the potential users, residents and/or tourists are also identified, in addition to the definition of the attraction and generation areas involved with each one (right upper corner of Figure 5). For example, the main attraction areas for residents are the business areas and third-level campuses because they make these trips on a daily basis, although they also visit the rest of the identified attraction areas during their leisure time. However, tourists are usually interested in visiting all types of leisure areas and places with cultural activities.

Once all these elements have been identified according to the target user of the BSS, some questions should be considered to design an adequate deployment area able to attract users and make the BSS profitable. As the lower part of Figure 5 shows, if the main target users are residents, the key is the extension of the deployment area to make bicycle trips efficient; that is, there will be sufficient bicycle stations to link residential areas with attraction areas. Moreover, the distance should be far enough to make the trip by bike worthwhile.

This type of user guarantees a steady level of usage, although detailed studies on seasonality and student mobility patterns should be developed to continue improving the scheme. If the target users are tourists, becoming aware of the seasonality of their visits is essential to understanding the usage of the system, as might be Galway's case in the first stage. In this case, the deployment area would be less important because tourists usually make circular trips, enjoying the city while stopping for sightseeing and shopping, so they use the BSS in a different way than residents. Finally, if the BSS covers both types of users, in addition to the two previous questions, it is important to identify possible overlapping between resident and tourist attraction areas to be able to take advantage of this overlapping and make the BSS more profitable. Obviously, these are general considerations that help in initiating the layout of a BSS in small cities. They should be complemented with specific studies for each city.

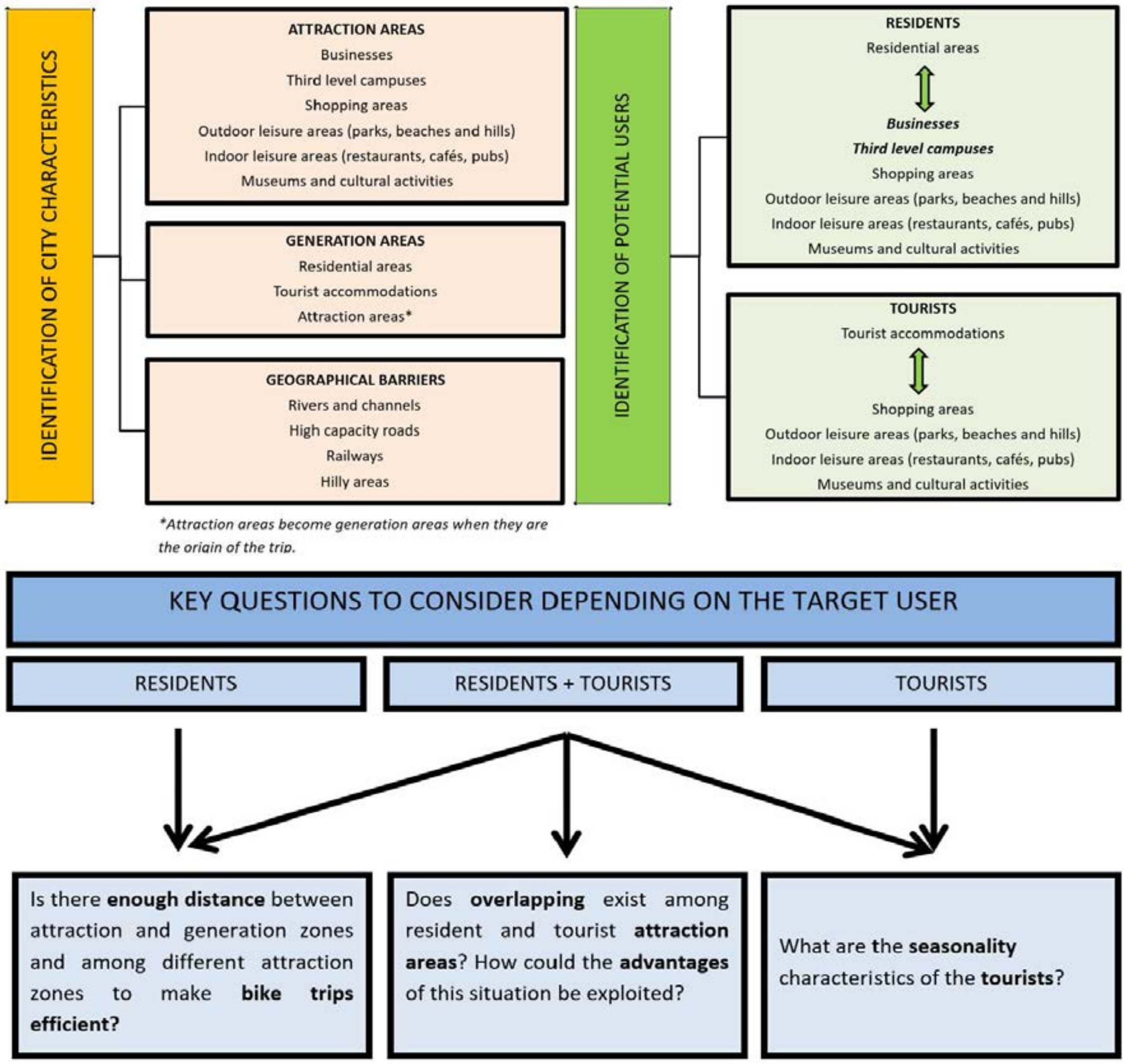

Fig. 5 – Synopsis of key questions to consider when designing a BSS deployment area in small cities.

4. CONCLUSIONS

A BSS in Dublin (large city), a BSS in Cork (medium-sized city), and two BSSs in Limerick and Galway (small cities) have been analysed during their first two years of implementation to try to understand how the size of the city and its scheme could affect the usage of each BSS.

The number of daily rentals per bike is a good metric from the point of view of the transport operator. However, a higher density of bikes, stations or docking points does not imply greater usage, whereas the size of the deployment area could be a key factor in improving bike usage.

In general terms, the development and operation of BSSs in medium-sized to large cities are usually satisfactory because of the high population density, the several groups of interest and the suitable distance covered by bicycle trips. In contrast, the usage level of BSSs in small cities is different from large cities because the deployment area is usually inefficient for bicycle trips and the management of potential users is not adequate. Thus, based on these current experiences, to extrapolate general results from the BSSs of large cities to schemes in small cities would not be recommendable.

Improving BSS performance, mainly in small cities, requires the identification of the city's characteristics from the point of view of the offer available, attraction and generation areas, along with possible geographical barriers and the identification of the potential users, residents and tourists. All these elements could help to guide the initial design or new measures to put into practice to improve BSS performance in the short term.

In fact, studying the first two years of BSS implementation in small cities is very helpful to be able to understand the mobility patterns of users and how to manage a BSS to obtain successful operation in the future. Developing a BSS depending on the characteristics of the main group of users registered during the studied period, i.e., annual or occasional users, to achieve the desired results in the short term, and then expanding the system to other types of users if desired, is recommended. Thus, studies on each group of specific users and how to adapt BSSs to them in small cities will be the next topic to research in order to improve the knowledge in this area and to be able to adapt better schemes to achieve efficient and profitable results. For these studies, not only the identified critical issues should be considered, but also how to improve cycling infrastructure, new 30 km/h zones or communication campaigns for the development and operation of small BSSs.

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METODOLOGÍA BASADA EN GIS PARA LA PLANIFICACIÓN DE UNA RED URBANA DE CARRILES BICI

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RESUMEN

En los últimos tiempos ha cobrado fuerza en las ciudades españolas la necesidad de contar con una red de carril bici con gran parte de su recorrido segregado del resto del tráfico. En paralelo, la pandemia de COVID-19 iniciada en 2020 provocó el interés de muchos municipios por crear redes provisionales de carril bici segregadas, mediante obras que se limitaban a alterar la señalización del viario. Para ambas situaciones -planificación de una red definitiva o una red provisional- se desarrolla un método de planificación rápida basado en herramientas GIS que consiste en analizar el conjunto de vías urbanas consolidadas, recabando datos de parámetros como la geometría transversal y longitudinal, la existencia de aparcamientos o la definición del tráfico en su sección tipo. A partir de los datos se obtiene el conjunto de calles que están en condiciones de ser modificadas para introducir en ellas un carril bici sin alterar el esquema circulatorio previo. El método se aplica a la zona centro de la ciudad de Gijón, España.

1. INTRODUCCIÓN

Las ventajas del empleo de la bicicleta como medio de transporte urbano son harto conocidas, y alcanzan la sostenibilidad ambiental o la repercusión positiva en la salud de los ciudadanos, por citar algunas (Frank et al., 2006; Gotschi, 2011; Mueller et al., 2018). Pese a ello, España ha mostrado una fuerte reticencia a la bicicleta como vehículo urbano. Así, el Eurobarómetro sobre la actitud de los europeos hacia la movilidad urbana (European Union, 2013) preguntaba la frecuencia con la que se empleaba la bicicleta, y España estaba en las últimas posiciones (sólo por delante de Chipre y Malta) con un 4% de los ciudadanos que reconocían el uso diario de la bicicleta (lejos del 43% de los Países Bajos, y de la media europea, que se situaba en el 12%).

Del mismo modo, en el Eurobarómetro sobre calidad del transporte (European Union, 2014) a la pregunta “En un día normal, ¿qué modo de transporte utiliza con más frecuencia?” el 8% de los europeos citaba la bicicleta por el 3% de los españoles, y lejos por tanto de neerlandeses (36%), daneses (23%) o húngaros (Plasencia-Lozano, 2021).

Sin embargo, en los últimos años se han puesto en marcha políticas y proyectos que incrementan el número de carriles bici con el propósito de cambiar el paradigma tradicional de la movilidad urbana, que situaba al coche particular en el centro durante décadas. No en vano, los informes del Observatorio de la movilidad urbana (Monzón de Cáceres, López García de Léaniz, Del Cuvillo, Julio Castillo, y Sánchez Sacristán, n.d.) muestran un incremento significativo de las infraestructuras ciclistas construidas en España (Tabla 1): Sevilla fue la primera gran ciudad en plantear una red amplia, tras el Plan Director de la Bicicleta del 2007 (Morales Carballo, 2011); en ciudades como Madrid, Barcelona o Alicante el incremento ha sido significativo desde el 2012, mientras que los casos de Málaga, Granada o Tarragona prueban que aún hay ciudades reticentes al cambio.

	2008	2010	2012	2014	2016	2018
Madrid						
Longitud	151	151	290	447	590	601
Densidad	47	46	90	88	186	186
Barcelona						
Longitud	140	159	187	558	1167	1468
Densidad	87	98	115	-	725	906
Valencia						
Longitud	80	139	137	168	168	175
Densidad	99	171	172	174	212	220
Sevilla						
Longitud	147	147	136	136	166	166
Densidad	210	209	194	195	240	241
Málaga						
Longitud	25	30	35	-	35	44
Densidad	44	53	62	-	62	77
Granada						
Longitud	9	9	9	27	27	27
Densidad	38	38	38	116	115	117
Alicante						
Longitud	23	41	111	155	155	174
Densidad	69	122	332	-	469	522
Tarragona						
Longitud	-	6	10	11	13	14
Densidad	-	42	75	76	91	99

Tabla 1 – Longitud (km) y densidad (km /millón de habitantes) de los carriles bici construidos en algunas ciudades españolas. Incluyen todo tipo de carriles concebidos para bicicletas, incluyendo calles compartidas. Fuente: Observatorio de la Movilidad Metropolitana

En paralelo, la irrupción de la COVID-19 ha provocado profundos cambios en la movilidad de nuestras ciudades (Awad-Núñez, Julio, Moya-Gómez, Gomez, y Sastre González, 2021).

Los nuevos hábitos de transporte indican una tendencia decreciente del uso del transporte público, y un aumento en la movilidad en vehículos individuales, especialmente bicicletas o patinetes, que ha provocado la construcción de nuevos carriles bici en todo el mundo. No en vano, durante la pandemia, las más diversas ciudades realizaron modificaciones en el uso del espacio público (con mayor o menor éxito) para implantar redes de carriles bici provisionales (Soengas, 2020): en ocasiones, la actuación se limitaba a introducir alguna señal vertical y a disponer señalización horizontal, pintando sobre la propia calzada o acera (Abad, 2020). Aparentemente, no había un trabajo previo de planificación.

Figura 1 – Carriles bici provisionales construidos en diversas ciudades durante la pandemia: Oviedo (Abad, 2020), Vigo (Vila, 2020), Barcelona (Blanchar, 2020) y Berlín (Redacción).

La planificación en detalle de una red de carril bici, dentro de una estrategia amplia de movilidad es una tarea compleja que implica muchas horas de trabajo. El espacio público en los centros urbanos suele ser escaso y por ello la introducción de una nueva malla de transportes (el carril bici) implica la reducción o eliminación de alguno de los usos existentes. En tiempos recientes, se han desarrollado métodos para poder realizar determinar con eficacia una red (Koh y Wong, 2013; Winters, Davidson, Kao, y Teschke, 2011), entre los que destacan aquellos derivados del método BLOS (Bicycle Level of Service) desarrollado por el Transportation Research Board, que evalúan las condiciones de las vías urbanas para incorporar un espacio ciclista (Terh y Cao, 2018).

En paralelo, las herramientas GIS están revolucionando la planificación gracias a la capacidad que ofrecen para plasmar información diversa en relación a una realidad territorial.

En esa línea, creemos interesante desarrollar una metodología rápida de planificación que pueda ser usada tanto para realizar una primera evaluación de red, dentro de un proceso prolongado de planificación integral de la movilidad urbana, como para determinar con rapidez la viabilidad o no de poder implantar una red de carril bici de forma provisional sin afectar especialmente a los esquemas de circulación de vehículos privados. Esta metodología se realizará con herramientas GIS, a partir de datos públicos y de otros datos recabados en trabajo de campo.

El propósito será, por tanto, evaluar si las condiciones geométricas del conjunto de calles permitirán introducir un carril bici en ella sin afectar al esquema de circulación ya existente.

Aquellos ayuntamientos que deseen introducir una red provisional mediante la inserción de señalización vertical y horizontal pueden encontrar útil este método para analizar si puede plasmarse con rapidez una red válida que no afecte al esquema circulatorio; aquellos consultores que están realizando un plan de movilidad pueden encontrar válido el método para determinar, a priori, qué conjunto de calles son las idóneas para intervenir en ellas introduciendo un nuevo carril bici.

El método desarrollado se aplica a la zona centro de Gijón, ciudad de tamaño medio situada en el norte de España, donde la red de carril bici se encuentra aún poco desarrollada pese a que ya hay planes para ampliarla (Ayuntamiento de Gijón, 2021).

Figura 2 – Ubicación de Gijón y área de estudio.

2. MÉTODO

El método desarrollado se basa en la recopilación de datos y en el uso posterior de una herramienta GIS para tratarlos y analizarlos.

En primer lugar, se seleccionan una serie de guías de diseño y publicaciones de referencia relacionados con la planificación y diseño de carriles bici. Las publicaciones de referencia son: el Manual CROW (2011), el Cycle Infrastructure Design del Department for Transports (2020); Focus on cycling, de Copenhague (2013); Cycle concepts, de Dinamarca (Andersen et al., 2012); el manual Sustrans (2015); las recomendaciones incluidas en el Plan Andaluz de Bicicleta 2014-2020 (2014); y las Recomendaciones para el proyecto y diseño de viario urbano del Ministerio de Fomento de España (2000). En ellos se buscan los valores recomendados para los siguientes parámetros: pendiente máxima de la calle; anchura necesaria para un carril bici adosado al viario al mismo nivel; velocidad máxima del tráfico rodado en la calle; tipo de pavimento; idoneidad o no de coexistencia de la bicicleta en calles peatonales. Los valores obtenidos serán cotejados con los valores reales de las calles incluidas en la zona de estudio, y permitirán determinar qué tramos viales cumplen con criterios teóricos.

En paralelo, se determina el valor mínimo que pueden tener las distintas bandas de las distintas zonas: aparcamiento y calzadas; para ello se emplea como referencia las recomendaciones para el proyecto y diseño de viario urbano del Ministerio de Fomento de España. Con estos valores se podrá determinar qué espacios actuales pueden ser sustituidos por carriles bici futuros sin modificar el esquema de circulación existente: esta será la premisa mínima que debe cumplir la red de carril bici resultante. Para realizar el análisis se emplea el software libre QGIS, que permite introducir el viario junto con los valores reales y realizar así el estudio de cada tramo de calle. Finalmente, se analiza el viario resultante, y se extraen conclusiones.

3. RESULTADOS

3.1. Datos procedentes de documentos técnicos

En primer lugar se realiza la comparación de los valores otorgados por los documentos técnicos utilizados a los diferentes parámetros (Tabla 2). Se observa que la pendiente máxima admisible suele establecerse en el 5%. Con respecto al tipo de pavimento, se consideran adecuadas las superficies suaves como las mezclas bituminosas o incluso el hormigón, y se desaconseja el empleo de adoquines.

En cuanto a la anchura adecuada para un carril bici adosado a una vía con tráfico, sin separación física, se ha buscado información para dos casos: carril bidireccional y carril unidireccional.

La opción de disponer un carril bici bidireccional adosado a uno de los sentidos es desechada porque las publicaciones analizadas lo desaconsejan o ni siquiera lo consideran.

En cuanto a la opción de disponer un carril bici unidireccional adosado a cada uno de los sentidos, se establece que el valor mínimo es de 1,5 m, con lo cual el total de la calzada a ocupar sea de 3,0 m. Otro parámetro importante para la seguridad de circulación es la velocidad máxima admisible de la circulación rodada de la calle cuando no existe una separación física clara. En general, los manuales no recomiendan un carril bici adosado en calles donde se circule a más de 50 km/h, y se decide que esa velocidad sea el límite máximo admisible. En calles con una mayor velocidad de circulación admisible sí se podría introducir el carril bici igualmente, pero tendría que limitarse la velocidad a 50 km/h.

Finalmente, se evalúa la posibilidad de incluir bicicletas en calles peatonales. En los documentos técnicos consultados no se recomienda cuando hay bastante afluencia de peatones. En Gijón no hay aforo de peatones: por ello se decide no utilizar las calles peatonales dentro de la malla.

PARÁMETRO		CROW	Cycle Infrastructure Design	Focus on cycling	Cycling concepts	Sustrans	Plan Andaluz de Bicicleta	Recomendaciones para el proyecto y diseño de viario urbano
Pendiente de la calle		5% máximo recomendable	5%, máximo recomendable	-	5% máximo recomendable	6% máximo recomendable	5% máximo recomendable	7% máximo recomendable
Ancho de un carril bici adosado a un carril con tráfico al mismo nivel	Caso de un carril bici bidireccional	No recomienda	-	-	-	No recomienda	Mínimo 2,5 m	No recomienda
	Caso de un carril bici unidireccional	Mínimo 1,5 m; adecuado 2,0 m; máximo 2,5 m	Mínimo 1,5 m; adecuado 2 m	Mínimo 1,6 m; adecuado 2,2 m	Mínimo 1,5 m	Mínimo 1,5 m; adecuado 2 m	Mínimo 1,5 m; adecuado 1,8 m	Mínimo 1,8 m; adecuado 2 m
Velocidad del tráfico rodado en la calle en un carril bici al mismo nivel		Prohibido en vías > 70 km/h. Poco recomendable en vías > 50 km/h	Prohibido en vías > 50 mph. Poco recomendable en vías > 30 mph. Precaución en vías > 20 mph	-	Prohibido en vías > 55 km/h. Poco recomendable en vías > 35 km/h	Prohibido en vías > 40 mph	Prohibido en vías > 50 km/h	-
Tipo de pavimento		Asfalto bien; hormigón adecuado; adoquines mal	Asfalto bien; adoquines mal	Asfalto bien; adoquines mal	Asfalto bien; adoquines mal	Asfalto obligatorio en rampas	Asfalto bien; adoquines mal	Asfalto bien; adoquines mal
Calles peatonales. Espacio compartido con el peatón.		Sólo si hay menos de 100 peatones por hora y por metro	Hasta 300 peatones por hora, en calle de 3 m	-	Desaconseja el uso mixto en general	-	-	-
Calles peatonales. Espacio compartido con el peatón.		Sólo si hay menos de 100 peatones por hora y por metro	Hasta 300 peatones por hora, en calle de 3 m	-	Desaconseja el uso mixto en general	-	-	-

Tabla 2 – Parámetros obtenidos en los documentos técnicos consultados.

3.2. Anchuras mínimas de las franjas de espacio viario. Árbol de decisión

Una vez cuantificados los valores adecuados para los parámetros se determinan las anchuras mínimas que presentan las distintas franjas de espacio viario ocupado por los vehículos.

Para ello se toman los valores mínimos establecidos por las Recomendaciones del Ministerio de Fomento, como documento de referencia en España (Tabla 3). Gracias a ello, podrá decidirse qué espacios de tipo calzada o aparcamiento pueden ser sustituidos por sendos carriles bici unidireccionales.

Espacio	Ancho (m)
Carril bici unidireccional. Un carril de 1,5 m por cada sentido	3 m
Aparcamiento en línea	2 m
Aparcamiento oblicuo 30° (más restrictivo que oblicuo 45° o 60 °)	3,6 m
Calzada	3 m

Tabla 3 – Anchura mínima de los diferentes espacios urbanos.

A partir de esos datos se establece un árbol de decisión (Figura 3). Se establece que la modificación menos contundente es la sustitución de un carril de calzada por dos carriles bici unidireccionales, siempre y cuando uno de los sentidos de la calle tenga más de un carril.

Con ello se logra no alterar el sistema de circulación existente y tampoco disminuyen las plazas de aparcamiento ofertadas. Una modificación que altera algo más el *statu quo* de la calle sería eliminar plazas de aparcamiento. Se tiene así que una calle con dos líneas de aparcamiento puede ver sustituidas dichas líneas por dos carriles bici unidireccionales.

Asimismo, una fila de aparcamiento oblicuo puede ser sustituida también por dos carriles bici.

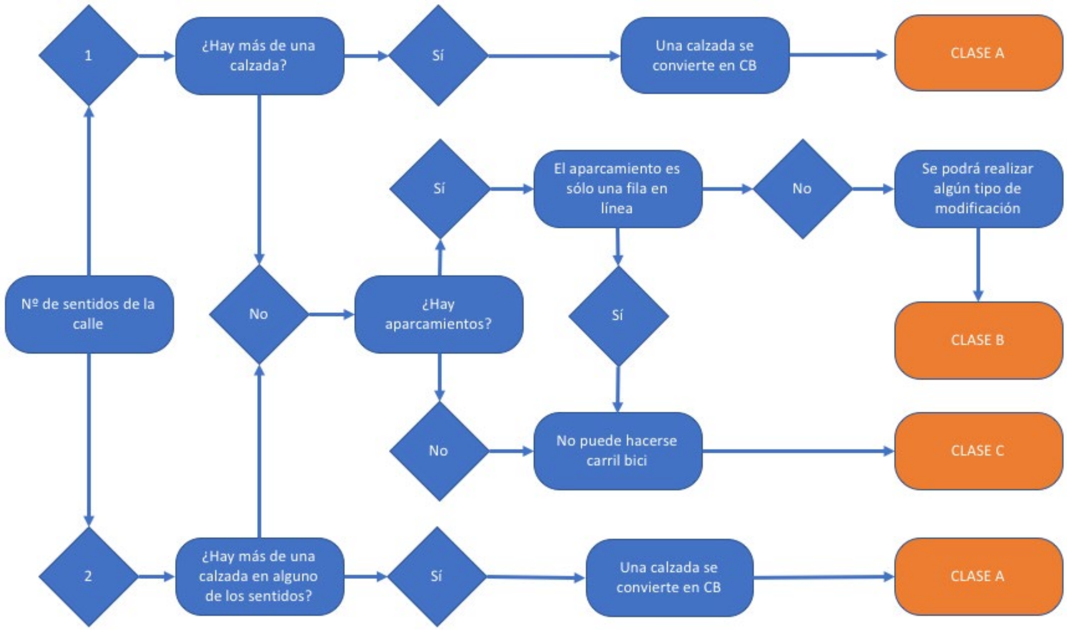

Figura 3 – Árbol de decisión.

3.3. Análisis con QGIS

Como consecuencia de los pasos anteriores, se generan una serie de capas en QGIS que recogen los distintos parámetros. Las pendientes de la zona de estudio son adecuadas para la circulación en bici, salvo en la zona sur. En relación a los pavimentos, sólo se aprecian adoquines en el conjunto de calles de la península de Cimavilla, así como algunas vías en la zona central y occidental presentan adoquines. Del mismo modo, se ha comprobado que todas las calles del ámbito tienen limitada la velocidad máxima permitida a 50 km/h; por tanto este parámetro lo cumple todo el conjunto. Por último, se han determinado el conjunto de calles de tipo A, B y C en función de lo definido en el apartado anterior. Se puede comprobar que la mayor parte de las vías de la zona occidental son C, mientras que en la mitad oriental son de clase B. Las vías tipo A quedan reducidas a algunos tramos puntuales.

Figura 4 – Datos de pendientes, tipo de pavimento, velocidad máxima permitida y tipos de calles (A, B o C, en función del árbol de decisión citado).

A partir de estos resultados se establece una clasificación de vías (tipos 1, 2 y 3; Tabla 4) y se determina el conjunto de vías aptas para trazar la red de carriles bici (Figura 5). Se observa que en el ámbito no hay calles tipo 2. El esquema resultante pone de manifiesto que sería factible realizar una ampliación notable del carril bici en la zona este; asimismo, podría realizarse una conexión con la zona oeste. Además, se comprueba que es inviable introducir un carril bici adecuado en la zona central de la ciudad sin modificar el esquema de circulación de la ciudad.

Tipo	Descripción	Detalle
Tipo 1	Vías idóneas para la circulación en bicicleta	Pendiente menor a 5 % y pavimento bituminoso y velocidad máxima de 50 km/h y ser de tipo A o B
Tipo 2	Vías a las que se puede incorporar un carril bici segregado, pero incómodas para el ciclista por incumplir un criterio (pendiente excesiva o pavimento inadecuado)	Pendiente menor a 5 %, o pavimento adoquinado, y velocidad máxima de 50 km/h y ser de tipo A o B
Tipo 3	Vías a las que no se puede incorporar un carril bici sin modificar el esquema de circulación actual. Vías a las que se puede incorporar un carril bici, pero son excesivamente incómodas por tener pendiente excesiva y pavimento inadecuado	Tipo C. Tipo A y B con pendientes iguales o mayores a 5 % y pavimento adoquinado

Tabla 4 – Tipos de calles, en función de la idoneidad o no para albergar un carril bici

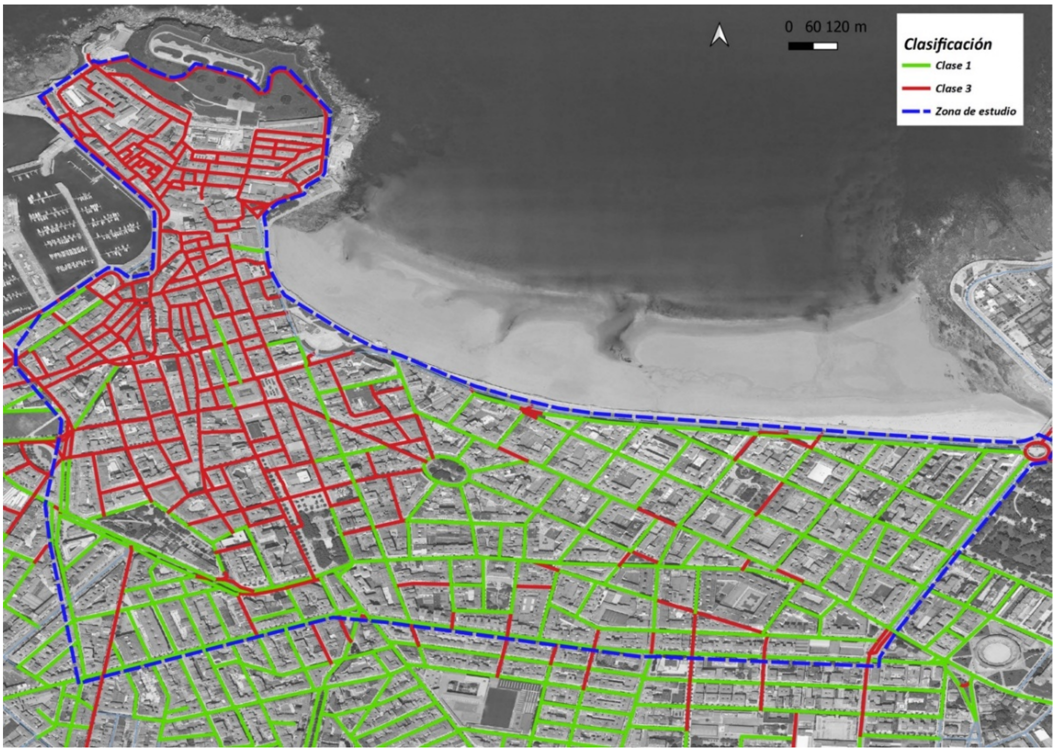

Figura 5 – Vías en las que se podría insertar un carril bici

4. DISCUSIÓN Y CONCLUSIÓN

Los nuevos paradigmas de movilidad en los núcleos urbanos, aceleradas por la pandemia asociada a la COVID-19, han provocado un interés creciente de las ciudades hacia la planificación de redes de carril bici segregado del tráfico rodado, provisionales o permanentes. Este texto propone un método de evaluación rápida de las condiciones actuales del viario urbano que permite determinar con facilidad qué vías son aptas para introducir en ellas un carril bici segregado, de doble sentido, adosado a los carriles de circulación.

El análisis de diversos documentos técnicos de referencia ha permitido establecer las condiciones mínimas requeridas por un carril bici segregado de doble sentido en un entorno urbano: una pendiente menor a un 5%; una anchura de 3 m; una velocidad máxima de 50 km/h en los carriles de tráfico rodado aledaños; un pavimento suave (hormigón o mezcla bituminosa). Se ha observado que, en general, hay notables similitudes entre ellos a la hora de determinar los valores recomendados y no recomendados de los parámetros.

Además, a partir del estudio de las anchuras mínimas de carriles bici, bandas de aparcamiento y carriles de circulación, se ha generado un árbol de decisión que permite determinar la aptitud de una calle para ser reconfigurada con el propósito de introducir en ella un carril bici, y que por tanto es otro de los resultados de esta investigación. El criterio tomado ha sido el de sustituir bandas de aparcamiento o carriles de circulación (cuando hay más de uno en alguno de los sentidos) por un carril bici de doble sentido.

El método desarrollado se ha aplicado en la zona centro de Gijón. Los resultados han permitido mostrar su aplicabilidad para la planificación futura de carriles bici en centros urbanos, donde las calles suelen ser más estrechas que en las periferias y los aparcamientos escasean, y para la generación de mallas provisionales como las surgidas durante la pandemia, consiguiendo así aumentar el espacio público destinado a la bicicleta. Del mismo modo, el método podría aplicarse para otros propósitos, como el aumento de la superficie de espacio público destinado al peatón.

Los resultados particulares de Gijón permiten también caracterizar el carril bici ya existente. Así, se ha comprobado que el carril bici actual discurre por calles particularmente anchas (de Clase A, según el método empleado), con pendientes inferiores al 2 % y con una velocidad de tráfico rodado limitada a 50 km/h. Es decir, el viario por donde discurre el carril bici es idóneo para albergarlo, según nuestra investigación.

En relación con la malla obtenida tras la aplicación del método en Gijón, se observa que un número relevante de calles analizadas sí podría albergar un carril bici segregado, y por ello podría ser sencillo realizar una ampliación provisional o permanente de la actual malla urbana para las bicicletas.

También se observa un posible recorrido de unión entre el Este y el Oeste de la ciudad que podrían completar la red de carril bici y prolongarlo a las zonas aledañas. En la zona más céntrica se acumulan calles que no permitirían introducir el carril bici sin realizar un estudio detallado que comprendiera el estudio de la presencia de garajes y accesos rodados a determinados negocios (talleres, aparcamientos de pago…) para redefinir el sistema circulatorio actual, y sin un estudio geométrico particular de cada vía. El método, así, ha permitido restringir la necesidad de realizar dicho estudio detallado a menos de la mitad de las calles del ámbito, con el consiguiente ahorro en tiempo.

En vista a futuros estudios sobre redes de carril bici en centros urbanos, podrían tenerse en cuenta algunos parámetros adicionales como las servidumbres citadas (garajes, talleres, etc.), el porcentaje de vehículos pesados que circulan por cada calle, que podría afectar al confort de los ciclistas en el caso de ser muy elevado, los radios de giro en las intersecciones (muy importantes para los ciclistas), etc. Otra investigación futura que se desprende de ésta es la aplicación de este mismo método en otras ciudades de tamaño similar a Gijón para realizar una comparación de los parámetros obtenidos en cada una de ellas, de este modo, se podrá caracterizar cada una de las ciudades y encontrar similitudes entre ellas.

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CONDITIONING FACTORS FOR BIKE SHARING SUCCESSFUL EVOLUTION. THE CASE OF BICIMAD

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ABSTRACT

Bike sharing systems (BSS) have gained great acceptance in many cities arround the world. Since the deployment of the first system, many cities promote the public bike not only as a sustainable mode of transportation, but also as a way to make visible the use of bicycles in urban environments. Four generations of BSS with great advances in between are recognized. BiciMAD in Madrid is one example of the last generation. A system deployed in mid-2014 with 1,560 bicycles and 123 stations.

During the early stage, TRANSyT-UPM conducted a series of studies to identify the intention of use, before the system deployment, and the user satisfaction and the relation between the use intention and real adoption, after the deployment. Since the last study in 2016, the system experienced some substantial changes and improvements in order to subsist.

Now that the system has reached its maturity, we conducted a survey in May of 2019, to study the evolution in the user satisfaction with the main factors that conditioned the success of BiciMAD. We asked subscribers, occasional users and non-users about their satisfaction with the elements of the system obtaining over 6,500 valid responses.

First, we compare the results obtained in previous surveys (2015 and 2016) with the latest, in order to identify changes in user profile and the conditioning factors for bike-sharing use.

Our results suggest that there are external and internal characteristics of the system that made it successful. For instance, the electric pedaling assistance is an attribute positively valuated that make user consider the streets slope unimportant. Also, the system had achieved some important goals, such as reduce the total trips in private car of the subscribers and not deterring users from walking.

1. INTRODUCTION

The phenomenon of urbanization, driven by the continuous rise in the population moving to cities, is prompting public authorities to pay more attention to the design, operation and management of urban transportation systems (Banister, 2005; Goldman & Gorham, 2006).

Therefore, transportation professionals and researchers are devoting efforts to promote sustainable travel alternatives, such as foster the use of public transport, and active modes such as walking and cycling, both affordable options to counter the negative effects of private car usage.

In this line, one popular strategy implemented among many cities since the early years of the 21^{st} century is the installation of public bike-sharing systems (PBSS) (Fishman et al., 2013). Bike-sharing systems have enjoyed a widespread acceptance around the world. Since the deployment of the first system, many cities have promoted public bikes not only as a sustainable mode of transportation, but also as a way to give bicycles visibility as a practical mode of transport in urban environments. This popularization phenomenon is so called the "*renaissance of bike-sharing systems*" (Pucher et al., 2011 ;Shaheen et al., 2010), especially in Europe, East Asia and North America.
PBSS have gained popularity in cities at the time they did in scientific literature. The research on PBSS could be divided in three research lines: the history and evolution of bike-sharing systems and the suitability of their implementation, functioning and governance; PBSS integration in the transport network; and user satisfaction.

With this work, we aim to combine the study of the evolution of a bike sharing system, at the time we intend to identify the key elements that made BiciMAD a successful system and would enhance the user satisfaction. This is done by comparing the results of a series of surveys (2015, 2016 and 2019) on some special attributes of the user profile and the factors that influence the use of bicycles, as well as performing an Importance Performance Analysis (IPA) and applying the Three-Factor theory (3FT) to identify the key elements of the system.

2. LITERATURE REVIEW

Bike-sharing is a relatively new concept, since the implementation of the first system in the Netherlands in 1965. Since, the systems evolution could be divided in four generations. The first generation, "white bikes" consisted of unlocked bicycles randomly located throughout the city. The bicycles were painted in one bright color. They could be picked up and left anywhere in the city, and their use was free of charge. In most of the cases where this scheme was implemented, bikes were vandalized and the attempts were not successful. The second generation of BSS, the coin-deposit system, was introduced in the 1990s. In this generation, the system was properly organized by a transportation authority and some features were introduced in order to avoid the first generation problems.

These systems were characterized by the particular, strong construction and bright color of the bicycles. The designated docking stations where bicycles were borrowed and returned were also a special characteristic, and the fact that a payment was required for using the bikes (DeMaio, 2009).

These systems were mainly introduced in north European countries such as Denmark and the Netherlands (Bachand-Marleau et al., 2012). In addition to the second generation, the third incorporated transaction kiosks that allowed for identification of users that deter the misuse the bicycles. These introductions succeeded in reducing theft rates as users were subject to penalties if they failed to return the bicycles to the stations. The latest generation of BSS is the demand responsive (Shaheen et al., 2010). The main innovations include the solar powered stations, the use of mobile apps and smart carts, and the incentives for automatic redistribution of bicycles.

User satisfaction is one success determinant of a provided service. The greater the increase in satisfaction, the more likely it is that the user will continue to be a client of the service (Anderson & Sullivan, 1993; Boulding et al., 1993; Yi, 1991). With this consideration, there has been an increase in the analysis of the perceived quality of BSS and the keys to its success. Manzi & Saibene, (2017) investigate the reliability of PBSS customer satisfaction surveys and the potential of emerging technology to improve transportation systems.. Kim et al., (2017) evaluate policy strategies for optimal PBS implementation. Alvarez-Valdes et al., (2016) investigate the impact of bicycle distribution imbalances across stations on user perceptions of service quality, which is one of the attributes considered in this study as station occupancy/bicycle availability. According to Albiński et al., (2018), several factors affect the performance of a bike-sharing scheme, but the two that have the biggest impact on customer satisfaction are bike accessibility and pricing.. (Médard de Chardon et al., 2017) conduct a comprehensive analysis of 75 PBSS to identify the determinants of success in terms of number of uses per day, while (Eren & Uz, 2020) analyse external factors such as weather, land use, PT connection and the influence of safety on bike-sharing demand.

Finally, Morton's (2018) assessment identifies how the PBSS in London will maintain or attract new customers by improving service quality.

3. DATA AND METHODOLOGY

3.1 Case study

Madrid is the capital city of Spain. It has 3.27 million inhabitants (2019) and traditionally was not considered a "cycling city" (Muñoz et al., 2013). Some special characteristics, such as the lack of extensive cycling infrastructure, their inhabitants' mobility behavior and the hilly topography (differences in elevation of up to 200 m) make it less attractive for cyclists than other European "cycling capitals". However, there is a positive movement by cycling collectives and public authorities to foster cycling. The implementation of BiciMAD.

Madrid was the first to introduce a city-center-wide large bike-sharing fleet of pedal-assisted bicycles in Western countries (Munkácsy & Monzón, 2018). As well as the development of segregated cycling infrastructure – 282 km in 2018 (MITECO, 2020) –, the prioritization of roads in the city center for cyclists and pedestrians and active campaign strategies for raising awareness of the benefits of cycling are encouraging people to cycle.

BiciMAD, Madrid's public bike-sharing system, was implemented in 2014. BiciMAD was originally deployed in the inner and denser districts of Madrid with approximately 15,000 to 30,000 inhabitants per km2. At that time the system had 123 stations and 1,560 bicycles; the system has now grown to 258 stations, 2,964 bicycles and over 60,000 subscribers.

BiciMAD was a pioneer of demand-responsive systems (Munkácsy & Monzón, 2017). Its general configuration is:

- The first city-wide bike-sharing system with electric pedal-assisted bicycles only (pedelecs)
- The whole fleet is GPS tracked
- Minimum fee per use of €0.50, including the 30 first minutes
- User-based redistribution, rewarding users by applying a discount of €0.10 for taking a bike from a full station and €0.10 for returning it at an empty station.
- User interface fully supported by online mobile applications and solar-powered totems at the stations.
- Occasional user scheme, with a €4 per hour pay-by-use fee structure.

The general characteristics of BiciMAD subscribers (Ayuntamiento de Madrid, 2017) are:

- 35% woman, 65% men
- 40% between 30 and 40 years old, 25% between 20 and 30 years old
- 85% have a university degree, 13% general certificate of education or vocational studies, and 2% primary or secondary studies

3.2 Data collection

This research is based on data collected in a series of surveys. The first conducted in 2014, with 1859 responses, the second in 2015 with 430 responses, the third in 2016 with 336 and the fourth and last in 2019 with 5540 valid responses. The first one at an early stage, before the system deployment to evaluate the intention of use, the second, on year after, as part of a before-and-after panel survey and the third to explore the effects of pedelec-sharing on travel patterns, and the fourth to evaluate the system maturity and evolution.

The latest survey was specially tailored to evaluate the influence of specific service attributes performance and influence over overall satisfaction. The attributes were selected ad-hoc, considering the system particularities as recommended in the literature (De Oña & De Oña, 2015).

A hybrid methodology was applied to achieve a representative sample to the four surveys. The method combines the advantages of personal intercept interviews and online questionnaires to fulfil the basic requirements of a survey, namely good data quality, representativeness and minimal costs (Monzon et al., 2020).

3.3 Methodology

The first part of this study, is a comparative analysis of the results obtained with three of the four surveys. The results of the 2014 *ex-ante* survey are dismissed, as the questions posed were exclusive for this stage and do not allow further comparison. Therefore, we use only the results of the 2015, 2016 and 2019 surveys.

For the comparative analysis, we will address only the responses given by the subscribers, as they are more frequent users and compose the BiciMAD system orientation, rather than occasional leisure usage.

To study the relationship between the cycling experience of the respondents and the assessment of the factors that influence the use of bicycles the different aspects of use were distinguished.

- Frequency of use. We have distinguished 6 discrete scales of frequency of use of the bike. Respondents had to choose between whether they used the bike to commute daily, sometimes a week, once a week, sometimes a month, sometimes or never. These categories have been summarized for ease of interpretation in the results section.
- Reasons for use. The reasons for use have been analyzed from two close perspectives but not matching:
- By forced mobility or not: we understand by forced mobility that whose motive is a permanent and systematic daily activity such as work or study. The rest of reasons (leisure, sports, personal affairs, shopping, others) are not required mobility.

The subjective factors that influence the use of the bicycle have been selected after a extensive review of the literature (Fernández-Heredia and Monzón, 2010). The factors have been valued by respondents on a semantic Likert scale graduated in 6 levels to judge the degree of importance between nothing, very little, little, something, very important or fundamental.

4. RESULTS

4.1 Sociodemographic evolution

Regarding the socio-demographic characteristics of the users, it is possible to observe that the gender distribution remains equal since the system deployment, with men slightly overrepresented with an average of 64% versus 36% of woman.

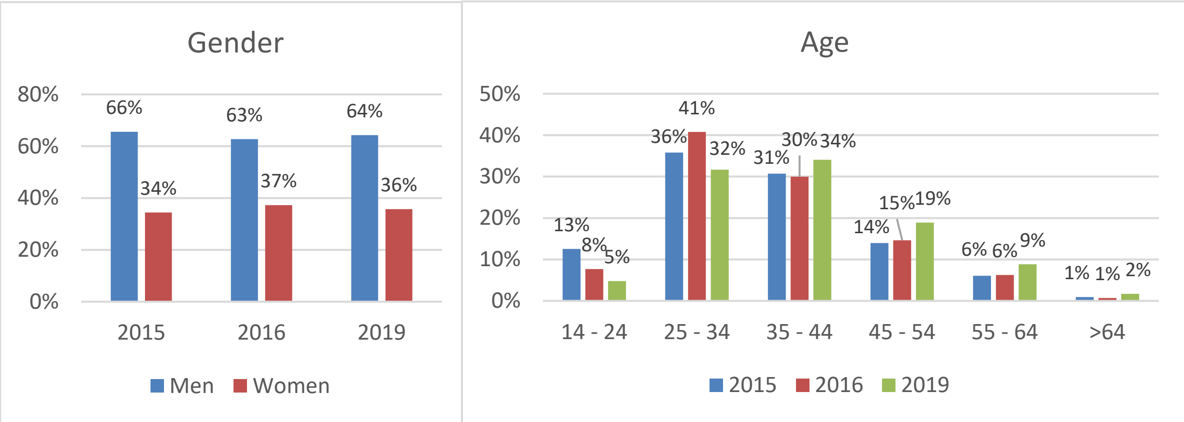

Figure 1. Gender and age evolution of BiciMAD subscribers

It is also possible to observe in figure 1, the aging of BiciMAD users, as all the intervals have increased in percentage on intervals over the 35 years and reduced on the lower intervals, from 14 to 34 years old.

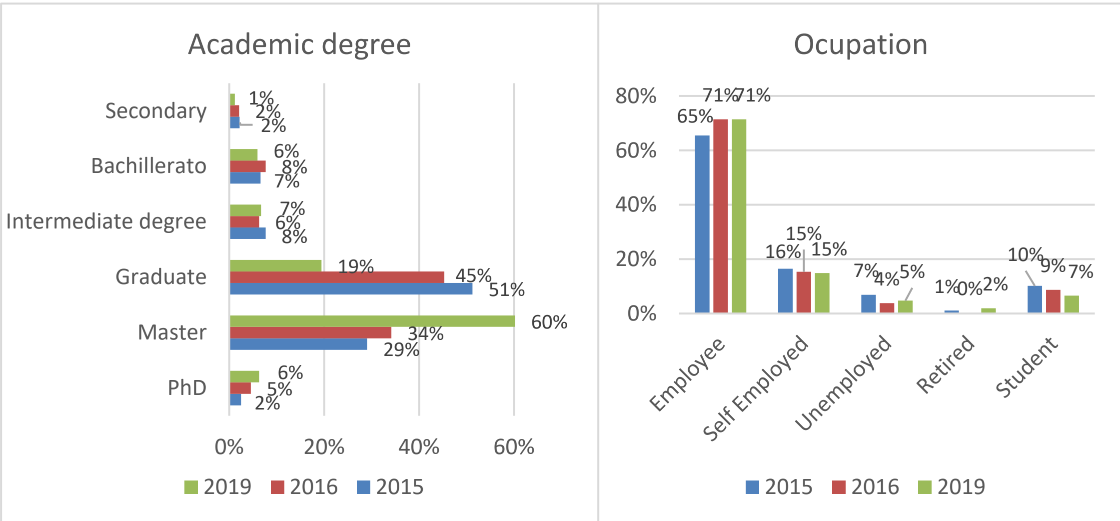

Figure 2. Academic degree and occupation evolution of BiciMAD subscribers

Regarding the academic degree, it is possible to observe that the average user of BiciMAD is becoming more educated. Especially if we concentrate in the difference between graduate, master and PhD. In 2015 and 2016 the majority of the sample was graduate, while in 2019 60% has a Master. This change could be explained with the introduction of the Bologna

Process, in which many careers demanded professionals to have a Master degree. The proportions of occupations remain steady. 85% of BiciMAD users have an income, either as employees or self-employed. It is noticeable that the percentage of students slightly decreased, while the retired slightly increased. Coherent with the aging of the user profile.

4.2 External factors evolution

We evaluate some external factors, general in the bicycle usage. This attributes are considered as a the more influential for the general cyclist.

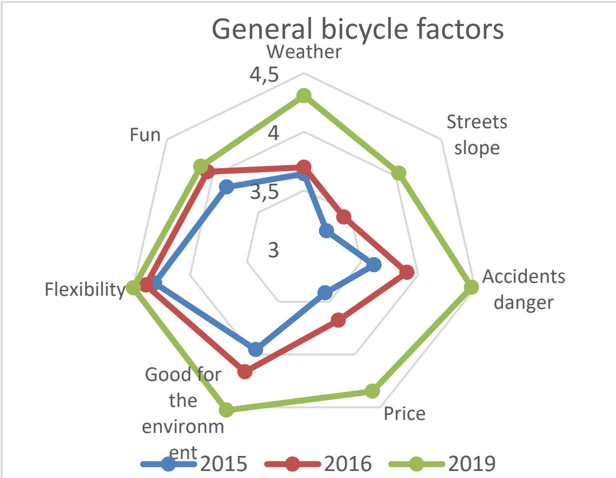

Figure 3. Evolution of factor importance

In general, subscribers of BiciMAD pose higher importance to all the attributes in 2019, compared with the results of previous years. Moreover, most of the factors have proportional increase along the years. That is to say, that factors such as the street slope remain as the less important. This might be conditioned due that BiciMAD is a fully electric BSS, then the effort needed for cycling using the service is less than a normal bicycle, therefore in Madrid, street slopes are not important.

The most important factors reported in the three surveys are “flexibility”, “good for the environment” and the “accident danger”. The first received the highest score for importance.

The absence of attachments for the use of BiciMAD, such as the storage, helmet and parking space make one of the most flexible modes for transportation in the city center of Madrid.

The good environmental perception of cycling is an important factor for subscribers, this factor could foster the use of bicycle and the promotion of the service in this sense could increase the use frequency.

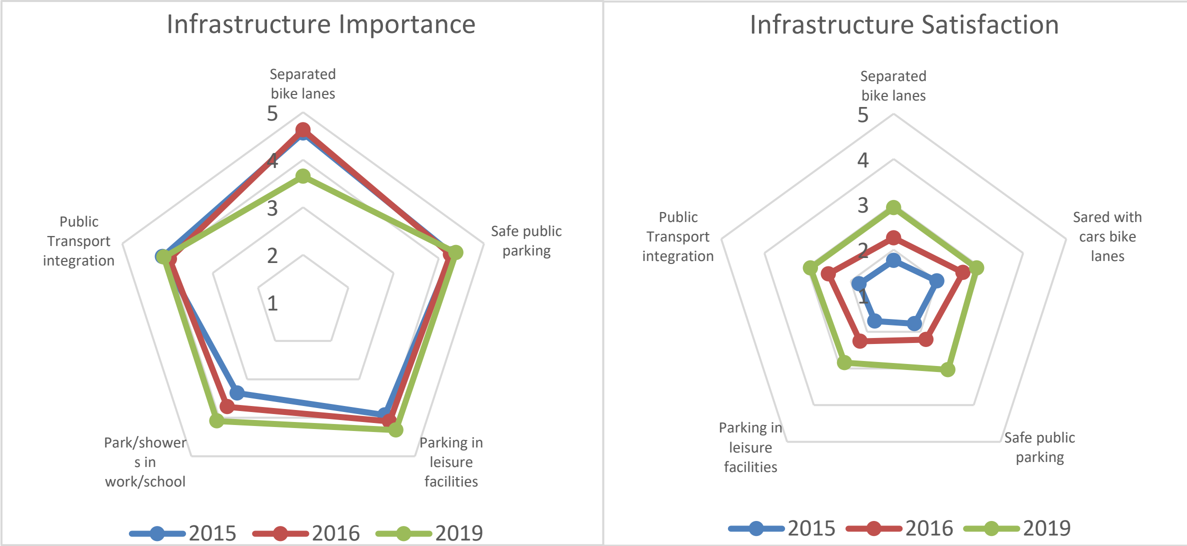

Figure 4. Evolution of infrastructure importance and satisfaction

In general, subscribers assign higher importance than satisfaction to Madrid cycling infrastructures. Regarding the importance, the "separated bike lanes" and the "safe public parking" are the infrastructures that receive more importance from subscribers. Moreover, BiciMAD do not require private parking places, users recognize that it is important for the general use of bicycle among all the years when surveys were conducted. Regarding the separated bike lanes, there is a clear change in the importance assigned to this infrastructure.

We consider that as cyclist are more familiar with sharing space with motorized vehicles, at the time there are more separated bike lanes than when the two first surveys were conducted. Therefore, this attribute is less important that at the beginning of the service introduction. It is possible to observe that the parking and showers at work and study places are gaining in importance, this is probably due to the popularization of cycling, then users demand better conditions on the facilities they regularly use.

There is a steady increase in satisfaction with all the infrastructures along the years. This might be due to a combination of familiarity with the bicycle usage, and the improvements in this regard.

4.2 Changes in use frequency and travel patterns

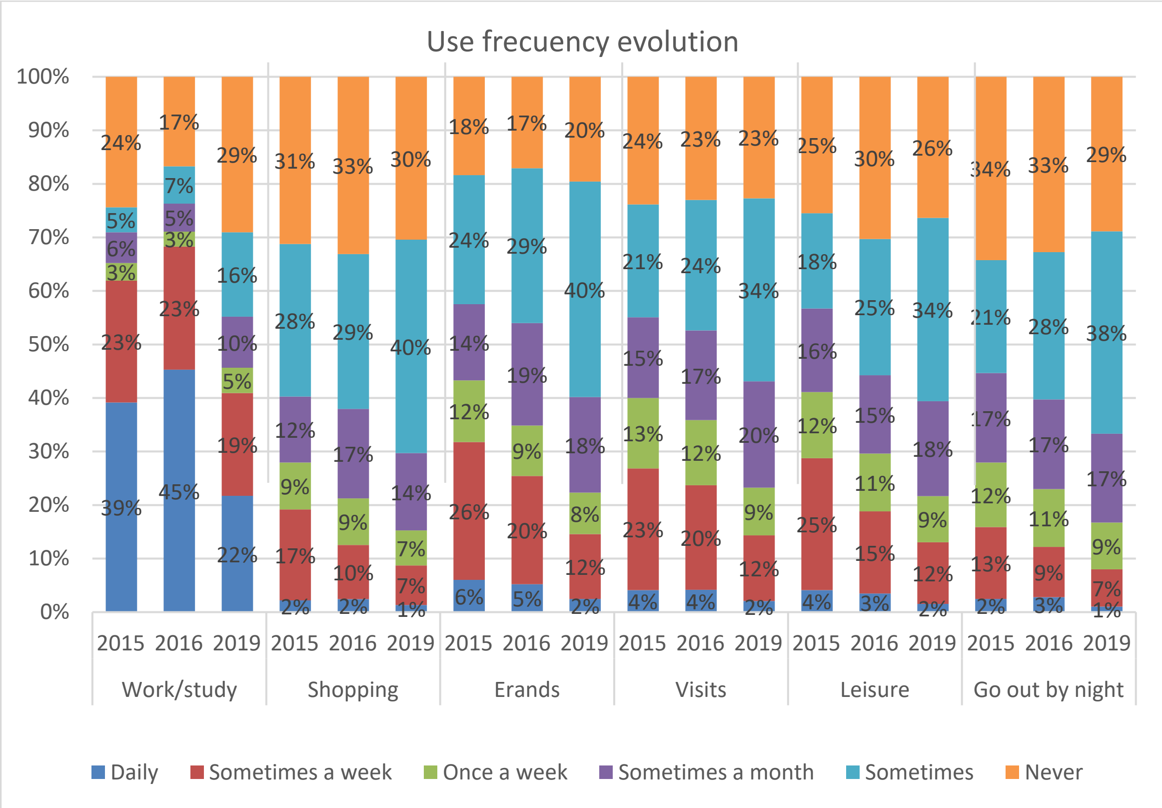

Figure 5. Evolution of use frequency

The frequency of use has reduced in general for all the purposes. It is notorious that the most intensive use categories have reduced significantly when, especially when it comes to the *daily* and *sometimes a week* frequency. If we focus on the work/study purposes, the percentage of daily use drops from 45% to 22%. The *sometimes a week* use for shopping reduces constantly all the years, from 17% in 2015 to 7% in 2019. Similar drops in use frequency could be observed for errands (26% in 2015 to 12% 2019), for visits (23% in 2015 to 12% in 2019), leisure (25% in 2015 to 12% in 2019) and go out by night (13% in 2015 to 7% in 2019).

The category that increases the most among the trip purposes is *sometimes*. It is worth of further studies to investigate the possible reasons for the drop in frequency of use, as well as to analyze the evolution of the number of subscribers

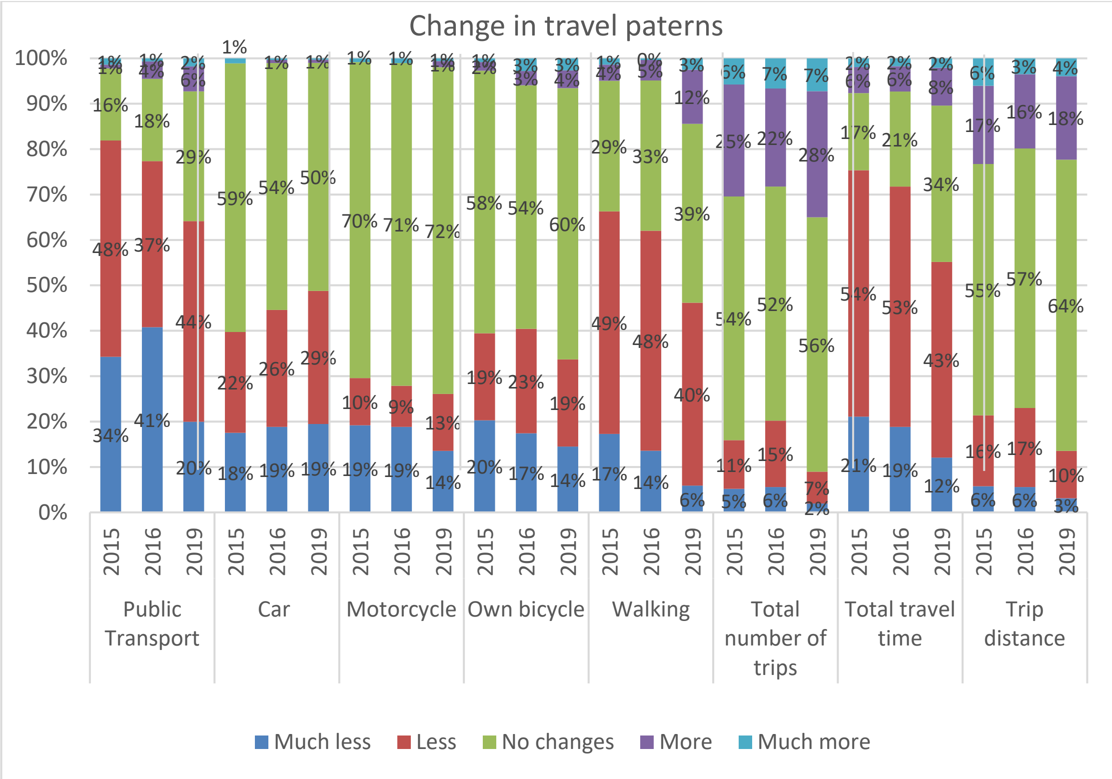

Figure 9. Evolution in travel patterns since the BiciMAD deployment

The respondents claim that they reduced their usage of public transport, this is possible to observe on a steady tendency since 2015 to 2019, if we focus on the values of much less and less putted together. This could be considered as a drawback of the BSS, as the purpose is not to take users out of the public transport, but from private vehicles, especially from the car.

In this regard, it is possible to observe that car usage also decreased from a 40% in 2015, up to a 48% in 2019, if we put together the values of *less* and *much less* together. A positive outcome of the implementation of the BSS.

There is a slightly increase in the use of the private bicycle, from around the 3% in 2015 to 7% in 2019. This positive effect is also compensated with the drop from 39% in 2015 to the 33% in 2019.

It is also positive that the walking passed from a 66% of reduction in 2015 to 46% in 2019. This is an indicator that the fee per use is effective when deterring the subscribers to take a bicycle that they could do walking. Indeed, it is possible to observe that from 2014 and 2015, the percentage of users that walk more since they subscribed to BiciMAD passed form around 5% to 15%.

Since 2015, less subscribers declare that the total travel time have reduced. A similar result with the trip distance, that almost remain steady since 2015.

4. CONCLUSIONS

As a result of the comparative analysis, it is possible to observe that there is significate change in some attributes and related with the user profile, perception of cycling factors and service use behavior and mobility patterns. This could be considered as conditioning factors for the evolution of BiciMAD system.

The profile of the user remains steady in most of the attributes, except the age and the academic degree, where is possible to observe the ageing of the subscribers, as well as possible effects of the Bologna Program, as there is a higher percentage of users with a master degree.

Pedelec bicycles are an influential factor of success. Due to this feature, the users assign little importance to the slopes of the streets in Madrid.
It is worthy to study the possible reasons for drop in use frequency, and if this is related with the number of daily use, and overall system performance in terms of Trips per Day per Bike (TDB) (Médard de Chardon et al., 2017). It is possible as well that user's perception of the use intensity would be due to the familiarity with the system, then their perception of use intensity is less than the reality. To conduct this verifications, it would be worthy to analyze the data of use intensity and number of subscribers in the system, as the administration claim that this values have stabilized in nearly 8 TDB and the number of subscribers is nearly 63,000.

The system has double effect over cycling, as it is possible to observe an increase in use of private bicycles, maybe because more users realize that it is possible to move by bicycle in Madrid, then are encouraged to start using it. At the same time, it reduces the usage on others, possibly because the convenience of BiciMAD, as there is no need of storage, maintenance, and other issues related to a bicycle ownership.
BiciMAD achieved the goal of not deter subscribers from walking, or at least reduce the number of users that stopped in 2015, that was much higher than in 2019.

Based on the results of this study, we identify a research gap, on the reasons conditioning the decrease in use frequency and its relationship with the above mentioned factors and the data from the service administration. This future research line could be conducted by performing and ordered logistic regression to understand the influence of each common variable among the three waves of surveys with the use frequency.

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ESTUDIO DE LA PERCEPCIÓN DEL RIESGO DE CICLISTAS EN CARRETERAS CON REALIDAD VIRTUAL

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RESUMEN

El comportamiento de los ciclistas es esencial a la hora de evaluar la seguridad vial de una carretera convencional con una alta demanda ciclista y, especialmente, a la hora de proponer mejoras en este tipo de carretera. Para su análisis, una de las principales variables es la Percepción Subjetiva de Riesgo (PSR) que manifiestan los ciclistas ante determinadas configuraciones de la infraestructura, ya que esta puede condicionar su manera de circular.

En este estudio se presenta una nueva metodología para obtener datos de PSR de ciclistas, basada en encuestas y en realidad virtual. Para ello, se ha preparado una sala con el siguiente equipamiento: una bicicleta sobre un rodillo de entrenamiento, unas gafas de realidad virtual y un video wall. En estas instalaciones, 26 ciclistas, con diferente experiencia en circulación por carretera, han recorrido 10 tramos de carretera convencional con diferentes infraestructuras ciclistas, con las correspondientes intersecciones, que fueron previamente grabadas con cámaras 360º.

Durante cada recorrido, los ciclistas manifestaron su PSR para cada uno de los elementos que componían los diferentes tramos recorridos, valorando el riesgo de 1 a 5. Asimismo, valoraron en una escala de 1 a 7 el grado de inmersión al realizar los recorridos con las gafas de realidad virtual (sistema inmersivo) y con la video wall (sistema semi-inmersivo).

Los resultados del estudio han permitido identificar qué elementos de la carretera y configuraciones de esta son considerados más y menos peligrosos por los ciclistas, así como las diferencias que hay entre ciclistas dependiendo de su grado de experiencia en la circulación por carretera. Estos resultados serán la base para valorar el potencial impacto de posibles medidas de seguridad vial en su comportamiento y su percepción del riesgo.

1. INTRODUCCIÓN

De acuerdo con el Anuario Estadístico de Accidentes 2019 de la DGT, en 2019 fallecieron 48 ciclistas en vías interurbanas y 2363 resultaron heridos en accidentes de tráfico siendo el 90% de ellos hombres. Esta cifra que ha ido aumentando progresivamente en los últimos años, a diferencia de lo que ocurre con los accidentes con vehículos motorizados que ha disminuido progresivamente. De los 2530 accidentes con víctimas con bicicletas involucradas, 567 se produjeron debido a infracciones de los conductores, mientras que en 1023 no se produjo ninguna infracción. Por lo que es posible que una de las causas sea la infraestructura.

Este aumento en la siniestralidad relacionada con la bicicleta está relacionado con un aumento también en su utilización. De hecho, de acuerdo con el barómetro de la bicicleta en España de 2019, desarrollado por GESOP para la DGT, alrededor de 9 millones de españoles utiliza la bicicleta semanalmente y más de 4 millones la utiliza alguna vez en los desplazamientos por trabajo o estudios.

Por todo ello, es importante considerar la circulación ciclista a la hora de evaluar la seguridad vial de una carretera convencional con presencia de bicicletas, así como en el momento de implementar medidas para la mejora de su seguridad. El desafío es conocer el comportamiento que los ciclistas tienen en la carretera y este aspecto está íntimamente relacionado con el riesgo que perciben al circular por ella, representado por su Percepción Subjetiva de riesgo (PSR).

Para el análisis del comportamiento de los ciclistas en carretera pueden utilizarse metodologías de toma de datos basadas en grabaciones desde cámaras fijas (Silvano, 2015), en el uso de bicicletas instrumentalizadas (López et al., 2020) o incluso de simuladores de conducción (Thorslund y Lindström, 2020). Sin embargo, con cámaras únicamente se obtienen datos del comportamiento ciclista en una localización concreta y no se dispone de información sobre la percepción del riesgo de los ciclistas. En el caso de las bicicletas instrumentalizadas puede disponerse del dato de la percepción subjetiva del riesgo de los voluntarios que las conducen, pero la muestra es reducida. Esta metodología es más idónea para el análisis del comportamiento de los conductores que interaccionan con la bicicleta.

Mientras que, en el caso de los simuladores de conducción, generalmente los escenarios son reducidos por la carga que supone su modelización. Por ello, para llegar a una mayor muestra y aumentar la casuística, se recurre, en ocasiones, a las encuestas, muy utilizadas en la planificación para conocer las preferencias de los usuarios.

En este sentido, Monsere et al. (2012) evaluaron el nivel de aceptación de una nueva infraestructura ciclista tanto de ciclistas, como también de peatones y de conductores de vehículos motorizados.

Posteriormente, McNeil et al. (2015) utilizaron esta misma metodología para analizar el grado de comodidad que sentirían los ciclistas al circular por infraestructuras ciclistas con diferentes elementos de separación con el tráfico motorizado, mostrando estas configuraciones en imágenes de escenarios simulados. Por su parte, Ng et al. (2017) centraron su investigación, basada en una encuesta, en el grado de seguridad declarado por ciclistas ante imágenes de diferentes configuraciones de intersecciones no señalizadas y con diferentes maniobras. Los resultados de estas encuestas, aunque con una alta participación, son aplicables a una población muy limitada y podrían no ser extrapolables a otros países por la diferencia de comportamiento y de percepción del riesgo y comodidad de los usuarios de diferentes países e, incluso, regiones.

En España, López et al. (2019) llevaron a cabo una encuesta online sobre hábitos, situaciones de riesgo, cumplimiento de la normativa y percepción de los ciclistas ante diferentes medidas de seguridad vial y diferentes diseños de la infraestructura, tanto en cuanto a sección transversal como diseño de intersecciones. En este caso, la encuesta también estuvo basada en imágenes, algunas fotografías de ubicaciones reales y otras simuladas.

Los resultados de estas encuestas al referirse a imágenes aisladas reflejan la percepción del riesgo mostrada por los ciclistas teniendo en cuenta más su experiencia anterior que el riesgo que pudieran suponerles las configuraciones reales.

El objetivo del estudio que se presenta es el desarrollo de una nueva metodología basada en entrevistas a voluntarios durante la realización de una serie de recorridos en una bicicleta de carretera sobre una bancada mientras visualizan los recorridos con gafas de realidad virtual y en PowerWall, mostrando así una percepción del riesgo que se ajusta más a la realidad.

2. METODOLOGÍA

2.1 Selección de los tramos

El objetivo de la investigación es analizar la percepción del riesgo de los ciclistas ante diferentes configuraciones de la infraestructura ciclista en carreteras convencionales, incluyendo el tronco de las carreteras, así como también las intersecciones. Por ello, la selección de los tramos sobre los que realizar las entrevistas a los voluntarios se basó en identificar tramos de carretera con conocida afluencia ciclista en la provincia de Valencia, con diferentes diseños de sección transversal y equipamiento próximos a intersecciones. Además, teniendo en cuenta que cada voluntario realizaría 10 recorridos y que el tiempo máximo del total no debería superar los 15 minutos, en la selección de los tramos se consideró la necesidad de que cada recorrido pudiera realizarse en no más de 1.5 minutos.

Teniendo en cuenta estas consideraciones, se seleccionaron para el análisis seis glorietas y dos intersecciones, para analizar la percepción del riesgo en ellas y en los tramos de carretera que en ellas concurren. A continuación, se muestra un análisis somero de cada uno de los recorridos seleccionados.

2.1.1 Glorieta CV-333 / CV-25

La glorieta en la que confluyen la CV-333 y la CV-25 dispone de un único carril en su anillo central y seis entradas/salidas, tres de ellas se corresponden con las vías citadas, una corresponde a una vía acondicionada para tráfico de vehículos motorizados circulando a baja velocidad y dos corresponden a vías de menor entidad, teniendo una de ellas un carril bici paralelo.

En su entorno se han seleccionado dos recorridos (Figura 1):

- R1.1: comienza en el carril bici segregado paralelo a la CV-25, cruza la intersección por el paso ciclista habilitado en la rama sur y se incorpora a la vía de tráfico mixto, para continuar hacia el norte.
- R1.2: comienza por la vía de servicio paralela a la CV-25, se incorpora a la glorieta por la entrada de vehículos motorizados y realiza la glorieta completa para incorporarse a la rama sur de la CV-333.

Fig. 1 – Recorridos R1.1 y R1.2

2.1.2 Glorieta CV-25

La glorieta en la que confluyen la CV-25 y el acceso al municipio de Olocau dispone de dos carriles en su anillo central y cuatro entradas/salidas, dos de ellas se corresponden con la CV-25, una con la entrada al municipio de Olocau y otra con una con un camino.

En su entorno se han seleccionado dos recorridos (Figura 2):

- R2.1: comienza desde el oeste por el carril bici adosado a la CV-25 (separado por bordillos y bolardos), cruza la glorieta por el cruce diseñado para tal efecto y continua por el carril bici hacia el norte.
- R2.2: transcurre desde el oeste hacia el norte por la CV-25, circulando por el arcén de la calzada de la carretera e incorporándose a la glorieta junto con el tráfico motorizado.

Fig. 2 – Recorridos R2.1 y R2.2

2.1.3 Glorieta e intersección T CV-333 / Urb. Torre Porta Coeli

El tramo seleccionado está delimitado por una glorieta y una intersección en T. La glorieta dispone de un único carril central y cinco entradas/salidas, dos se corresponden a la CV-333, una al acceso a la Urbanización Torre Porta Coeli y dos a vías de menor entidad. Por su parte, la intersección en T, canalizada y con carriles centrales de espera, constituye el acceso sur a la citada urbanización.

En su entorno se han seleccionado dos recorridos (Figura 3):

- R3.1: comienza en la vía de tráfico a la altura de la glorieta, cruza la misma por el cruce diseñado para ello y se incorpora al carril bici segregado, circulando hacia el sur hasta llegar a la intersección, que cruza por el cruce habilitado para ciclistas.
- R3.2: comienza en el acceso de la glorieta correspondiente a la vía de tráfico mixto, realiza la glorieta por el anillo de la misma en convivencia con el tráfico motorizado, para continuar por el arcén de la CV-333 y girar a la derecha en la intersección.

Fig. 3 – Recorridos R3.1 y R3.2

2.1.4 Glorieta CV-310 / CV-305 y glorieta CV-310 / Urbanización Mont Ros

El tramo está delimitado por dos glorietas. La glorieta situada más al norte une las carreteras CV-310 y CV-310, disponiendo de dos carriles en su anillo central y 4 vías confluyentes, dos de ellas se corresponden con la CV-310, en la que en su rama norte se dispone de una vía de servicio paralela y en la sur un arcén coloreado, una con la CV-305 y otra con una vía de menor entidad.

En su entorno se han seleccionado dos recorridos (Figura 4):

- R4.1: comienza al sur de la glorieta norte, transcurre por el arcén coloreado que finaliza en dicha glorieta y la cruza en convivencia con el tráfico motorizado.
- R4.2: comienza al norte de la glorieta norte, en la vía de servicio, se incorpora a la glorieta para atravesarla junto con el tráfico motorizado, se incorpora al arcén coloreado de la rama sur de la CV-310, que finaliza unos metros antes de llegar a la glorieta, volviendo a mezclarse con el tráfico motorizado para atravesar la glorieta sur.

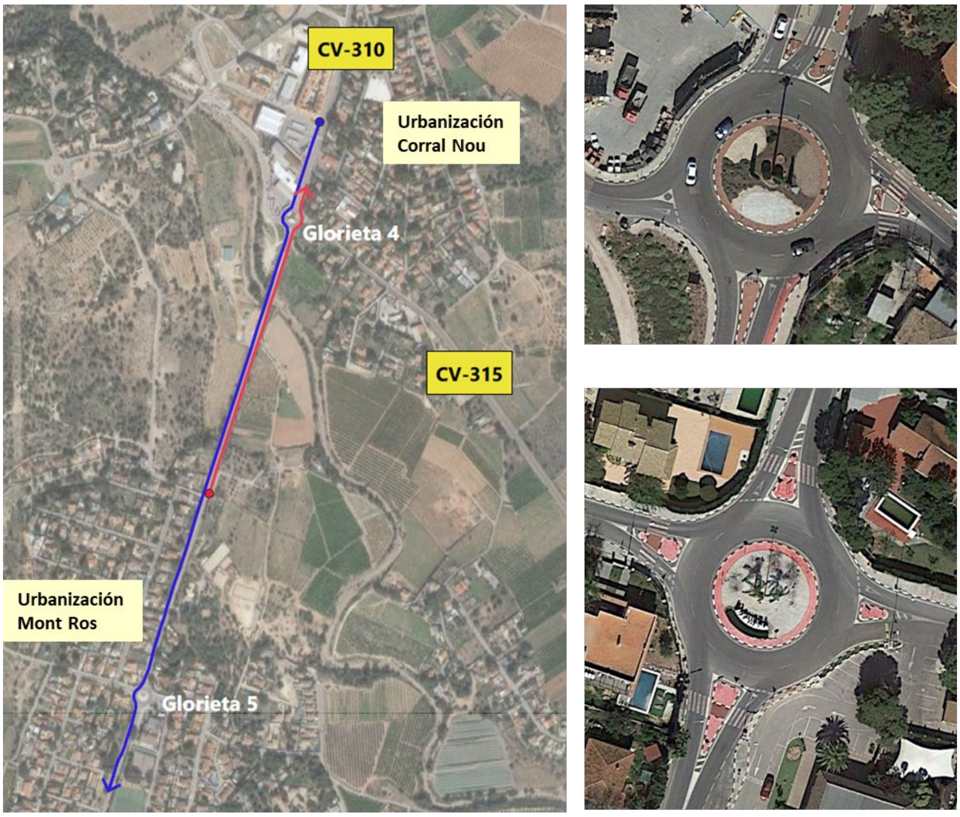

Fig. 4 – Recorridos R4.1 y R4.2

2.1.5 Glorieta CV-315 / CV-305 e intersección CV-305 / Urbanización Bonanza

El tramo está delimitado por la glorieta que une las carreteras CV-315 y la CV-305 y la intersección que da acceso a la Urbanización Bonanza desde la CV-305. La glorieta dispone de dos carriles en su anillo central y cuatro patas, tres de ellas se corresponden con las carreteras que une y una con el acceso a una urbanización, mientras que la intersección en T da acceso desde la CV-305 a la Urbanización Bonanza, siendo canalizada y con carriles centrales de espera.

Entre ellas, se han seleccionado dos recorridos (Figura 5):

- R5.1: comienza al este de la intersección, circulando por el arcén coloreado, cruza la intersección, donde el ciclista tiene prioridad de paso, y se dirige a la glorieta, en cuyo acceso el arcén coloreado para a carril bici segregado, para volver a convertirse en arcén coloreado al norte de la glorieta.
- R5.2: comienza al norte de la glorieta, circulando por arcén coloreado, atraviesa la glorieta por un carril bici segregado, que se convierte de nuevo en arcén coloreado al sur de la misma.

Fig. 5 – Recorridos R5.1 y R5.2

2.2 Grabación de los recorridos

Los 10 recorridos seleccionados fueron grabados con una bicicleta instrumentada, equipada con una cámara Nikon KeyMission 360, que cuenta con dos objetivos ultra gran angular a cada lado de la cámara, que se combinan para crear el entorno 360º (Figura 6).

Fig. 6 – Cámara Nikon KeyMission 360

A pesar de que la cámara ya cuenta con una función de reducción de la vibración, fue necesario utilizar un estabilizador tras comprobar en el primer recorrido que los movimientos de la cámara recogidos en el vídeo no permitían una visualización adecuada para la realización de las pruebas, especialmente con las gafas de realidad virtual.

El estabilizador utilizado fue el G360 Panoramic Camera Gimbal (Figura 7) que tiene un sistema de cuatro contrapesos verticales que garantiza un vídeo estable. Este estabilizador hace que la cámara gane altura con lo que colocado en el manillar queda a la altura del punto de vista del ciclista, dando una mayor sensación de inmersión en su reproducción.

Fig. 7 – Estabilizador G360 Panoramic Camera Gimbal

2.3 Preparación de la sala

Para la realización de los recorridos por parte de los voluntarios, el Instituto de Investigación e Innovación en Bioingeniería habilitó una sala insonorizada, permitiendo así que la sensación de inmersión fuera mayor. La sala contaba con los siguientes equipos (Figura 8):

- PowerWall: sistema semi-inmersivo que consta de dos proyectores de vídeo Mirage HD3 (Christie Digital Systems USA Inc, Cypress, CA, USA), que proporciona una pantalla estereoscópica de 2 metros de alto por 6 metros de largo.
- Gafas de realidad virtual: unas gafas de HTC Vive Pro Head Mounted Display (HMD), suponiendo un sistema totalmente inmersivo.
- Bicicleta de carretera sobre una bancada, de forma que los voluntarios pudieran pedalear durante los recorridos, llegando incluso a poder girar la rueda delantera.

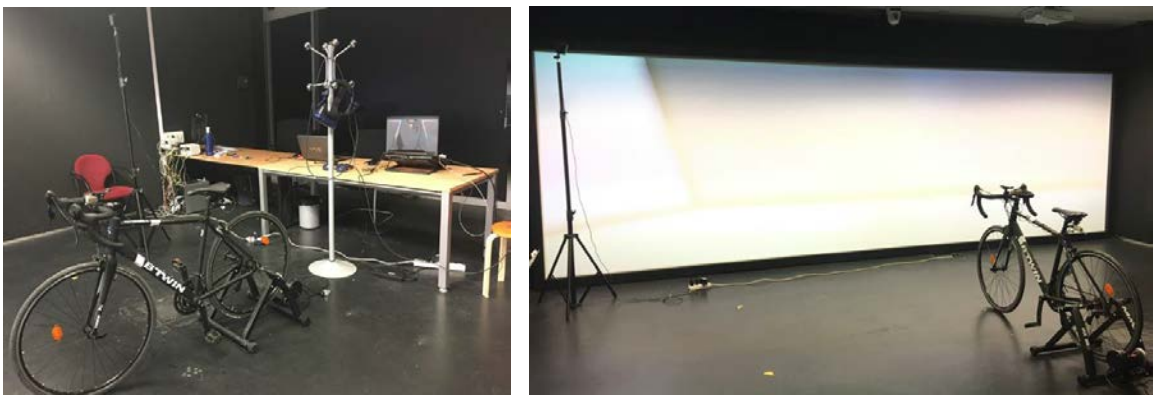

Fig. 8 – Sala habilitada para la realización de las pruebas

El hecho de que los voluntarios puedan pedalear y girar el manillar y la rueda delantera proporciona una inmersión mayor en el escenario.

Si bien es cierto que la velocidad de pedaleo puede no corresponderse con la velocidad del ciclista del vídeo, la diferencia se estima en ± 5 km/h, por lo que no es excesivamente perceptible.

2.4 Recorridos de los voluntarios

Para la realización de las pruebas, se solicitó la colaboración de diferentes asociaciones ciclistas de la provincia de Valencia. Asimismo, se dio difusión de las pruebas por las redes sociales del grupo de investigación, de la Escuela y de la Universidad. Con todo ello, se obtuvo la colaboración de 31 voluntarios, de los cuales 4 eran mujeres y 27 eran hombres.

De ellos, durante la realización de las pruebas, cuatro hombres y una mujer sufrieron episodios de mareo que les impidió realizar los recorridos adecuadamente, con lo que sus datos no han sido contabilizados en el análisis.

De esta forma, se dispone únicamente de 26 voluntarios, contando solo con 3 mujeres. En función de su experiencia en ciclismo por carretera se observaron 3 perfiles diferenciados (Figura 9):

- Ciclistas semiprofesionales con alta experiencia en ciclismo deportivo por carretera y un alto número de kilómetros recorridos semanalmente. Todos ellos son hombres.
- Cicloturismo. Son ciclistas con un alto número de kilómetros recorridos semanalmente, pero, generalmente, no por carreteras con un elevado tráfico vehicular. Todas ellas mujeres.
- Ciclismo urbano/montaña. Ciclistas que utilizan la bicicleta de forma habitual pero no por carretera.

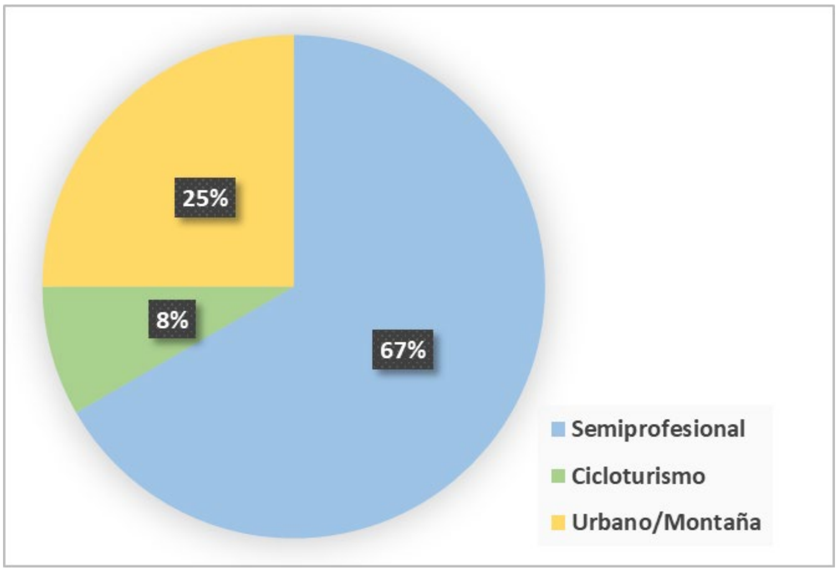

Fig. 9 – Distribución de voluntarios en función de su experiencia

Los voluntarios que completaron todos los recorridos realizaron 10 recorridos, cinco de ellas con el vídeo proyectado en el PowerWall y cinco con las gafas de realidad virtual.

La distribución de los recorridos entre estos dos sistemas de visualización entre los diferentes voluntarios se realizó de forma aleatoria, así como también el orden en el que fueron visualizados. Finalmente, el número de veces que fue visualizado cada uno de los recorridos fue el que se muestra en la Tabla 1.

Recorridos	Gafas Realidad Virtual	PowerWall
R1.1	11	15
R1.2	16	10
R2.1	15	11
R2.2	12	14
R3.1	14	12
R3.2	15	11
R4.1	11	15
R4.2	14	12
R5.1	10	16
R5.2	12	14

Tabla 1 – Visualización de cada recorrido en función del sistema

A cada uno de los voluntarios se les realizó una serie de preguntas antes de comenzar las pruebas, al finalizar cada recorrido y al finalizar las pruebas:

- Previo a los recorridos. Los datos recogidos se referían a sus datos personales:
    - Nombre
    - Experiencia en ciclismo por carretera (años)
    - Kilómetros recorridos semanalmente
    - Formación o experiencia en seguridad vial y/o tráfico
- Al finalizar cada recorrido:
    - Valoración de la seguridad de la intersección (1 más segura – 5 menos segura)
    - Valoración de la seguridad del tramo (1 más seguro – 5 menos seguro)
    - Percepción de la realidad (1 menos real – 7 más real)
- Al finalizar todos los recorridos:
    - En general, ¿prefiere usted el uso del carril bici o de la calzada?
        - Carril bici en todo momento
        - Carril bici solo cuando voy solo
        - Carril bici solo cuando voy en pelotón
        - El carril bici en ningún momento
        - Ninguna de las anteriores

- Valoración de la sensación de mareo con las gafas de realidad virtual (1 menos mareo – 5 más mareo)
- Valoración de la sensación de mareo con el PowerWall (1 menos mareo – 5 más mareo)

Adicionalmente, la mayor parte de los ciclistas, durante la realización de los recorridos comentaban su percepción del riesgo de los elementos que consideraban de mayor riesgo.

Aunque inicialmente no se había contemplado esta posibilidad, la información facilitada por los ciclistas, especialmente por los más experimentados fue muy valiosa.

3. ANÁLISIS Y DISCUSIÓN

A lo largo de este apartado se analizan diferentes aspectos, comenzando con aspectos relacionados con el comportamiento ciclista, como son la percepción subjetiva del riesgo declarada por los ciclistas y la preferencia de uso de los carriles bici, para continuar con la comparativa entre ambos sistemas en cuanto a sensación de mareo y a grado de inmersión.

3.1 Percepción subjetiva del riesgo

La percepción del peligro que tienen los ciclistas sobre una infraestructura puede animarlos a circular por ella o todo lo contrario, es lo que se denomina la Percepción Subjetiva del Riesgo (PSR). Esta depende de cada persona, pero a la hora de realizar una encuesta, depende también de como se muestre la infraestructura. En el caso del presente estudio, se han utilizado dos sistemas: un sistema semi-inmersivo, como es el PowerWall, y las gafas de realidad virtual, que suponen, en principio, una inmersión mayor.

En la Figura 10 se muestran los resultados de la PSR para cada una de las glorietas de los recorridos realizados, contabilizando tanto las visualizaciones con PowerWall como con gafas de realidad virtual. Como puede observarse, las glorietas con una mayor PSR son por las que han circulado en el recorrido R2.1, en el R5.2 y en el R4.2. La glorieta del R2.1 se encontraba en obras en el momento de llevar a cabo las grabaciones, siendo esta la causa principal del aumento del PSR, según comentaron la mayor parte de los ciclistas.

En el R5.2 los ciclistas circulan por arcén coloreado que, al aproximarse a la glorieta, pasa a ser un carril segregado, realizando el cruce por uno de los ramales. Los ciclistas indicaron como uno de los problemas la falta de visibilidad, así como la falta de claridad en quien tiene la preferencia de paso.

En el R4.2, los ciclistas indicaron como principales problemas la proximidad de las entradas a la glorieta, la alta intensidad de tráfico y la ausencia de arcén.

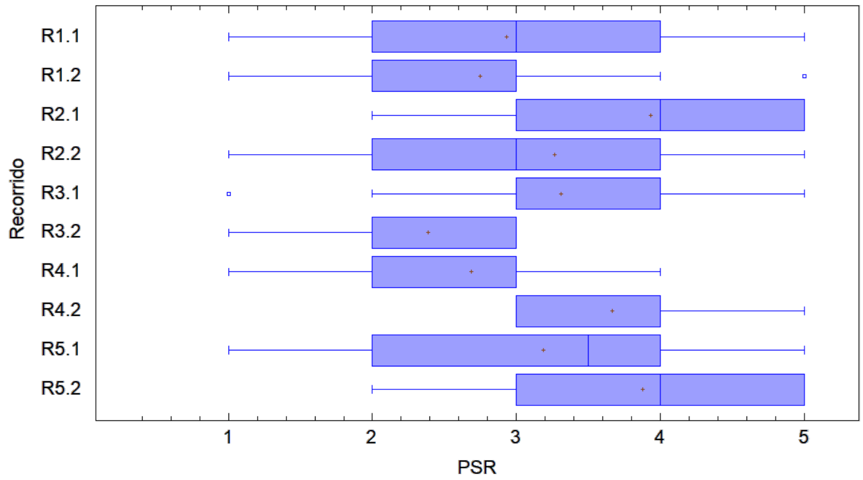

Fig. 10 – PSR de las glorietas analizadas

Estos resultados, como se ha mencionado, están basados en la PSR indicada por los ciclistas que realizaron las pruebas tanto con el PowerWall como con las gafas de realidad virtual.

En la Figura 11, se muestran los resultados distinguiendo según el sistema utilizado para la visualización. Como puede observarse, la percepción del riesgo varía según el sistema utilizado. De hecho, en la mayor parte de los casos la PSR es mayor al realizar la visualización con el PowerWall que con las gafas de realidad virtual. Únicamente en los recorridos R2.1, R3.2 y R4.1 la PSR es mayor con las gafas de realidad virtual. En todo caso, la variabilidad es alta y los valores medios no varían sustancialmente entre un sistema y otro.

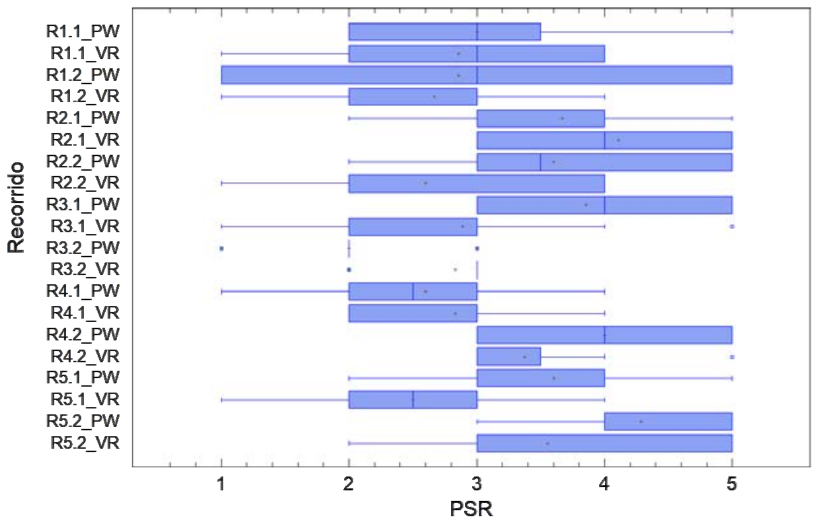

Fig. 11 – PSR de las glorietas analizadas según el sistema de visualización

Además de las glorietas, los ciclistas también valoraron los tramos por los que circularon.

Sin embargo, no sería adecuado establecer un valor de PCR por recorrido, ya que dentro de un mismo recorrido los voluntarios indicaron elementos que podrían hacer aumentar su percepción del riesgo y otros que les aportaban seguridad, siendo estos similares a los identificados en las encuestas de López-Maldonado et al. (2019).

Los principales elementos que son decisivos a la hora de valorar un tramo de carril bici segregado como más o menos peligros desde el punto de vista de los ciclistas son:

- Falta de mantenimiento de la infraestructura, tanto por el estado del firme como por el estado de la vegetación, que reduce la visibilidad, especialmente en las proximidades de los cruces.
- Falta de señalización, indicando la preferencia en los cruces.
- Entradas y salidas al carril bici mal diseñadas. Los ciclistas deportivos alcanzar una velocidad relativamente alta y, al circular en pelotón, si tienen que reducir la velocidad para incorporarse o salir de un carril bici, pueden producirse caídas.

En el caso de la circulación por calzada, los elementos que suponen una mayor influencia en la percepción del riesgo son:

- Anchura del arcén.
- Estado del pavimento del arcén, así como la invasión del arcén por parte de la vegetación.
- Color del arcén. En general, los ciclistas consideran más seguros los arcenes coloreados, siempre y cuando tengan un ancho suficiente, ya que, en caso de no tenerlo, los vehículos motorizados no dejan suficiente distancia lateral con el ciclista. Este resultado es similar al observado en las encuestas realizadas por López-Maldonado et al (2019). Sin embargo, en el caso de las encuestas online, únicamente dispusieron de porcentajes de valoraciones de los encuestados, sin los comentarios adicionales de los que se dispone después de este proyecto, en el que la conclusión es que la PSR depende del ancho del arcén coloreado.
- Las barreras de seguridad metálicas. Estas barreras son la causa de heridas en las piernas de los ciclistas.
- Los elementos situados en los márgenes. En los márgenes con acequias adosadas a la carretera o con desniveles, la PSR aumenta considerablemente ante la posibilidad de una caída.

Además de estos elementos relacionados con la infraestructura y su equipamiento, los ciclistas indicaron que el elemento que más hacía aumentar su percepción del riesgo son los vehículos motorizados. De hecho, algunos de ellos destacaron que al hacer algunos de los recorridos se sentían seguros porque en ese momento no había una alta intensidad de vehículos motorizados, pero que su PSR aumentaría al aumentar el tráfico.

3.2 Preferencia de uso del carril bici

Al finalizar todos los recorridos, se les preguntó a los voluntarios si, en general, prefieren el carril bici o la calzada. Como puede verse en la figura 12, la mayor parte de ellos indicaron que prefieren el carril bici en todo momento. Sin embargo, puntualizaron que siempre y cuando el carril bici sea suficientemente ancho y las entradas y las salidas estén adecuadamente diseñadas. Para ello, deben estar libres de bolardos u otro obstáculo y que las embocaduras sean amplias y sin curvas de bajo radio.

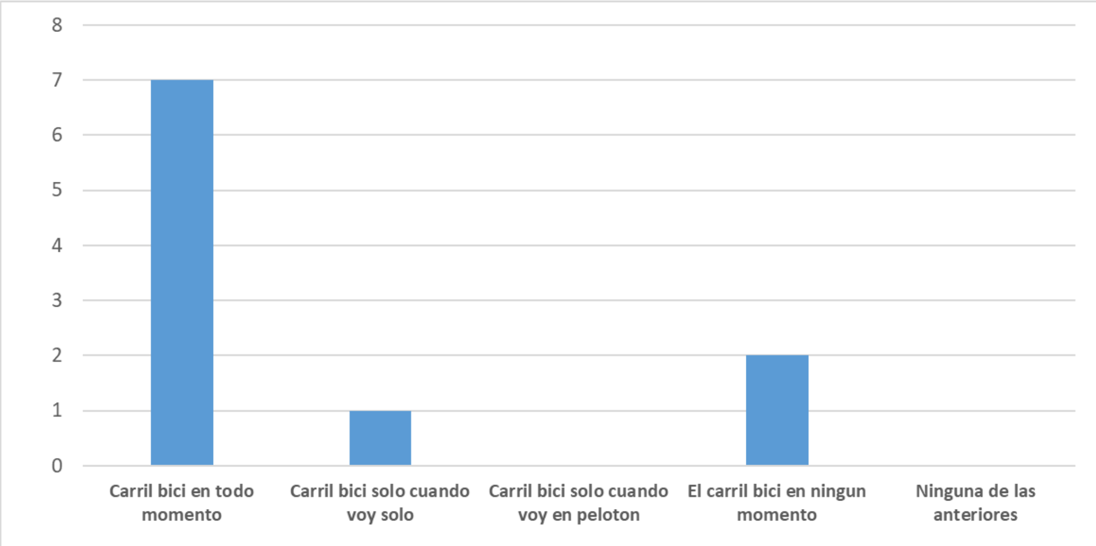

Fig. 12 – Preferencia de carril bici

En la encuesta realizada por López-Maldonado et al. (2019), los ciclistas indicaron que para circular en grupo un 45.6% prefería realizarlo por el arcén. Tras el presente estudio, podemos concluir que los ciclistas en grupo optarían por ir por carril bici si este estuviera adecuadamente diseñado y mantenido.

3.3 Comparativa entre sistemas

Para llevar a cabo la comparativa entre ambos sistemas, se establecen como principales parámetros el grado de inmersión y la sensación de mareo.

Como se ha indicado anteriormente, cuatro hombres y una mujer tuvieron que interrumpir las pruebas a causa del mareo. La edad de la mujer y de uno de los hombres era inferior a 35 años, mientras que los otros tres hombres tenían una edad superior a los 60 años. Todos ellos visualizaron los primeros recorridos con las gafas de realidad virtual. Este es un primer indicador de que la sensación de mareo es mayor en las gafas de realidad virtual que con el PowerWall.

Al resto de los participantes, al finalizar las pruebas se les solicitó que valoraran la sensación de mareo con cada uno de los sistemas (1 menos mareo – 5 más mareo).

La Figura 13 muestra como las respuestas fueron similares, siendo un poco mayor la sensación de mareo en el caso de las gafas de realidad virtual.

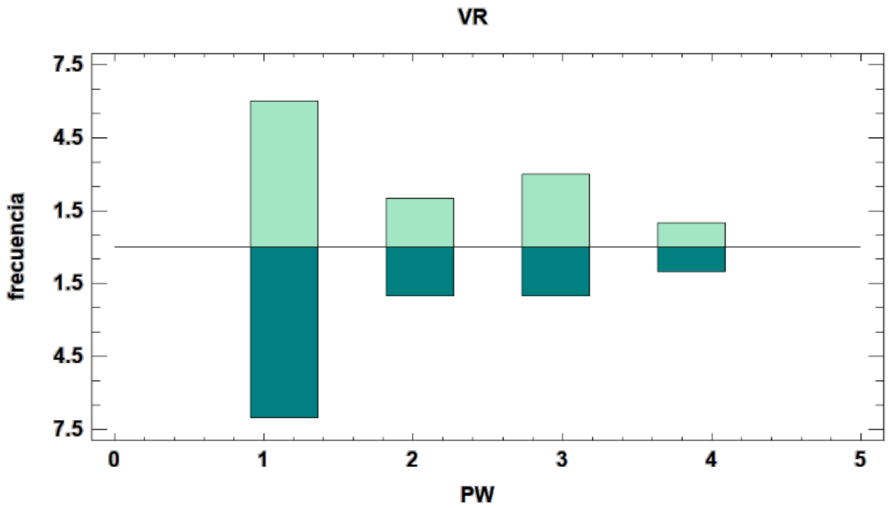

Fig. 13 – Sensación de mareo que producen las gafas de realidad virtual (VR) y la PowerWall (PW)

Adicionalmente, al finalizar cada recorrido, los voluntarios indicaron el grado de realidad de la experiencia que acababan de vivir con un rango de 1 (menos real) a 7 (más real). Como se muestra en la Figura 14, las gafas de realidad virtual presentan un grado de inmersión mayor que el sistema PowerWall, especialmente porque los voluntarios pueden girar la cabeza y contemplar todo el escenario y porque la calidad de la imagen es mayor.

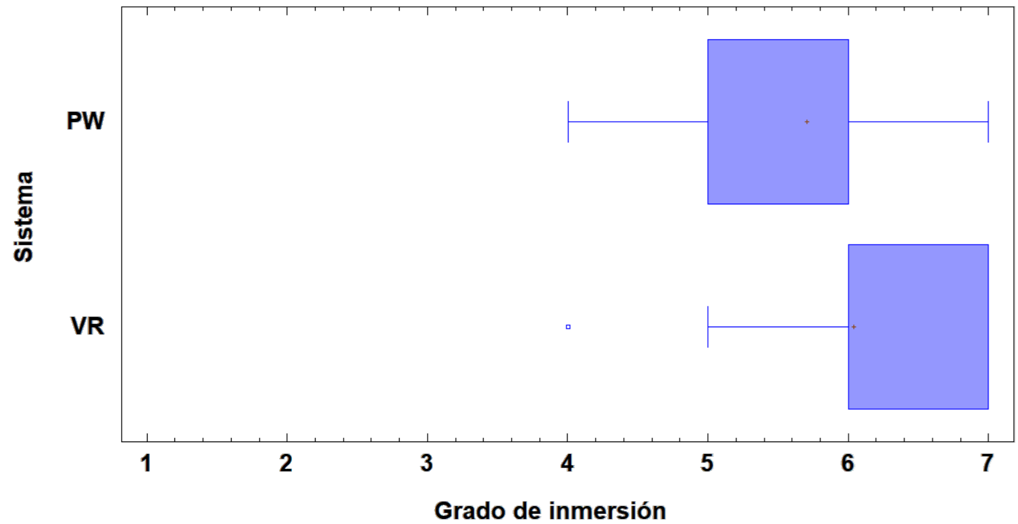

Fig. 14 – Grado de inmersión de las gafas de realidad virtual (VR) y la PowerWall (PW)

4. CONCLUSIONES

La circulación ciclista, especialmente deportiva, en las carreteras convencionales ha aumentado considerablemente en los últimos años, lo que ha supuesto un aumento progresivo de la accidentalidad. A pesar de las actuaciones que se han ido realizando, la accidentalidad relacionada con los vehículos motorizados ha disminuido, pero no la accidentalidad de las bicicletas. Por ello, es necesario estudiar los factores que suponen un mayor riesgo para este tipo de usuarios.

Existen diferentes alternativas para realizar estos estudios, siendo la más extendida las encuestas online por el alto número de participantes que puede alcanzarse. Sin embargo, esta metodología se basa principalmente en mostrar imágenes, sobre las que los encuestados deben valorar el nivel de riesgo de una infraestructura o un elemento de la misma. Al tratarse únicamente de imágenes la percepción del riesgo no es comparable a la real, sino que se basa principalmente en la experiencia de la persona que responde.

Por ello, en este estudio se ha desarrollado una nueva metodología para estudiar la percepción del riesgo que los ciclistas experimentan ante ciertos diseños de las carreteras por las que circulan y su equipamiento. Esta metodología consiste en el recorrido de varios tramos de carretera sobre una bicicleta instalada en un rodillo de entrenamiento, visualizando los recorridos en una PowerWall y con gafas de realidad virtual, en una sala adecuadamente insonorizada.

Tras la realización de los recorridos, los voluntarios indicaron su Percepción Subjetiva del Riesgo (PSR) tanto de los tramos por los que circularon como de las intersecciones que en ellos se encontraban, valorando el riesgo de los mismo de 1 a 5. De esta forma, se han identificado las intersecciones y los tramos que suponen un mayor riesgo para los ciclistas.

Sin embargo, el resultado más importante ha consistido en los comentarios de los propios ciclistas mientras realizaban los recorridos, identificando los elementos que consideraban como un mayor riesgo para su seguridad. Entre ellos destacan, en el caso de los carriles bici segregados, la falta de mantenimiento de la infraestructura, la falta de señalización y el inadecuado diseño de las entradas y salidas del carril bici. Mientras que, en el caso de los recorridos realizados por la calzada, los elementos que aumentan el riesgo según los ciclistas son una anchura reducida de los arcenes, especialmente si estos son coloreados, el estado del pavimento del arcén, las barreras de seguridad metálicas y el diseño de los márgenes (acequias y desniveles). Aunque todos coinciden en que el mayor riesgo es el comportamiento de los conductores de vehículos motorizados.

Adicionalmente, se les preguntó a los voluntarios sobre su preferencia a la hora de circular por el carril bici o por la calzada, concluyendo que prefieren en su mayoría por el carril bici, siempre y cuando este esté adecuadamente mantenido, su anchura sea suficiente y, sobre todo, que las entradas y salidas estén libres de obstáculos y no supongan una reducción considerable de la velocidad para los pelotones, ya que en ese caso la probabilidad de caídas es alta.

Finalmente, se han comparado ambos sistemas de visualización, tanto en cuanto al grado de inmersión como en cuanto a sensación de mareo. Mientras que el grado de inmersión es mayor en el caso de las gafas de realidad virtual, gracias a su imagen envolvente y a la calidad de la misma, la sensación de mareo también es mayor en ellas. Sin embargo, la mayor parte de los voluntarios realizaron las pruebas sin sufrir una sensación de mareo significativa.

Estos resultados muestran esta nueva metodología basada en la realización de entrevistas a voluntarios circulando con gafas de realidad virtual como una buena opción para identificar los elementos que suponen un mayor riesgo para los ciclistas al circular por carreteras convencionales. Con ello, aumentando la muestra se podría llegar a valorar el potencial impacto que algunas medidas de seguridad vial tienen en el comportamiento de los ciclistas y en su percepción del riesgo.

AGRADECIMIENTOS

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A PREDICTION OF BIKE FLOW IN BIKE RENTING SYSTEMS WITH THE TENSOR MODEL AND DEEP LEARNING

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ABSTRACT

Rental bikes are popular in many urban areas to help people expand their mobility. It is important to make the rental bicycle usable and available to the general public at the appropriate time and place. Inevitably, providing the city with a steady supply of rental bicycles becomes a major concern. The most important aspect is the estimation of the number of bicycles required in each bicycle sharing station at any given hour. This paper gives an examination of human mobility as indicated by bicycle renting information of the bike sharing system. In this paper, we proposed a new approach for forecasting the bike inflow and outflow from one station to another during certain time slots. Our method analyses human mobility pattern by two steps: (1) Using Tuckers tensor decomposition to create a 3D tensor to model human mobility and extract latent temporal and spatial characteristics of various stations and time slots. (2) to use a Long-Short Term Memory

Neural Network to model the relationship between mobility patterns and the derived latent spatial and temporal features in order to predict bike flow between stations. The main contribution of this study that with the extracted latent characteristics through Tuckers factorization we improve the accuracy of prediction by 16% and decrease the amount of training data that used in prediction. Also, a root mean squared error of prediction is 1,5 bike.

We compare our model with baseline models as historical average, ARMA, the feed-forward neural network, and KNN. The proposed method showed the best results

1. INTRODUCTION

Public bike rental systems have become popular in recent years. People increase attention to bicycles because of their flexibility, low cost, and benefit for health. The list of cities, that provides public bike-sharing systems are still growing. A bike-sharing world guide can be found from the following link www.bikesharingmap.com.

For the ideal execution of such frameworks, there must be (a) the likelihood of finding a bike when the client needs to start the ride, (b) the likelihood of leaving the bike at the client's destination, and (c) the distribution of bike stations around the city.

To avoid overgrowing the structure, there are two different ways to solve these problems: firstly, inform the client in advance about where to get or leave bicycles, and improve the redistribution of bicycles from entire stations to empty ones.

In this study, we developed a solution to these problems by analysing cyclical mobility models, which we then used to predict hourly the number of bicycles available at stations by predicting inflow and outflow between stations. These predictions will be made by the current bike rental systems; increase user satisfaction with the system. Knowing the established patterns that follow people can lead to optimization of the bike sharing system, forcing the operator to predict in advance overcrowding or shortage of bicycles at precise stations and optimize their redistribution according to the situation.

The understanding of human mobility and find traveling patterns of passengers is crucial for public transportation systems, taxi providers, and bike renting companies because predicting it accurately can increase citizens living conditions and increase profit of transportation companies. The transportation-related works published in different fields, such as sociology, urban planning, computer science and other areas. In this section, some studies on human mobility discussed.

Many machine-learning algorithms were used to predict the demand for bicycles. Jia et.al (2019) used a Gaussian mixture model for the bike-sharing system clustering to group stations by migration trends, then apply the gradient boosting regression tree to predict renting traffic. Sathishkumar et.al. (2020) applied the data mining technique to predict hourly rental bike demand and found that Gradient Boosting Machine showed the highest and best result. Graph structured information was added to deep learning models in the study of Yang et.al. (2020) to short term forecasting of travel demand. Feng et.al. (2017) analysed the future availability of bicycles at cycle stations using instant analysis of a Markov chain model with continuous time and time-dependent metrics. A random forest model applied in work of Huang et.al. (2013) to predict the demand of bikes, and then authors applied the hub-firs-route-second bike repositioning technique to redistribute bikes.

Raviv et. al. (2013) analyses bike-sharing systems imbalances caused by various levels of attractiveness and generation of station-level trips. Systems and Lacker (2013) and Garcia-Palomares (2012) provides efficient bike redistribution strategies to reduce bike distribution imbalance. With a similar goal of introducing a more balanced system, other studies by Khatri (2015) modeled demand or developed models that optimize the location of stations. Wergin and Buehler (2018) have focused on the GPS analysis of casual cyclists' routes. Artificial neural networks have been widely used in several fields of transportation engineering. The work of Polson and Sokolov (2017) found the fact that the deep learning architecture can capture spatio-temporal effects and deep learning provides accurate short-term traffic flow predictions. The temporal relationship is significant in the task of a forecasting time series. LSTM is a time series prediction algorithm that designed to merge short-term and long-term time information with good forecasting performance.

Zhao et al. (2015) proposed an LSTM model in which the two measurements straightforwardly shown to the spatial-temporal association with inspect the spatio-temporal connections in busy time gridlock transfer. The work of Yu et al. (2017) proposed a combined deep LSTM approach that uses deep LSTM to reenact normal traffic from case in exceptional conditions. Ma et al. (2015) used another deep LSTM on far off microwave sensor information to catch non-linear traffic elements.

2. METHODS

In this work, to predict the demand of bikes, first, we modelled human mobility patterns using tensor decomposition, and then this pattern was used to estimate the number of bikes to be taken and returned to stations. We compress all historical bike trip data to the 3-dimensional tensor to reduce the amount of input data for training model as shown in Fig.1. We use tensor to extract mobility patterns. Only this pattern is used to train model. Also, for training the model we use last month's trip information and weather condition information. This section describes the tensor model, a model for prediction, and input parameters to the model.

2.1 Tensor model

According to the study of Kolda and Bader (2009) tensor is an array with more than three-dimension. A higher order tensor decomposition used to compress a volume of data or to find some dependencies between data. Tensor decomposition is widely used in graphical analysis, numerical analysis, computer vision, data mining, neuroscience, etc. In this article, we propose to simulate the movement of a bicycle between different stations using a three-dimensional tensor $\mathcal{H} \in \mathbb{R}^{N \times N \times L}$, as shown in Figure 1.a. The first tensor dimension $\mathcal{H}$ means the identifiers of the source cycling stations, the second dimension means the N identifiers of the destination stations, and the third dimension means the L time intervals.

Each element of the tensor $\mathcal{H}$ (i, j, l) stores an average amount of trips from station i to station j over a period of time l. With this tensor model, we extract the latent spatial characteristics of each source station, destination station, and the latent temporal characteristics of each time slot using the Tucker decomposition.

The Tucker is a higher-order principal component analysis technique (PCA). In each dimension, it decomposes a tensor into a base tensor multiplied by a matrix. In our case, we decompose the tensor $\mathcal{H}$ into three matrices $o \in \mathbb{R}^{N\times P}$, $Sd \in \mathbb{R}^{Q\times N}$, $T \in \mathbb{R}^{L\times R}$ and the base tensor $G \in \mathbb{R}^{P\times Q\times R}$, as shown in Fig. 1. In terms of a mathematical formula, this relationship can be written as in equation (1):

$$\mathcal{H} \approx G \times {}_1So \times {}_2Sd \times {}_3T \quad (1)$$

The feature vector indicating the characteristics of origin station i is the row i of matrix So after tensor factorization. The feature vector indicating the characteristics of destination station j is the same, the row j of matrix Sd, Sd_j. T_k is a feature vector that indicates the quality of the time gap k. The degree of cooperation between different components of So, Sd, and T is specified by each element of the core tensor G.

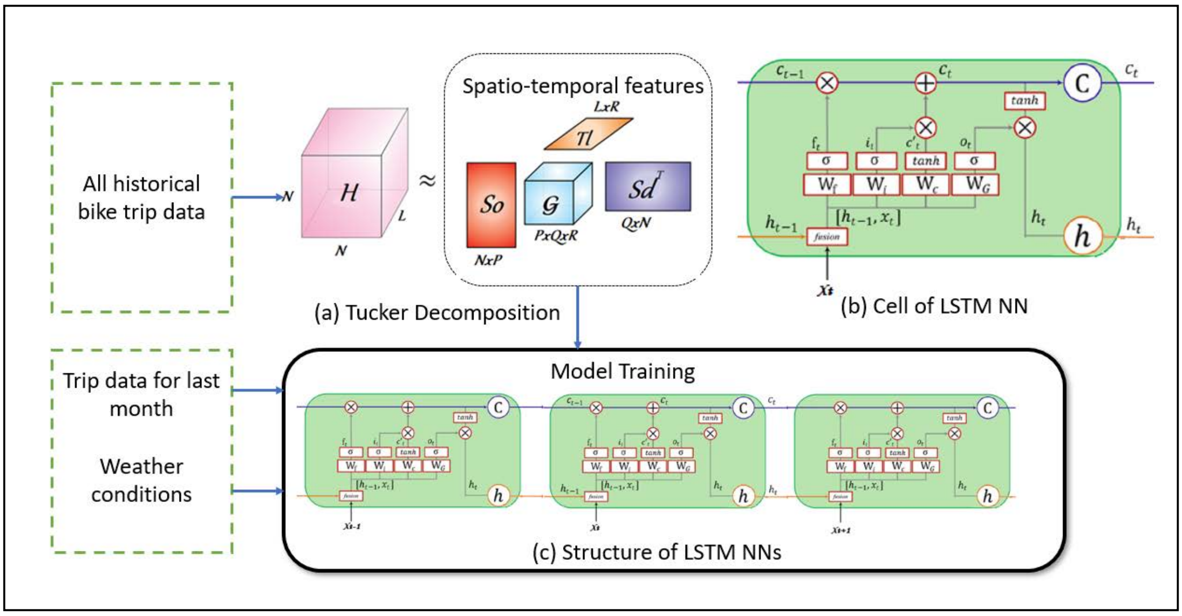

Fig. 1 – Illustrations of LSTM NN and its inputs.

The volumes of outflow $x_{oj:k}$ and inflow $x_{lj:k}$ of a station i at time gap k are under on their hidden spatial features So_i, Sd_j, latent temporal features T_k , and their previous values, $x_{oi:k-1}$, $x_{li:k-1}$ respectively. This is verified using the PC algorithm in the work of Guo and Karimi (2017). To see this dependency, we draw the values of the matrix T when P, Q, R is equal to 1 (Fig. 2). According to the graph, we have two maximum points at time slot (8-9) in morning rush hour, and at time slot (17-18) in evening rush hour. In addition, there is a minimum number of bike riders in the early morning. Likewise, the sum of all bikes taken from one station is high correlated with So matrix. Correlation coefficient is 0.806. It means that these values can be used to estimate the demand for bikes.

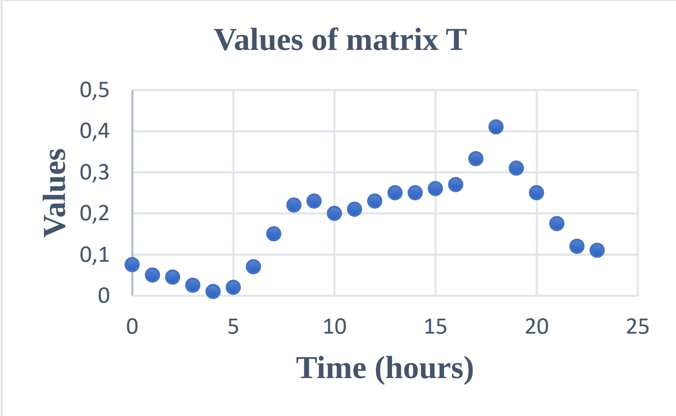

Fig. 2 – Values of matrix after tensor decomposition

2.2 Model Inputs

Anticipating the inflow and outflow of groups in each the bicycle sharing station is exceptionally testing, influenced by the accompanying three complex components:
Spatial conditions. The inflow of one station is influenced by outflows of another close-by stations. In like manner, the outflow of one station would influence the inflows of other stations.

Temporal conditions. The flow of groups in a station is influenced by ongoing time stretches, both all over. For example, a traffic flow happening at 8 am will influence that of 9 am.

Moreover, traffic conditions during morning times of heavy traffic might be comparable on successive workdays, rehashing like clockwork. Moreover, morning heavy traffic times can continually occur later when winter comes. At a time when temperatures constantly drop and the sun rises later, people rise later and later.

External conditions. Some external variables, such as climatic conditions and circumstances, can dramatically alter the flow of groups in different locations in a city. There spatial conditions and worldly conditions are separated from Tucker decomposition. The external impact is very troublesome. The traveler streams can be influenced by different outside elements, for example, climate and occasions. To investigate the impacts of these variables, Liu et al (2019) looked at traveler streams under various conditions. The precipitation information got for the examination records the evaluation of precipitation. Creator contrasted with a typical day, occasion, and end of the week have an obvious impact on the traveler streams. For example, on the off chance that a hefty downpour is seen on Monday, we will at that point contrast it and the information of past Monday to guarantee that they have similar qualities. To see is there some closeness in non-weekend days we look at them.

We found that the use of bicycles does not generally rely upon workday or end of the week data. At last, non-weekend day data, season of the day, and grade of precipitation is included as info boundaries for the demonstrating. Ashqar et.al. (2019) investigated climate conditions on bicycle checks and found that mugginess, season of-day, and temperature are noteworthy indicators of bicycle tallies. These boundaries were taken as an outer impact for forecast.

For metadata (for example, day of the week, hour of the day, and rainfall estimates), the insertion procedure is used to plan irreducible qualities in 3D vectors. It should be noted that the provisioning suite and the test suite are processed using the same bounds. At this point, the model itself can learn the data, which improves the accuracy of the predictions.

3. RESULTS AND DISCUSSION

The methodology given in this paper is trained and tested on public data available on web site https://www.citibikenyc.com/system-data. There can be found information about all CitiBike New York users' trips and annual monthly reports from May 2013. The data used in work contain records from 1st January 2017 to 31st December 2017 and January 2018. We use all data for 2017 to build 3D tensor and used data of January 2018 to test and train the model. From January 2018, we chose the last 10 days as the testing set and the left samples as the training set. In this case, the time period for traffic aggregation for forecasting is 1 hour. It's worth noting that if the chosen time interval is too short, the forecast would be incorrect and meaningless. Furthermore, short-term flows are often trivial, making the prediction approach difficult to use. We used the Min-Max normalization technique to scale the passenger traffic data in the range [-1, 1] for both the training and test sets. During estimation, the normalized predicted values are scaled and compared to the actual performance.

The results of the proposed method are compared with the following baseline models:

Historical average: We use the average historical supervision at the same time gap, the average of the past week's bike flow at the same time gap is set as the prediction outcome.
ARMA: Autoregressive moving-average model - is the mathematical model used for the forecasting and analysis of stationary time series data in statistics. The ARMA model combines two simpler time series models - the autoregressive (AR) model and the moving average (MA) model. The ARMA(p, q) model, where p and q are numbers showing the order of the model, a time series {Xt} is generating by next process:

$$X_t = c + \varepsilon_t + \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{j=1}^{q} \beta_j \varepsilon_{t-j}, \quad (2)$$

Where c is a constant, ε_t is white noise, that is, a sequence of identically and independent normally distributed random variables, with zero mean, and $\alpha_1, \dots, \alpha_p$ and $\beta_1, \dots, \beta_q$ – autoregressive coefficients and moving average coefficients.

This model can be explained as a linear multiple regression model, in which the previous values of the dependent variable itself go as illustrative variables and moving averages of white noise elements go as the regression remaining.

FFNN: The dynamic nonlinear relationship between different variables can be captured by a feedforward neural network. We use the passenger flow in recent tree adjacent time intervals to reflect temporal dependencies in FFNN. (i.e. $[x_{t-1}, x_{t-2}, x_{t-3}]$).

KNN: K-nearest neighbours' algorithm, k-NN - a metric algorithm for automatic classification of items or regression. In our case, the object is given an average value based on the k objects closest to it, whose values are already known, using the regression method. In this article, we use a value of 4 for k..

The study's efficiency metrics are as follows: Root Mean Square Error (RMSE), , Mean Absolute Error (MAE), Symmetric Mean Absolute Percent Error (SMAPE), and Mean Relative Error (MRE).

The proposed methodology is assessed using RMSE, SMAPE, MRE, and MAE. The outcomes are shown in Table 1.

Performance metrics	HA	ARMA	FFNN	KNN	LSTM	LSTM ST
SMAPE	92.5	88.	48.1	46.4	46.1	44.2
RMSE	3.3	3.1	2.5	2.4	2.4	1.5
MAE	2.1	1.9	1.5	1.5	1.5	1.2
MRE	72.8	66.8	65.7	61.9	59.2	47.6

Table 1- Performance comparison

Different variation models were checked and compared to the baseline outcome to assess the forecast accuracy of the models in terms of RMSE, SMAPE, MRE, and MAE. Table 1 shows that using only the average bike flow over the previous time period (Historical average) results in a lower forecast.. Autoregressive models show better result than just calculating average. The accuracy remarkably improved when we apply FFNN, KNN and LSTM NN models. If we compare results of FFNN, KNN and LSTM NN, LSTM NN is better than other models, because LSTM NN model best suits for time series forecasting problem.

Models FFNN, KNN, LSTM accuracy approximately the same, the error in the number of bikes is about 2 or 3. But after applying the Tucker decomposition result error decreased to 1 or 2 bikes. That is good enough to help a bike managements system to improve the availability of bikes and docks in stations. The Tensor model increased forecasting accuracy for RMSE metric to 15 % from 2.43 to 1.53

4.CONCLUSION

We proposed a method for forecasting spatial-temporal bike mobility patterns, namely the inflow and outflow of bicycles from one station to another during a time gap. Our approach consists of two stages: (1) using a 3D tensor to model human mobility and recovering hidden spatial and temporal characteristics such as origin and destination stations and timeframes through tensor factorization; and (2) determining a connection between mobility patterns and recovering hidden features using a Long-Short Term Memory Neural Network for human mobility forecasting. We conduct a study of bicycle trips in New York City in order to validate the proposed technique. The results showed that the recover hidden features effectively identify attributes of timespans and spatio - temporal features with a strong correlation coefficient with bicycle sharing station inflow and outflow. The proposed method for extracting hidden characteristics can be applied to existing models to increase precision (MAE error is reduced by 16 percent).

By picking up from past historical bike rent data and past weather information, the proposed LSTM model with Tucker decomposition results can foresee the interest in bikes at a particular time. Considering the estimate, we can make the proposal for bike associations about how to scatter the bikes expressly to each station to satisfy the need of customers similarly as saving a silly cost of keeping bikes. The use of the proposed model will be a useful answer for both the bike renting organizations and the bike riders

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MODELLING INDIVIDUAL PERCEPTION OF BARRIERS TO BIKE USE

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ABSTRACT

People face different barriers when choosing to commute by bike. The predominance of these barriers in users' perception could explain the low cyclability rates present in many cities. An investigation of cyclists' perceptions is developed using the data set obtained through a survey made to individuals from Quito, Ecuador. This study is aimed to evaluate the perception of a group of individuals about barriers to bike use, in particular, assesses how perception varies according to the available information and the different profiles. Using ordered probit models, the study compares the overall evaluation of bike acceptance before and after making individuals reflect on the importance of certain variables (e. g. lack of bike infrastructure, city temperatures, etc.). The main results show that to improve bike use acceptance, enhancing multimodality or providing facilities like electric bikes must be considered. The results also demonstrated a high heterogeneity of individuals' perceptions caused by their socio-demographic characteristics and the environmental context.

1. INTRODUCTION

Nowadays cities face major environmental, socio-economic, and transport challenges, whereby, the importance of promoting non-motorized modes of transport such as the bicycle, is recognized. Bike transportation offers many important benefits at environmental, health, social interaction, and urban mobility levels. However, despite its wide advantages, regular bike use is still not broadly accepted in many cities, especially in Latin America (Gutiérrez, Hurtubia, & Ortúzar, 2020; Keeling, 2013). The unconcern in integrating the bicycle in urban mobility has caused several challenges including identifying the most effective ways to spend the resources, usually limited, allocated to its promotion. Commonly, bike mobility planning is focused primarily on solving the service from a technical perspective (e.g. proposing the fastest routes or with lower agency costs). However, several authors conclude that to achieve a positive bike assessment and its acceptance among users, the system must also comply with other subjective aspects that respond to individuals' needs (Cepeda

Zorrilla, Hodgson, & Jopson, 2018; Heinen, Maat, & van Wee, 2011; Jakovcevic, Franco, Visona Dalla Pozza, & Ledesma, 2016).

From this perspective, in contexts with low rates of bike use, it seems reasonable to focus on identifying the weakest points of the system to work and invest in them, reducing the risk of investing in solving other aspects that will not necessarily motivate people to commute by bike (Dell'Olio, Ibeas, & Cecín, 2010).

This study aims is to identify the barriers that influence individuals around bike use, as well as obtaining the comparative weights of each of these variables. Previous studies have proven that *Ordered Probit Models* are satisfactory for the analysis of categorized or non-quantitative ordered choices and replies (Dell'Olio, Ibeas, De Oña, & De Oña, 2018c). The contribution is a model that identifies and ranks the perceived barriers of bike use, therefore, this research pretends to better understand citizens' needs to facilitate better bike mobility planning.

This work is divided into several parts. First, a brief contextualization of the problem is presented. Afterward, the methodology, the collected data, and some results are discussed. And to finish, the main conclusions are presented.

2. LITERATURE REVIEW

2.1 Choice to commute or not by bicycle

Studies conclude that bike commute decision is highly complex since it can be influenced by both objective and subjective factors (Konstantinidou & Spyropoulou, 2017; Muñoz, Monzon, & Lois, 2013). This section describes the role of psychological factors, such as attitudes and perception towards bike use in its acceptance among individuals. These factors are related to travel motivations, socio-economic, journey, and environmental characteristics, among others (Cepeda Zorrilla et al., 2018; Majumdar & Mitra, 2013).

Likewise, other authors conclude that these aspects are not necessarily equally perceived by all individuals or have the same weight in the overall perception of the service (Dell'Olio et al., 2010; Weinstein, 2000). Therefore, the importance of understanding the relationship between individuals' perception towards bike use and their different profiles is recognized (Dell'Olio et al., 2010; Dell'Olio, Ibeas, De Oña, & De Oña, 2018b; Garrido, De Oña, & De Oña, 2014).

The literature suggests that aspects such as the *weather conditions* incluiding the *temperature, rain or wind* (Fernández-Heredia, Monzón, & Jara-Díaz, 2014; Freitas & Maciel, 2017; Heinen, Maat, & van Wee, 2011; Helbich, Böcker, & Dijst, 2014), *long-distance travels* (Corcoran, Li, Rohde, Charles-Edwards, & Mateo-Babiano, 2014; Fernández-Heredia et al., 2014; Heinen, Maat, & Van Wee, 2011; Konstantinidou &

Spyropoulou, 2017), *lack of well-connected and high-quality cycle-path networks* (Buehler & Pucher, 2012; De Sousa, Sanches, & Ferreira, 2014a; Fernández-Heredia et al., 2014; Gutiérrez et al., 2020; Konstantinidou & Spyropoulou, 2017), the *perception of risk* (Fernández-Heredia et al., 2014; Gutiérrez et al., 2020), *traffic insecurity* (Branion-Calles, Nelson, Fuller, Gauvin, & Winters, 2019; Muñoz et al., 2013), *topography* (De Sousa, Sanches, & Ferreira, 2014b; Fernández-Heredia et al., 2014; Majumdar & Mitra, 2013), *physical abilities* (Branion-Calles et al., 2019; Freitas & Maciel, 2017; Majumdar & Mitra, 2013), *insecurity against crime and vandalism* (Eren & Uz, 2019), and the *personal appearance* (Iwińska, Blicharska, Pierotti, Tainio, & de Nazelle, 2018) affect bike commutes and reduce the frequency of trips.

Wide studies have investigated barriers to cycling, however, this number is limited when identifying the weight of each variable in individuals' perception (Handy, van Wee, & Kroesen, 2014; Porter, Suhrbier, & Schwartz, 1999). Dell'Olio, 2010 among others authors (Dell'Olio et al., 2010; Garrido et al., 2014; Weinstein, 2000) have estimated the different influence that each attribute's perception exerts on users' global assessment, focusing mainly on public transport (PT) services, however, the implemented methods are found suitable to the present study.

2.2 Service Quality and User Satisfaction

Service Quality (SQ) has been widely studied since Parasuraman, Zeithaml, & Berry (1985) first introduced it, defining SQ as the difference between both, the expected and the perceived quality of service. User perceived quality has been shown to have a positive effect on user satisfaction with transport services (Braun et al., 2016; J. De Oña, De Oña, Diez-Mesa, Eboli, & Mazzulla, 2016; Rocío De Oña, 2013). However, evidence suggests that although users perceive a good quality of service, taking this indicator as a criterion of success could be precarious, hence, it cannot be used as the only reference when planning policies aimed at retaining customers and attracting new ones (J. De Oña et al., 2016; Dell'Olio, Ibeas, De Oña, & De Oña, 2018a; Fernández-Heredia et al., 2014).

Parasuraman et al. (1988) suggested that for the study of the SQ of transport services, their defining variables or attributes should be established, proposing a generic list of 22 attributes and dimensions applicable to any type of service. However, many authors criticized this generic list stating that the attributes must respond to each specific case (Babakus & Boller, 1992). Likewise, other evidence demonstrates that the predictive value of the model developed by Parasuraman et al. 1988 increased when the items were adapted to the study context (Carrillat, Jaramillo, & Mulki, 2007). The key then is to enlist the generic attributes but adding other aspects own of each specific context and service.

Diversity of methodologies and tools have been developed to evaluate SQ variation according to users' preferences. For example, *satisfaction surveys* allow researchers to associate quality perception to a type of user classifying them accordingly to their socio-economic and journey characteristics (Alonso, Barreda, dell'Olio, & Ibeas, 2018; Bordagaray, Ibeas, & Olio, 2012; Branion-Calles et al., 2019). Others studies establish this relationship by developing methodologies based on *structural equations* (J. De Oña, De Oña, Eboli, & Mazzulla, 2013; Rocio De Oña & De Oña, 2015; Dell'Olio, Ibeas, De Oña, & De Oña, 2018d) or the application of *decision trees*, the latter permits to generate models able to differentiate between different kinds of users (Rocío De Oña, 2013). Likewise, other not model-based methods have provided interesting results, such as *descriptive statistics* (Eboli & Mazzulla, 2011) or *neural networks* (Garrido et al., 2014).

Ordered probit models have proven to be a highly efficient and useful tool for modeling perceived quality (Alonso et al., 2018; Bordagaray et al., 2012; Dell'Olio et al., 2010, 2018c). This particular methodology allows ordered qualitative responses to be modeled, meaning that the *non-linearity* existing between the different replies can be considered (Dell'Olio et al., 2010, 2018c). Another key feature of the model is its ability to use interactions to incorporate systematic variations resulting from the socio-economic characteristics of the different users (Bordagaray et al., 2012), assuming that these factors follow a *statistical distribution*.

However, evidence on the combination between systematic and random variations in the same model, as well as the inclusion of attributes' importance within the modeling of bike use perception is limited (Porter et al., 1999). Therefore, using *ordered probit models,* the present research aims to fill this gap and complete the knowledge about bike use perception, by studying the *relative importance* of barriers to bike use in the general individuals' perception (Dell'Olio et al., 2018b).

3. METHODOLOGY

3.1 Description of the study area

The city of Quito has an area of 372 square kilometers and approximately 1.7 million people (INEC, 2017). Its particular allocation close to the equatorial line, its altitude, and its closeness to the Andes mountain range gives the city special climate conditions (spring relatively constant throughout the year), and a mostly irregular landscape with steep slopes (IGM, 1992). In 2011, inhabitants' global mobility rate was 2 trips per day, which is equivalent to almost 3.4 million daily trips. From these, the majority were made by public transport (62%), 20 % by private car, 15% by foot, and only 0.3% by bicycle (Metro de Quito, 2012). Since 2012, Quito has a Public Shared Bicycle Service (BiciQuito) and a 173 km long cycle path network of which only 32% are exclusively for bikes, the rest are shared spaces with pedestrians or motorized vehicles.

3.2 Data Collection

Data collection was conducted in the city of Quito, Ecuador. After a deep literature review aimed to identify psychological, socio-economic, environmental, and travel-related factors that could affect bike use, in particular, the barriers, a first draft of the survey was developed and presented to specific groups of individuals from the study area.

Afterward, considering this first stage's feedback, a second draft was designed and applied in a pilot survey tested to verify the clarity of the questionnaire and to ensure the proper capture of the information necessary for the model estimation. The final survey was applied via the web in the last week of January of 2021 and collected 422 completed forms. Figure 1 presents a flow chart of the process.

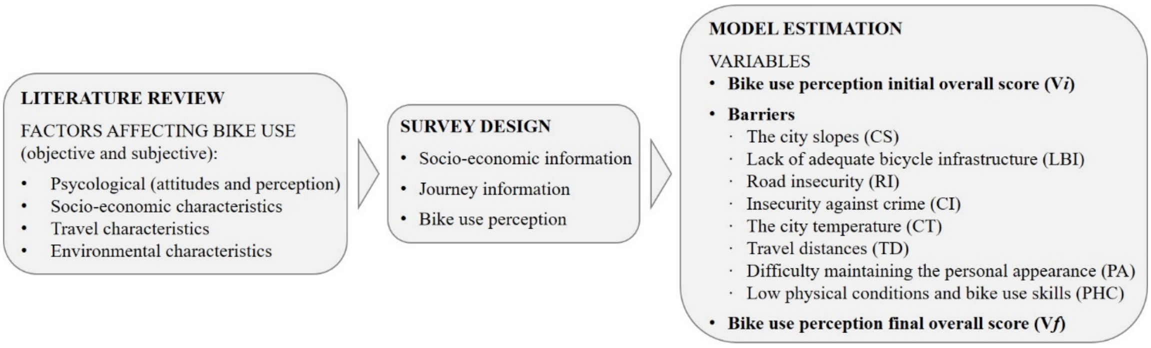

Figure 1 – Methodology flow chart

Survey design

The questionnaire consisted of two main segments. The first part collected information about the person's *socio-demographic* and *journey characteristics* (see Table 2). This information will permit respondents' stratification into different profiles. The second part enclosed bike use perception and consisted in asking an individual to give an opinion about a subjective aspect related to bike use, in this case, a barrier. This segment consisted of three questions.

The first obtained a first valuation of the bicycle as an option to commute, representing individuals' initial opinion based on the information they have, ergo, their understanding of the service through the personal experience. The second gets separate values for each of the previously defined variables (barriers). The third and final question was asked right after individuals valued each barrier and consisted in a second score of the overall perception of bike use. This second score is required to analyze any changes on the bicycle's global score once individuals have had the opportunity to analyze every aspect that makes up the system.

Namely, to check the degree by which they changed their opinion after the reflection made on each barrier that may be affecting bike use (Dell'Olio et al., 2010, 2018b).

The set of selected barriers was: city slopes (CS), lack of adequate bike infrastructure (LBI), road insecurity (RI), crime insecurity (CI), city temperature (CT), long travel distances (TD), difficulty in maintaining the personal appearance (PA), and insufficient physical conditions and cycling skills (PHC).

Using a 5-point Likert scale, participants were asked to rate the variables (see Table 1).

Question 1	***Do you agree that the bike, in your city, is a good option to commute?***								
			Strongly disagree	1	2	3	4	5	Totally agree
Question 2	***The following aspects could DEMOTIVATE bike use, how much do you think they influence?***								
	Variable		Very influential	1		→		5	Not influential
	CS	The city slopes							
	LBI	Lack of adequate bicycle lanes and parking slots							
	RI	Fear of having a traffic accident							
	CI	Insecurity against crime							
	CT	The temperature of the city (too cold, too hot)							
	TD	Travel distances							
	PA	Difficulty maintaining the personal appearance							
	PHC	Low physical conditions and abilities to bike use							
Question 3	***Do you consider the bicycle as a good option to commute in your city?***								
			Strongly disagree	1	2	3	4	5	Totally agree

Table 1 – Survey segment 2: Perception on bike use

3.3 Statistical Approach

The type of model was selected after collecting and analyzing the data. Since that, the dependent variables (initial and final overall bike use perception) are ordinal by nature, ordered probit models seemed to be suitable. Following the belief that latent and continuous variables cannot be measured discretely, thus the variable (bike use perception) is intended to be segmented into several options associating each one of them with a range value of the latent variable (in this case from 1 to 5). The key idea of this method first proposed McKelvey & Zavoina, (1975) is that allows to transform a continuous latent variable into an ordered, observed, and discrete reply, so when individuals select an option, are in fact selecting not a discrete value but rather the closest answer to their true perception, of bike use in this case (Alonso et al., 2018; Dell'Olio et al., 2010, 2018a, 2018c; Echaniz, Ho, Rodriguez, & dell'Olio, 2019).

Segement 2 of the survey regarding bike use perception was performed as follows:

1st. *Initial overall valuation* of bike use (V_i).

2nd. Scoring the eight variables previously identified as possible *barriers* to bike use.

3rd. A *second overall valuation* of bike use (V_f).

Two types of models were estimated for the different profiles of respondents. Both V_i and V_f were related separately to the variables identified as possible barriers to bike commute. The first model aims to identify which variables are unconsciously relevant when an

individual decides not to commute by bike, and the second, which variables would individuals consider as important after having more information about the service.
According to the literature a *probit ordered model* consists of a direct relationship between the dependent variable, in this case, bike use perception -initial (V_i) and final (V_f) scores-, and the independent variables (barriers) V_{ik}. A constant β_0 and an estimation error ε_i associated with individuals' heterogeneity complements the model (Dell'Olio et al., 2018c).

The models are based on the following mathematical expression:

$$Q_i^* = \beta_0 + \sum_{k=1}^{N} \beta_k \cdot V_{ik} + \varepsilon_i \qquad \text{with } k \in [1, 2, \dots, N] \tag{1}$$

$\mathbf{Q}_i$ represents the general evaluation of the person i; $\boldsymbol{\beta_0}$ the model constant; N the number of evaluated bike use aspects (barriers); β_k the coefficient of the variable *k (barrier)*; V_{ik} is the valuation made by each individual *i* of each variable *k*.

To fit the models Log Likelihood function was used:

$$\log L = \sum_{i=0}^{n} \quad \sum_{j=0}^{J} m_{ij}\, log\left[F\left(\mu_j - \beta'_{V_i}\right) - F\left(\mu_{j-1} - \beta'_{V_i}\right)\right] \tag{2}$$

Once the corresponding models were estimated for each individuals' categories, possible relationships between them were identified.

4. RESULTS AND DISCUSSION

4.1 Initial data analysis

First, the data set composed of 422 observations were analyzed to characterize individuals' profiles as shown in Table 2.

Variable	Category	Frequency	Percen
Sample		**422**	
Gender	Female	186	44%
	Male	236	56%
Age (years)	< 24	121	29%
	25 to 44	142	34%
	45 to 64	132	31%
	> 65	27	6%
Main occupation	Student	104	25%
	Dependent worker	87	21%
	Self-employed or independent worker	57	14%
	Home care	62	15%
	Unemployed	91	22%
	Retired/pensioner/other	21	5%
Household income	< 400 USD	75	18%
	400 - 800 USD	166	39%
	800 - 1.200 USD	135	32%
	> 1.200 USD	46	11%
Mode of transport	Walking	43	10%
	Bicycle	23	5%
	Public Transport (bus, BRT)	186	44%
	Private car	31	7%
	Motorcycle	14	3%
	Taxi / Service on demand (Uber, Cabify)	27	6%
	Teleworking / No commute	98	23%

Table 2 – Profile of respondents

As explained in subsection 3.3, the overall valuation of bike use was asked twice, the first (V_i) immediately before and the second (V_f) immediately after scoring each variable (barriers) separately (see Table 1). So, the difference between V_f and V_i will show if there were any changes in people's opinion concerning the first valuation. The results showed that around 60% of individuals changed their score, either positively or negatively (see Tables 3 and 4). When categorizing the surveyed according to the previously defined characteristics (22 categories), some differences could be identified (see Tables 3 and 4).

In all categories, the second valuation had a higher score than the first, generally double, except for two: *bike users* and private car users, from now on *car users* (see Tables 4 and 5). These results show that people tend to be more critical than they would be if they had more knowledge about the service, that is, ignorance or misinformation prevents them from evaluating it impartially. Seem to be that, in the initial valuation(V_i), individuals tend to perceive more negatively the barriers. In this case, these results can be explained by the lack of familiarity with bike use present in the majority of the inhabitants of the city of study (see Table 1). However, in other contexts where bike use for commuting is more positioned, the results would be different. Since previous findings suggest that an individual is more positive towards modes that are included in the daily mobility patterns compared to the modes that are not (Ton et al., 2020).

Regarding the ‘working' category, this second higher evaluation could be because respondents possibly realized those bike use barriers would not actually be as influential for cycling. Since evidence suggests that bike use is more prevalent in young people, for reasons such as the smaller technological gap compared to other ages, resulting in more openness to route planners or bike-sharing systems (Goodman, Sahlqvist, & Ogilvie, 2013). About the positive variation of PT users, this is not necessarily unexpected. It is in accordance with previous studies that conclude the clear tendency to change from PT to cycling. This could be because users may find PT to be a relatively inflexible (and sometimes unreliable) mode, therefore they would choose more flexible options such as the bicycle (Thorhauge, Kassahun, Cherchi, & Haustein, 2020). Furthermore, in many cities, PT service quality is poorly perceived (Cepeda Zorrilla et al., 2018; Mark & Heinrichs, 2019), so the bike can be seen as a better choice. A fact that, within the bad, could be seen as an opportunity to position it in the urban transport offer.

This knowledge is important, since policies aimed at improving certain factors may have little effect on people's opinion if aspects with an apparently greater weight than they actually do are prioritized. Therefore, any strategy seeking to increase bike use acceptance must first focus on knowing what are the aspects that really influence people's perception.

The difference between V_f and V_i is denoted below by δ_{value}.

$$\delta_{value} = V_f - V_i \tag{3}$$

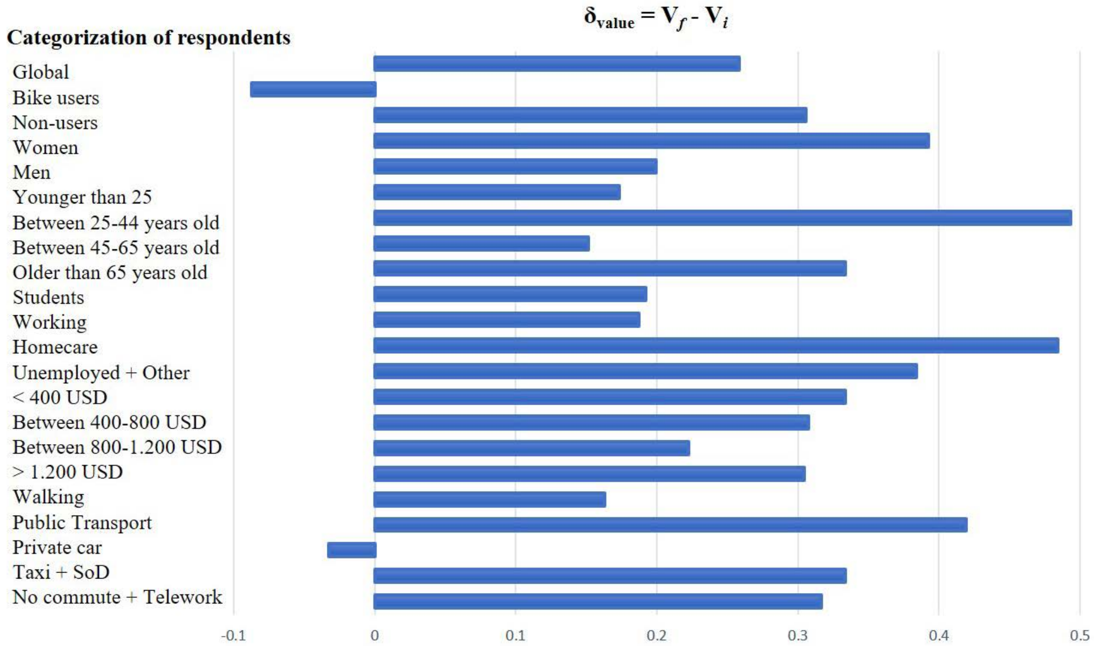

Table 3 – Variations on δ_{value} according to respondents' categorization

Given that bike use V_f trending was to change positively, this paper presents the *models* estimated for the two categories which did so negatively: *Bike users* and *car users*.

The negative change in bike users can be explained because in contexts with poor cycling facilities and lack of incentives, in short, non-friendly cycling mobility contexts, people who decide to commute by bike do so out of beliefs and not out of any kind of incentives (Iwińska et al., 2018; Jakovcevic et al., 2016). In other words, they are bike commuters 'no matter what', with which the reflection process may have made them focus on the weakest aspects of the system and therefore have been more critical. This agrees with previous studies concluding that bike use incentives work in the first stage, as a hitch for new users. However, if the aspects that users identified as barriers from the beginning are not improved, they will not find benefits in using it once the incentives are removed, and therefore, they will stop doing it (Jakovcevic et al., 2016). Therefore, it is important to prioritize the improvement of the weaknesses of the system if what is sought is the retention of users and the creation of habits.

		Negatively				No variation	Positively						
Respondents categories		**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**Variated**	**Positively**	**Negatively**
Global	**Freq.**	8	5	28	54	166	88	42	19	12	256.0	161	95
	%	1.9	1.2	6.6	12.8	39.3	20.9	10.0	4.5	2.8	**60.7**	**38.2**	**22.5**
Bike users	**Freq.**	1	0	3	4	8	4	1	2	0	15.0	7	8
	%	4.3	0.0	13.0	17.4	34.8	17.4	4.3	8.7	0.0	**65.2**	**30.4**	**34.8**
Non-users	**Freq.**	7	5	25	50	158	84	41	17	12	241.0	154	87
	%	1.8	1.3	6.3	12.5	39.6	21.1	10.3	4.3	3.0	**60.4**	**38.6**	**21.8**
Women	**Freq.**	3	2	10	27	71	34	21	10	8	115.0	73	42
	%	1.6	1.1	5.4	14.5	38.2	18.3	11.3	5.4	4.3	**61.8**	**39.2**	**22.6**
Men	**Freq.**	5	3	18	27	95	54	21	9	4	141.0	88	53
	%	2.1	1.3	7.6	11.4	40.3	22.9	8.9	3.8	1.7	**59.7**	**37.3**	**22.5**
Younger than 25	**Freq.**	5	2	6	18	48	21	11	6	4	73.0	42	31
	%	4.1	1.7	5.0	14.9	39.7	17.4	9.1	5.0	3.3	**60.3**	**34.7**	**25.6**
Between 25-44 years old	**Freq.**	2	1	8	12	56	33	20	4	6	86.0	63	23
	%	1.4	0.7	5.6	8.5	39.4	23.2	14.1	2.8	4.2	**60.6**	**44.4**	**16.2**
Between 45-65 years old	**Freq.**	1	2	13	18	54	26	8	8	2	78.0	44	34
	%	0.8	1.5	9.8	13.6	40.9	19.7	6.1	6.1	1.5	**59.1**	**33.3**	**25.8**
Older than 65 years old	**Freq.**	0	0	1	6	8	8	3	1	0	19.0	12	7
	%	0.0	0.0	3.7	22.2	29.6	29.6	11.1	3.7	0.0	**70.4**	**44.4**	**25.9**
Students	**Freq.**	5	1	4	16	40	19	11	6	2	64.0	38	26
	%	4.8	1.0	3.8	15.4	38.5	18.3	10.6	5.8	1.9	**61.5**	**36.5**	**25.0**
Working	**Freq.**	2	1	17	15	55	32	14	5	3	89.0	54	35
	%	1.4	0.7	11.8	10.4	38.2	22.2	9.7	3.5	2.1	**61.8**	**37.5**	**24.3**
Homecare	**Freq.**	0	0	3	9	24	15	5	4	2	38.0	26	12
	%	0.0	0.0	4.8	14.5	38.7	24.2	8.1	6.5	3.2	**61.3**	**41.9**	**19.4**
Unemployed + Other	**Freq.**	1	3	4	14	47	22	12	4	5	65.0	43	22
	%	0.9	2.7	3.6	12.5	42.0	19.6	10.7	3.6	4.5	**58.0**	**38.4**	**19.6**
< 400 USD	**Freq.**	0	1	6	7	32	16	9	3	1	43.0	29	14
	%	0.0	1.3	8.0	9.3	42.7	21.3	12.0	4.0	1.3	**57.3**	**38.7**	**18.7**
Between 400 - 800 USD	**Freq.**	6	1	12	19	61	35	18	6	8	105.0	67	38
	%	3.6	0.6	7.2	11.4	36.7	21.1	10.8	3.6	4.8	**63.3**	**40.4**	**22.9**
Between 800 - 1.200 USD	**Freq.**	2	1	8	22	57	24	11	7	3	78.0	45	33
	%	1.5	0.7	5.9	16.3	42.2	17.8	8.1	5.2	2.2	**57.8**	**33.3**	**24.4**
> 1.200 USD	**Freq.**	0	2	2	6	16	13	4	3	0	30.0	20	10
	%	0.0	4.3	4.3	13.0	34.8	28.3	8.7	6.5	0.0	**65.2**	**43.5**	**21.7**
Walking	**Freq.**	2	0	2	9	15	7	4	3	1	28.0	15	13
	%	4.7	0.0	4.7	20.9	34.9	16.3	9.3	7.0	2.3	**65.1**	**34.9**	**30.2**
Public Transport	**Freq.**	2	3	8	21	75	42	20	10	5	111.0	77	34
	%	1.1	1.6	4.3	11.3	40.3	22.6	10.8	5.4	2.7	**59.7**	**41.4**	**18.3**
Private car	**Freq.**	0	0	4	6	11	7	3	0	0	20.0	10	10
	%	0.0	0.0	12.9	19.4	35.5	22.6	9.7	0.0	0.0	**64.5**	**32.3**	**32.3**
Taxi + SoD	**Freq.**	1	1	0	3	11	8	0	1	2	16.0	11	5
	%	3.7	3.7	0.0	11.1	40.7	29.6	0.0	3.7	7.4	**59.3**	**40.7**	**18.5**
No commute + Telework	**Freq.**	2	1	9	8	41	17	13	3	4	57.0	37	20
	%	2.0	1.0	9.2	8.2	41.8	17.3	13.3	3.1	4.1	**58.2**	**37.8**	**20.4**

Table 4 – Variations on V_f according to respondents' categorization

Figure 2 shows the frequency diagrams of the δ_{value} according to the categorization of respondents. The distribution seems to be mainly asymmetrical in most of the cases

Figure 2 – δ_{value} frequency diagram according to respondents' categorization

4.2 Estimated models

Special statistical software STATA was used for its capability to estimate *ordered probit models* (Simons, 2018; StataCorp, 2017). These models were developed to work with the ordinal-natured dependent variables, in this case, V_i and V_f. Two models were developed: one for *bike users* and one for *car users*. The final data set enclosed 54 observations (23 bike users and 31 car users). Each respondent evaluated 10 variables. First, to track any data error, descriptive statics was performed. Said *data cleaning* examined mean, minimum, and maximum values of the variables (see Table 6).

Bike users						Private car users				
Variable	Mean	Std. Dev.	Min	Max	Obs	Mean	Std. Dev.	Min	Max	Obs
Bike_V*i*	4.3043	1.1455	1	5	23	3.4194	1.1482	1	5	31
CS	3.3043	1.5502	1	5	23	4.1290	1.2039	1	5	31
LBI	3.9565	1.2239	1	5	23	4.0323	1.1397	2	5	31
RI	4.1739	1.3702	1	5	23	4.5161	1.0286	1	5	31
CI	3.5652	1.3425	1	5	23	3.4839	1.1796	1	5	31
CT	4.0435	1.1862	1	5	23	4.2581	0.9650	1	5	31
TD	3.1304	1.4555	1	5	23	4.0645	0.8920	2	5	31
PA	2.8261	1.3702	1	5	23	2.7419	1.3655	1	5	31
PHC	3.3478	1.5843	1	5	23	3.1935	1.4473	1	5	31
Bike_V*f*	4.2174	1.0853	1	5	23	3.3871	1.1159	1	5	31

Table 5 – Descriptive statistics of the variables

Comparing the models, conclusions can be drawn about how the mode of transport affects the variables' evaluation (see Table 7). The most representative changes in barriers' perception are described as follows.

The insecurity against crime (CI), barrier perceived by *bike users* as important at the beginning, in the second evaluation does not appear. This may be because, as previously stated, urban cyclists choose bike use by beliefs, therefore, CI may not be such an influential factor in their perception. On the other hand, regarding *car users*, CI went from having null importance to being the most influential barrier. This finding is interesting since it shows that the reflection process to which individuals were subjected indeed had an impact on their perception, since it may be that *car users* perceive CI as the most influential barrier and that is why they decide to commute by car and not tby bike.

Physical conditions and abilities to use the bike (PHC) have the same weight in *car users*' perception in both initial and final evaluations. However, regarding *bike users*, PHC has significantly higher importance on the second valuation (in the first did not appear), this could be explained because maybe in the reflection process individuals comprehended the realities they are exposed to when using the bike (e.g. tiredness).

Travel distances (TD) represents a heavy barrier from *bike users*' perspective since they introduced this aspect after the reflection process (in the initial valuation it did not appear). This may be because individuals could reflect on the times and reasons why they do not use the bike to commute, identifying TD as an influential barrier. TD could be improved by promoting multimodality. Likewise, it is not surprising that *car users* do not take TD into account in either of the two evaluations, this may be because they are not familiar with TD as a commute barrier, as they commute by car.

	Bike users						**Private car users**					
Dependent variable	**Bike_V*i***			**Bike_V*f***			**Bike_V*i***			**Bike_V*f***		
Log likelihood	-19.013			-20.93			-40.47			-36.37		
Pseudo R2	0.17			0.17			0.11			0.20		
LR chi2(8)	8.04			8.51			10.12			18.12		
Prob > chi2	0.09			0.07			0.02			0.00		
Variable	**Coef.**	**z**	**P > | z |**	**Coef.**	**z**	**P > | z |**	**Coef.**	**z**	**P > | z |**	**Coef.**	**z**	**P > | z |**
CS							-0.255	-1.51	0.13			
LBI										-0.489	-2.02	0.043
RI	-0.301	-0.99	0.324	-0.649	-1.92	0.055						
CI	0.349	1.22	0.222							0.729	2.6	0.009
CT							-0.407	-2.33	0.02	-0.769	-3.5	0
TD	-0.701	-2.59	0.010	0.330	1.43	0.154						
PA	0.385	1.44	0.150	-0.672	-1.91	0.057				-0.231	-1.49	0.137
PHC				0.640	1.85	0.065	0.272	1.92	0.055	0.272	1.77	0.076
/cut1	-3.114		-6.383	-3.574		-6.244	-3.391		-5.691	-3.129		-5.750
/cut2	-2.291		-4.929	-2.209		-4.635	-2.494		-4.596	-2.396		-4.899
/cut3	-1.178		-3.683	-1.590		-3.967	-1.765		-3.798	-1.132		-3.526
/cut4							-0.420		-2.466	0.303		-2.148

Table 6 – Ordered probit models of bike users and car users

To perform a complete analysis of the results, table 7 was developed. It shows each variable's contribution (by percentage) in each of the models. The parameters of the model where the dependent variable was V_i are represented by Θ_i, and in the case of V_f, by Θ_f (see Table 8). Θ_f - Θ_i is the difference in the contribution of each variable (Θ) between the models estimated for *bike users* and *car users*.

	Bike users			Private car		
	Θi	Θf	Θf-Θi	Θi	Θf	Θf-Θi
CS	0	0	0	65.4	0	-65.4
LBI	0	0	0	0	100.1	100.1
RI	112.3	184.6	72.3	0	0	0
CI	-130.39	0	130.4	0	-149.2	-149.2
CT	0	0	0	104.4	157.4	53.0
TD	261.6	-93.8	-355.4	0	0	0
PA	-143.6	191.1	334.7	0	47.3	47.3
PHC	0	-181.9	-181.9	-69.8	-55.6	14.1

Table 7 – Percentage and difference in each variable (Θ) contribution to each model

4. CONCLUSIONS

This paper presents the first findings of an ongoing research aimed to identify the aspects of bike use that may be preventing its acceptance among people carried out in the city of Quito, Ecuador. Prior to this study, there was uncertainty about whether if all the elements that make out bike use have the same impact on the overall valuation, whereby the method proposed by Dell'Olio et al. (2010) is useful in identifying the *relative importance* of the barriers to bike use.

Considering their approach, the present study was performed from two points of view: Firstly, know bike use perception from the information held a priori by individuals (V_i). Secondly, to immerse individuals in a process of *problem-analysis* (bike use acceptance as an option to commute) asking them to evaluate specific aspects of bike mobility to measure the relative importance of the variables (barriers) that could be influencing their overall perception. Immediately after this phase of meditation, individuals were asked for the second time to globally assess bike use (V_f).

The two proposed situations arose when seeking to meet two objectives: 1) to identify which variables have an unconscious impact on individuals and, 2) build up valuable information on where to direct the strategies and efforts that seek to improve the overall perception of bike use, focusing on those variables to which individuals seem to be more receptive. This study increases the knowledge about the perception towards bike use according to individuals' characteristics.

The research verifies the different bike use perceptions of a group of individuals before and after having reflected on each of the components of the system. The analysis according to individuals' categorization confirms that bike use perception varies depending in this case, of the mode of transport (*bike users* vs. *car users*). On the one hand, *bike users*' reflection causes a reduction in the weight they placed on aspects such as the importance of *maintaining the personal appearance* and *insecurity against crime*, resulting in increased importance placed on *travel distances*, and the *physical conditions and abilities to use the bike*, this latter being of null importance when the initial valuation was made. Regarding *car users*, aspects such as *city temperatures* fell in the second valuation, while *insecurity against crime*, which in the first evaluation was missed, in the second evaluation was highly influential. Therefore, the greatest impact on bike use perception will be achieved by, regarding *bike users*, enhancing multimodality, and the provision of facilities for bike use such as electric bikes. Whilst for *car users* should be by focusing on *safety*.

The results of this study evidence the importance that people's socio-demographic and journey characteristics have in the perception of a service, therefore, taking into account their needs should be a crucial factor to be considered when developing strategies that seek promoting bike use. Thus, mobility services will be able to meet demand requirements to, firstly, retain existing users and, secondly, attract new ones, especially from motorized modes. Therefore, in the future, bicycle mobility planning should be the product of collaboration between different mobility actors, especially integrating people's knowledge and perception, and not a product developed solely by experts and technicians.

Given that in cities with low rates of bike commute, the majority of the population is not familiar with the benefits of cycling as a means of transport. Therefore, dissemination strategies could focus on communicating the benefits of cycling as a fast, comfortable and reliable option, presenting it as a mode of transportation and not only as a recreational activity or a healthy lifestyle (Handy et al., 2014; Savan, Cohlmeyer, & Ledsham, 2017). This could be a key factor in changing the mindset towards its adoption as a regular mode of transportation. Short-term targeted campaigns can be an effective policy measure to expose these benefits and potentially engage new users in active mobility.

The application of the proposed methodology may provide planners and policymakers with valuable information for developing strategies aimed at different profiles of people, to improve bike use acceptance and attract new users. Nevertheless, it is important to bring up that this study serves as a first attempt to capture the bike use perception of a group of individuals in a city with a particular size, topography, and climate conditions. Further research should focus on studying the preferences of other sub-groups of people (e. g. males vs. females, students vs. working population, and so on), as well as in other cities with other characteristics where different results could be obtained related to the different contexts.

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PREDICTING THE WILLINGNESS TO CARRY LIGHTWEIGHT GOODS BY BIKE AND KICK-SCOOTER: A DESCRIPTIVE ANALYSIS

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ABSTRACT

The social transformation caused by the COVID-19 pandemic may contribute to make cities healthier and more sustainable, with more space available for active modes of transport. This paper addresses people's willingness to go shopping by bike or kick-scooter and to transport lightweight goods in cities with low maturity for cycling and scooting. Data collection was based on a survey, applied in the two main urban areas of Brazil (São Paulo and Rio de Janeiro) and Portugal (Lisbon and Porto). The dataset was processed considering only two categories of respondents, that is, potential users and regular users. The results indicate that people are willing to transport lightweight goods by bike or kick-scooter, as long as the infrastructure is safe and comfortable. This research contributes to understanding mobility behavior changes and to identifying barriers to shopping by bike or kick-scooter. It also presents some recommendations for improving cycling and scooting use for shopping, which can be carried out by public authorities.

1. INTRODUCTION

The world is currently facing a new mobility paradigm driven by the impact of artificial intelligence, new cleaner energy sources and public health problems caused by the COVID-19 pandemic. These trends are changing the way people work, travel and purchase goods and services. Furthermore, the definition of sustainable mobility is broad and should cover the three pillars (social, environmental and economic), based on people’s need to have access to activities that facilitate their individual and societal development (Banister, 2008).

The reasons for using the car include convenience, time constraints, transporting heavy goods, picking up or bringing people, needing the car for the following trip and facing bad weather (Beckx et al., 2013; Mackett, 2001). The high car ownership rates, combined with a high percentage of short trips by car, has a negative influence not only on air quality, but also on living conditions in several cities (Soria-Lara et al., 2019).

The use of active modes of transport for this purpose becomes more difficult not only because of the weight of the load itself, but also because of the lack of safe and comfortable infrastructure (Félix et al., 2020), in addition to the lack of implementation of a public e-bike and e-scooter sharing systems in many places.

On the other hand, the COVID-19 pandemic is accelerating new lifestyles and the emergence of a new mobility scenario, in which public health and social distancing have become crucial challenges in transport policy and planning. In addition to mobility restrictions, the use of public transport has been limited and even discouraged in some places (Tian et al., 2020), having been identified as a vector for the spread of infection in dense populated areas (Buja et al., 2020). As demonstrated by the previous SARS pandemic, the fear of infection also discourages the use of public transport (Wang, 2014). As a consequence of that, the use of active modes of transport has also increased according to some studies (Abdullah et al., 2020; Bucsky, 2020; Haas et al., 2020).

Despite the ongoing vaccination for COVID-19, physical distancing may be necessary until 2022 (Kissler et al., 2020). Cities must adjust to that situation and compensate for some of the most negative long-term effects of the pandemic. The social changes prompted by the pandemic could be used to make cities healthier and more sustainable, with more space available for active modes of transport (Gutiérrez et al., 2020), which facilitates journeys by walking, cycling or scooting (Young & Whyte, 2020). In that scenario, this paper deals with the following research question: “are people willing to transport lightweight goods by bike or kick-scooter?”.

The paper focuses on the use of all types of bikes and kick-scooters (i.e., folding, electric, shared, rental, etc.) for personal shopping purposes by regular people (those working for a delivery company are not included). By actively promoting shopping by bike or kick-scooter, a new impetus can be given to improving and reinforcing sustainable shopping in cities. One possible contributor towards more efficient and environmentally friendly commercial transport is the use of bikes, especially cargo bikes (Nascimento et al., 2020; Schliwa et al., 2015), however, this paper does not deal with the feasibility of urban freight and city logistics. It also considers the hypothesis that part of the population can ride a bike and/or kick-scooter carrying some lightweight goods during their trips.

On the basis of a survey, a methodology was developed with the aim of characterizing the use of bike or kick-scooter for moving lightweight goods. The survey was applied to people of different age groups in the two main urban areas of Brazil (São Paulo and Rio de Janeiro) and Portugal (Lisbon and Porto). All those cities have low maturity for cycling (and also for scooting), meaning that they have: few cyclists (and even kick-scooter users), little infrastructure, no cycling (and/or scooting) culture (being considered unsafe and not respected), a car-oriented road design and a small modal share for active modes (Félix et al., 2017; Santos & Torres, 2020).

The main objectives of this paper are: (i) understand people's willingness to go shopping by bike or kick-scooter and to transport lightweight goods in cities with low cycling and scooting maturity, during the COVID-19 pandemic; and (ii) compare the results of the survey between regular users and potential users of bikes and kick-scooters.

The content of this paper is made up of this introduction plus other five sections. The second section presents the background and literature review. The third section deals with data collection and the fourth section presents the case study cities. The fifth section presents the results of the descriptive analysis, following the last section with the conclusions and future recommendations.

2. BACKGROUND AND LITERATURE REVIEW

Behavioral changes caused by the COVID-19 pandemic could be used to make cities healthier and more sustainable, with more space available for active modes of transport. Although it may not be easy to keep those habits over time, there is a clear window of opportunity available whereby temporary actions may inspire future policies (Gutiérrez et al., 2020).

Policy decision-makers, as well as the society in general, have a commitment to improve the quality of life in cities, air quality and public space, while ensuring equal accessibility in the urban context (Banister, 2008). The paradigm shift towards sustainable mobility is largely due to the transfer of fossil fuel-powered travel to electric vehicles; and from individual to collective transportation means and active modes, thus allowing short distances to be covered in the respective infrastructures (Moura et al., 2017; Santos & Torres, 2020).

Urban planning and transportation management policies must also be critically reviewed. The first actions taken during the COVID-19 pandemic sought to promote active modes and reduce the space allocated to private vehicles (Gutiérrez et al., 2020). However, the policies that will be implemented in the medium and long term are uncertain, as well as their impacts on active modes.

The benefits of active modes for urban mobility are well known for cities, including sustainability, equity, health, and quality of life. Increasing active mobility behavior, could help to address increasing rates of obesity, benefit physical and mental health, and reduce serious health problems associated with lack of exercise and air quality (Pérez et al., 2017; Sallis et al., 2004). However, changing the behavior of the population is a major challenge.

Planners and policymakers benefit from a greater understanding of available interventions to effectively promote cycling and scooting. In cities where cycling or scooting is starting to grow, as it is the case of the cities of this paper (i.e., São Paulo, Rio de Janeiro, Lisbon and Porto), little is known about who is cycling or scooting. Usually, in these cities, the attention of transportation agencies and mobility managers is not focused on active modes, so cyclists and kick-scooters users are not a priority. The resulting lack of useful data is also a problem because there is no basis upon which governments could justify investments in effective cycling and scooting infrastructure. Cities with low cycling maturity do not have historical experience with cycling, so it is necessary to better understand and inform urban planners about which strategic infrastructure investments should be made and programs to be implemented in order to leverage their participation and mature the culture of cycling (Félix et al., 2020).

The implementation and extension of segregated cycling networks and facilities are interventions that have a high chance to successfully induce cycling (Buehler & Pucher, 2012; Carr & Dill, 2003; Pucher & Buehler, 2006; Santos et al., 2013), and can also induce scooting. However, it was found that changes in travel behavior can also be associated with a change in life circumstances rather than a change in the external environment (Chatterjee et al., 2013), such as health problems, a job change, school or residence, etc. The built environment influences a lot the use of active modes, enabling or hindering cycling and scooting. Several authors have concentrated mainly on perceptions of risk in cycling and the provision of cycling facilities to overcome this barrier (Chataway et al., 2014; Götschi et al., 2018; McClintock & Cleary, 1996; Swiers et al., 2017; Vanparijs et al., 2015), and the perception of safety is possibly one of the most important factors influencing the decision to ride a bike or not (Félix et al., 2019; Fowler et al., 2017; Muñoz et al., 2016), and probably a kick-scooter as well.

In the case of bikes, for example, other barriers are related to the physical effort of cycling, which is related to the slope and cycling maturity of the city (Stinson & Bhat, 2003; Winters et al., 2010) and sweating (Engbers & Hendriksen, 2010). In order to overcome these common barriers, electric bicycles and kick-scooters, requiring less physical effort, have been promoted worldwide (Dill & Rose, 2012; Popovich et al., 2014). Enabling active modes through basic infrastructure may be a necessary first step for numerous cities with little or no infrastructure, but such an approach is likely to have only modest impacts on travel behavior. Furthermore, significant travel behavior changes may not be possible without policies and infrastructure levers that deter people from car driving, in order to increase active travel (Piatkowski et al., 2019).

In cities with few regular users of active modes, such as the case study cities, there is a large share of the population that prefer other commuting modes. Among them it is possible to distinguish potential users of active modes from those who are not able or willing to ride a bike (Félix et al., 2017) or a kick-scooter. There is a need to appropriately measure the relevant factors that determine whether people choose to ride (or not) a bike or kick-scooter, especially for shopping purpose.

The general assumption is that the factors that prevent people from cycling or scooting are caused by a combination of personal and external factors, which together constitute the perceived barriers to cycling or scooting and influence the expectations of potential users.

Some of these factors are subjective and others are objective. Some of the objective factors (for example, distance or slope) may be perceived differently among potential users, being a strong or irrelevant barrier to cycling or scooting. These factors vary over time and can potentially lead to a change in behavior in relation to the adoption of cycling or scooting.

Another assumption is that the paradigm shift reflects the behavioral change, in which perceived barriers are outweighed by perceived benefits (Kahneman & Tversky, 1979) and the resulting motivators and expectations lead to effective results. The influence of personal or external factors on decisions to ride a bike or a kick-scooter more often can change over time, especially during pandemic periods.

The current literature points out some recommendations for public authorities to improve cycling or scooting use for shopping, such as: (i) incite active modes by means of street design interventions (Barbarossa, 2020; De Vos, 2020); (ii) reduce the number of lanes on multi-lane streets to homogeneously expand the walking and cycling (or scooting) infrastructure in central business districts (Soria-Lara et al., 2019); (iii) define the total traffic restriction on selected streets with high retail activity in order to build an infrastructure for walking and cycling (or scooting) covering the entire traffic space (Soria-Lara et al., 2019); (iv) limit (free) car parking, as it is associated with a lower likelihood for cycling (Bueno et al., 2017) or scooting; and (v) provision of showers, lockers and parking for bikes (Bueno et al., 2017) and kick-scooters.

Based on the literature review, the main reason why people do not ride a bike or kick-scooter is the possibility of using the private vehicle for the same objective. Bike and kick-scooter sharing schemes, which are rapidly spreading in many cities, are also considered essential elements of urban transport policy. However, there may not be a significant cycling increase without dedicated cycling infrastructure (Félix et al., 2019; Pucher et al., 2010). Anyway, for those who do not have bike storage at home and thus are less likely to cycle (Fernández-Heredia et al., 2016), bike (or kick-scooter) sharing systems can be a practical option.

The literature points to many studies of urban freight and city logistics (mainly cargo bikes), considering mainly those people who work for a delivery company, which is not the focus of this paper. There are even fewer research studies focused on cities with low cycling and scooting development and maturity, which typically have sizeable non-users' population, and also potential users of bikes and kick-scooters. This is precisely the research gap that this paper intends to cover.

3. DATA COLLECTION

Data collection was based on a survey aimed at understanding respondents' current mobility patterns, attitudes towards urban cycling and scooting, willingness to change behavior, and some socio-demographic data. The survey is applicable to any city regardless of the level of maturity of cycling and scooting. All questions were closed-ended and are listed in the flowchart displayed in Figure 1.

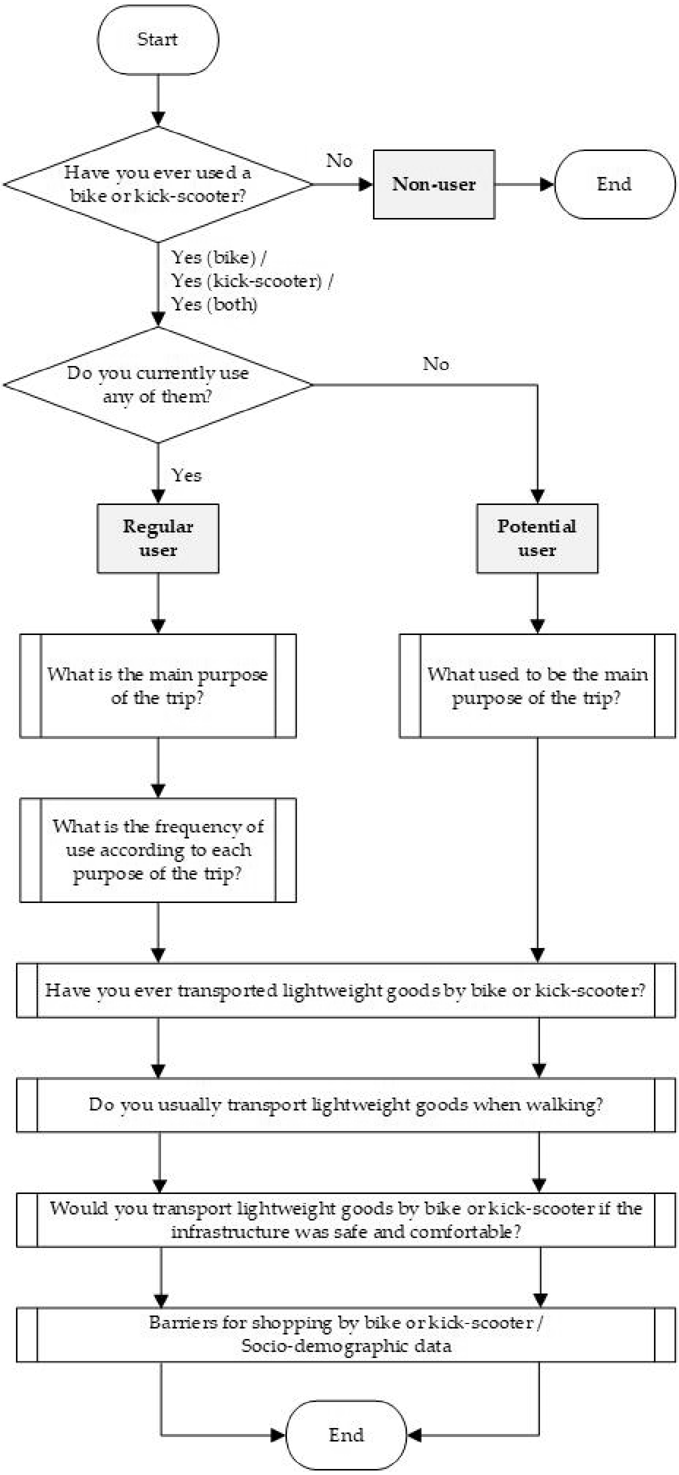

Figure 1 – Flowchart of data collection

It is worth mentioning that urban cyclists and kick-scooter users are not all the same, do not travel for the same reason or with the same frequency, or have the same needs (Christmas et al., 2010). Market segmentation has been used in transportation engineering for many years (Beirão & Sarsfield Cabral, 2007; Dallen, 2007; Jacques et al., 2013; Kassirer & Lagarde, 2010). To this end, the flowchart in this paper presents a categorization of the survey into smaller groups of similar individuals based on how they would likely respond to a particular marketing mix.

Respondents were categorized as “Non-users”, “Potential users” and “Regular users”, adapted after reviewing the literature (Kroesen & Handy, 2014; Bergström & Magnusson, 2003; Dill & McNeil, 2013; Félix et al., 2017), as follows: (i) Non-users: someone who has never ridden a bike or kick-scooter and has no particular interest in doing it; (ii) Potential users: someone who has ever ridden a bike or kick-scooter and would ride it again (or is willing to do so) if some conditions happen; and (iii) Regular users: someone who currently rides a bike or kick-scooter and should do so within the next month.

Different lines of inquiry were addressed to each group. The survey asked “Potential users” to recall their previous experiences when they used to ride a bike or kick-scooter, and “Regular users” to respond based on their current experience. The category of “Non-users” was not considered in the final dataset, as they have no particular interest in riding a bike or kick-scooter.

All questions were closed-ended, and all features were categorical. Regarding trip purpose, "Regular users" answered it for their current trips, while "Potential users" did it for the trips they would have made. Only "Regular users" had to answer what is the current frequency of use (i.e., “Sometimes”, “Once a week”, “2 to 3 times a week”, “Daily”), having to answer this question for each of the following four trip purposes: “Work or Study”, “Leisure”, “Shopping” and “Other”.

The next three questions were asked to the two categories of respondents in order to have a reference to test and validate the research question addressed in this paper (namely, are people willing to transport lightweight goods by bike or kick-scooter?). These three questions were “Yes/No” questions, involving: (i) “Have you ever transported lightweight goods by bike or kick-scooter?”; (ii) “Do you usually transport lightweight goods when walking?”; and (iii) “Would you transport lightweight goods by bike or kick-scooter if the infrastructure was safe and comfortable?”.

Finally, respondents had to answer a question to identify barriers for shopping by bike or kick-scooter in cities with low maturity for cycling and scooting (including the volume or cargo itself, etc.). They were also asked about some socio-demographic data (including gender and age).

4. CASE STUDY CITIES

The survey was applied to people of different age groups in the two main urban areas of Brazil (São Paulo and Rio de Janeiro) and Portugal (Lisbon and Porto). The two countries continue to be linked by a common language (Portuguese) and Portuguese-Brazilian ancestry, which facilitated the common application of the survey. These cities have important employment centers in their regions and have some differences related to urban morphology, transport infrastructure, modal share, etc. However, these cities have a low modal share for cycling (see Table 1) and scooting, as well as scarce infrastructure for active modes.

City	Cycling modal share	Reference
São Paulo (Brazil)	2.0%	Brand et al. (2019)
Rio de Janeiro (Brazil)	2.4%	Souza et al. (2017)
Lisbon (Portugal)	< 1%	Martinez & Viegas (2017)
Porto (Portugal)	< 1%	Costa et al. (2012)

Table 1 – Modal share for cycling in the case study cities

Cycling accounts for about 27% of trips in The Netherlands (Félix et al., 2019), unlike all cities in the case study that account for less than 3% of the participation in the cycling modal. Although information on the percentage of kick-scooter trips has not been found, it can be assumed that all cities have low development and maturity for the use of bikes and kick-scooters.

All cities in the case study face difficult challenges in adopting active modes for urban mobility: (i) low culture of cycling and scooting; (ii) little interest in collecting data on cycling or scooting; (iii) the general perception that cycling or scooting is neither safe nor respected; and (iv) car-oriented road projects.

On the one hand, the political choices that were made at the level of transport systems in these cities, were based on a bet on road infrastructure and the use of the car, in recent decades, with little significant investment in infrastructure and public transport services. The road infrastructure sector in these cities directly affects the accessibility of regions and the mobility of people and goods, contributing to access to work and income (Santos & Ribeiro, 2015, 2016a, 2018a) and road concessions have been the most strategic alternative feasible for maintaining roads at an appropriate level for traffic volumes (Santos, 2017; Santos et al., 2019; Santos & Picado-Santos, 2018, 2019; Santos & Ribeiro, 2018b). Traffic impact analysis is the key means to harmonize transport and land use planning (Santos & Gouvêa, 2012; Santos & Ribeiro, 2016b), but in these case study cities, such studies have only been used since the last few decades.

On the other hand, the conditions offered in these types of cities contribute to the individual's decision to ride (or not) a bike or kick-scooter, in a transitional way. Given that these cities do not have historical experience with cycling or scooting, it is necessary to better understand and inform city planners about what strategic infrastructure investments should be made and programs to be implemented in order to increase their participation in active modes, mature its culture, as well as encourage its use for shopping, which is the main objective of this paper.

5. DESCRIPTIVE ANALYSIS

Descriptive analysis was used to illustrate the basic characteristics of the dataset in this paper, providing simple graphical analysis and measurements. The survey was addressed to the residents, workers, students and visitors of the four cities already mentioned. As the survey was launched in different cities at the same time, no specific sampling methodology was used. The survey was distributed on social media and by university press advisory, with the title "Shopping by bike or kick-scooter in times of pandemic", and conducted in an online-only format, using the Google Forms. The survey was online in April and May 2020 and collected 294 responses. The representativeness of respondents and the three categories of population segmentation is shown in Figure 2.

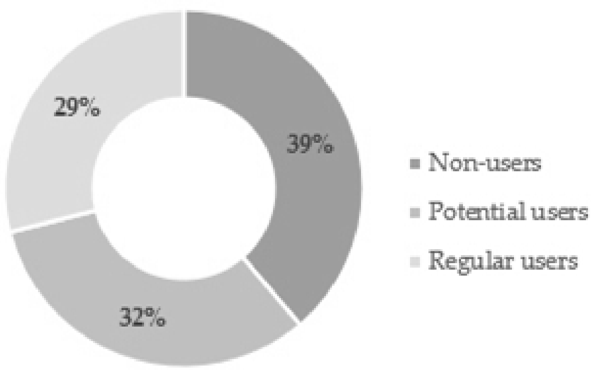

Figure 2 – Representativeness and categories of respondents (Note: 294 responses)

According to the representativeness and categories of the respondents, the category "Regular users" corresponds to 29%, which was expected in cities with low maturity for cycling and scooting. Then in second place it comes the category "Potential users" (32%), followed by the category "Non-users" (39%). In a low cycling and scooting maturity city, more non-users and potential users are expected, whereas in a high cycling and scooting maturity city, more regular users are expected (Félix et al., 2017). After the data cleaning process, the final dataset included only the categories "Regular users", as they are typically more proficient users, and also "Potential users", as they are willing but not convinced to ride a bike or a kick-scooter again if a number of conditions were fulfilled. The content of this dataset also confirms the initial hypothesis that part of the population can ride a bike and/or kick-scooter (around 61%).

Thus, the entire analysis from now on is based on the remaining 180 respondents, with almost half of them (53%) being “Potential users” and the remaining portion (47%) being “Regular users”.

The gender of respondents is shown in Figure 3, according to the category of respondents, as well as the grouping of these two categories.

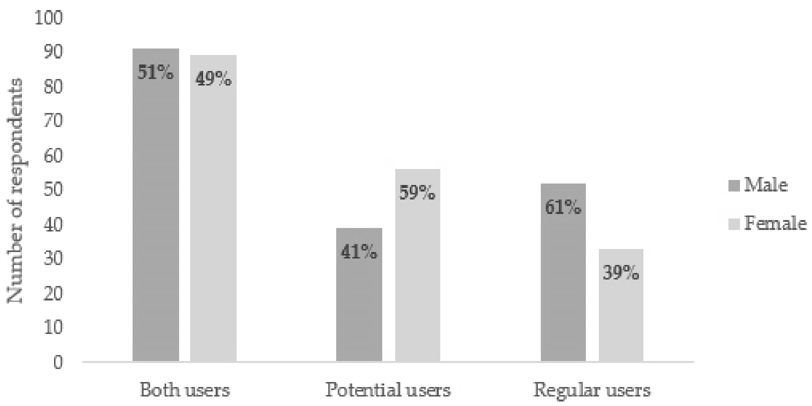

Figure 3 – Gender of the respondents

The gender of the respondents is well distributed among the sample (i.e., both users), in a total of 91 men (51%) and 89 women (49%). However, this distribution is not the same when analyzing the two categories of respondents. In the "Potential users" category, women represent the majority of the responses (59%), while in the "Regular users" category it was men who represented the majority of the responses (61%). These results are in line with the literature review, since among regular users, a higher percentage of men in countries with low maturity in cycling (and scooting) was expected (Garrard et al., 2008). The distribution of the age group of these respondents, as well as the grouping of these two categories, is shown in Figure 4.

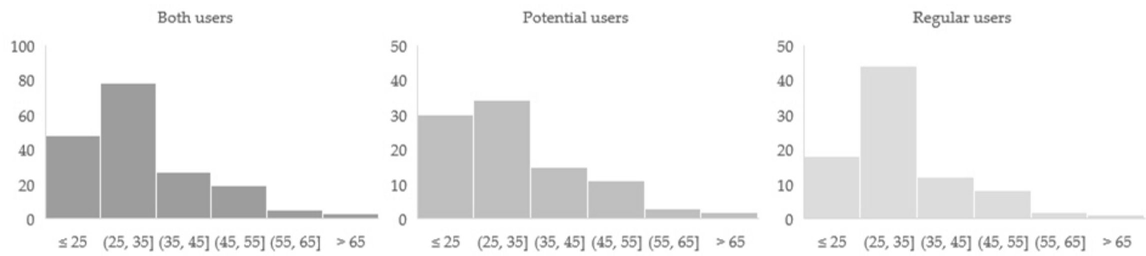

Figure 4 – Distribution of the age group

The distribution of the age group was similar in the two categories of respondents ("Potential users" and "Regular users"), as well as in the grouping of these categories (i.e., both users). In general, most respondents are between 25 and 35 years old, while a minority of respondents are over 55 years old.

The modal split is shown in Figure 5, according to the two categories of respondents.

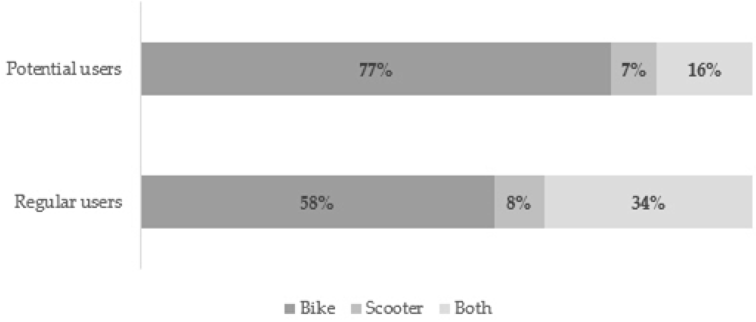

Figure 5 – Modal split according to the two categories of respondents

In the two categories of respondents considered, the modal split graph shows that the bike is the most used active means of transport, while the kick-scooter remains between 7% and 8%. However, it is observed that the use of both means (i.e., bike and kick-scooter) increases for the category "Regular users", which shows a better acceptance of these two means of transport.

The main travel purposes are shown in Figure 6, according to the two categories of respondents. As mentioned before, "Regular users" answered it for their current trips, while "Potential users" did it for the trips they would have made.

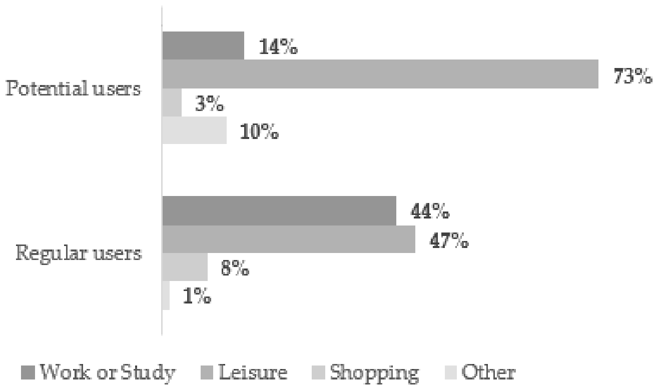

Figure 6 – Main travel purposes according to the two categories of respondents

According to the travel purposes graph, leisure was the most cited reason when analyzing the two categories of respondents. This reason is very high (73%) when analyzing the category "Potential users", followed by work or study (14%), shopping (3%), and other reasons (10%). On the other hand, the reason for leisure was the most cited among the category "Regular users" (47%), being very close to the reason for work or study (44%), which shows that these means of transport (bike and/or kick-scooter) are no longer used just for entertainment. In addition, its use for shopping is still relatively low (8%) but it also represents a growth trend (which meets the main objective of this paper).

Only "Regular users" had to answer what is the current frequency of use, having to answer this question for each of the four purposes of trip (“Work or Study”, “Leisure”, “Shopping” and “Other”), as shown in Figure 7.

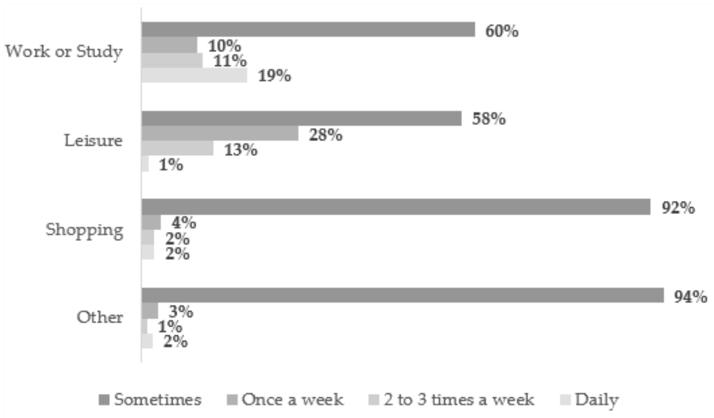

Figure 7 – Frequency of use according to each of the four purposes of trip (Note: applied only to the “Regular users” category)

The graph of the frequency of use according to each of the four purposes of trip shows that the “Regular users” often use active modes only sometimes, regardless of the four purposes of trip. It is worth mentioning that the reason for shopping is still not in use quite often, although a growth trend is expected in times of pandemic (especially in the medium- and long-term).

Some “Yes/No” questions were asked to the two categories to test and validate the research question addressed by this paper (namely, are people willing to transport lightweight goods by bike or kick-scooter?), as follows: (i) Q.1: “Have you ever transported lightweight goods by bike or kick-scooter?”; (ii) Q.2: “Do you usually transport lightweight goods when walking?”; and (iii) Q.3: “Would you transport lightweight goods by bike or kick-scooter if the infrastructure was safe and comfortable?”. The general results of these 3 questions are shown in Figure 8.

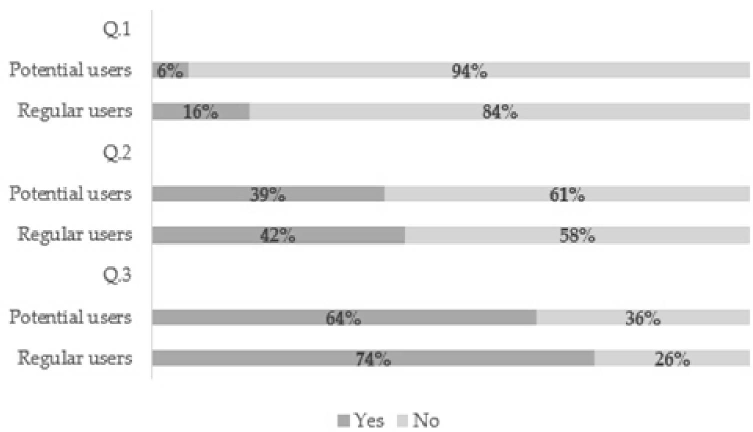

Figure 8 – General results of 3 questions to test and validate the research question

The general results of the 3 questions to test and validate the research question provide interesting results. When asked whether respondents have already transported lightweight goods by bike or kick-scooter (Q.1), both categories of respondents have mostly said "no", representing 94% for the category “Potential users” and 84% for the category “Regular users”. These results show that there is still a lot of work to be done to effectively promote active modes for shopping.

Then, when asked whether respondents usually transport lightweight goods when they walk (Q.2), the two categories of respondents have similar opinions, presenting an increase in the answers "yes" in relation to the previous question (Q.1). That is, 39% for the “Potential users” category and 42% for the “Regular users” category. It is worth mentioning that the figures are quite similar, even considering the “Potential users” (people who are willing but not convinced to ride a bike or a kick-scooter again), but who are willing to carry lightweights when walking.

Finally, when asked whether respondents would go shopping by bike or kick-scooter and transport lightweight goods if the infrastructure was safe and comfortable (Q.3), there was a significant share of the "yes" answer for both categories of respondents, representing 64% for the category “Potential users” and 74% for the category “Regular users”. Even “Potential users” would be willing to ride a bike or kick-scooter again (also for shopping purposes), if they had a safe and comfortable infrastructure, which is not common in cities with low cycling and scooting maturity. These results are in line with the literature review, indicating a high likelihood of changing mobility behavior (especially in times of pandemic). However, the change is conditioned to government interventions, such as the expansion of the cycling and scooting network and the implementation of public e-bike and e-scooter sharing systems.

Overall, the answer to the research question is “yes”, that is, people are willing to transport lightweight goods by bike or kick-scooter. Thus, the government interventions are a game-changer to start a city's progression towards higher levels of cycling and scooting maturity, and to meet the objectives of this paper, to transport lightweight goods by bike and kick-scooter if the infrastructure was safe and comfortable. This is essential, especially if they are implemented in cities with almost no cycling and scooting modal share, such as the case study cities.

To conclude, respondents answered a question to identify barriers for shopping by bike or kick-scooter in cities with low maturity for cycling and scooting. The main barrier declared by respondents was the volume or cargo itself. Other perceived barriers were: cycling or scooting in the traffic, living too far, motorists do not respect, not own a bike or kick-scooter, slope, arrive sweat, no safe route, no cycling or scooting network, taking more time, theft when parked outside, too hot or rainy, afraid of having an accident, do not ride for years, like driving a car, too dangerous, afraid of being robbed and physically unable.

6. CONCLUSIONS

This paper contributes to the understanding of the changing mobility behavior and the identification of barriers to go shopping by bike or kick-scooter in cities with low maturity in the use of these modes. In addition, it provides insight to the planning and definition of local policies and actions (hard and soft measures) that can potentially promote a modal shift for cycling and scooting in cities with low share of those modes.

The paper shows that people are willing to transport lightweight goods by bike or kick-scooter as long as the infrastructure is safe and comfortable enough. The main barrier for going shopping by bike or kick-scooter declared by respondents was the volume or cargo itself, while other perceived barriers include: cycling or scooting in the traffic, living too far, motorists do not respect, not own a bike or kick-scooter, etc.

Based on the literature review and the results of the descriptive analysis, the authors suggest additional recommendations to public authorities, with the aim to improve the use of bikes or kick-scooters for shopping purposes (especially in times of the COVID-19 pandemic), such as: (i) producing campaign to encourage car drivers for short shopping trips through active modes, especially bikes and kick-scooters; (ii) reducing distances and barriers for cyclists and kick-scooter users; (iii) fostering short travel policies; (iv) stimulating small- and medium-sized malls; and (v) avoiding planning large malls outside cities.

As a proposal for future studies, the research can be applied in different regions, for comparison purposes. In addition, the use of different machine learning techniques is expected to classify the use of active modes of transport to carry lightweight goods.

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A STATED PREFERENCE SURVEY FOR EVALUATING PEDESTRIANS' EXPECTATIONS ON WALKWAYS

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ABSTRACT

Pedestrian mobility is the oldest form of transport in urban areas. Due to the increase of private vehicles, transport planning has mainly focused on traffic congestion problems, neglecting pedestrian mobility and public transport. Given the current situation of pollution and climate change, walkability is again one of the most important transport modes to achieve urban sustainable mobility in the next future. As reported in the literature, city dwellers are willing to walk to carry out daily activities but complain about the lack of adequate pedestrian infrastructure. For promoting pedestrian mobility, the quality levels of pedestrian paths should be increased. Many researchers suggest methodologies for determining the pedestrian level of service. Among these, some studies consider both path physical characteristics and users' perception about the walkway. Investigating on users' perception represents a good strategy for implementing interventions aimed at increasing the quality of service. In addition to users' perception about the different characteristics of the pedestrian path, it is also necessary to take over the importance that users assign to each aspect.

This work proposes the design of a Stated Preferences survey and the analysis of the preliminary results. A questionnaire was addressed to a sample of 240 pedestrians on a walkway located in the University Campus of Rende (Italy). The aim is recording pedestrians' perception about the characteristics of the path and detecting the choices they would make in a hypothetical scenario. Then, the collected data has been analysed by means of a discrete choice model for assessing the weights assigned by pedestrians to each aspect included in the analysis.

The results have allowed the most relevant pedestrian path aspects for users to be identified. Just on these aspects it is necessary to intervene in order to make pedestrian paths increasingly attractive and to encourage users towards active mobility.

1. INTRODUCTION

Car traffic increasing undermines the quality of life in urban areas. Motorized traffic has grown so much that many important aspects of urban life are inhibited, so that the issue of sustainability has become a fundamental topic.

Promoting walking as an alternative to short trips made by car represents an important strategy to enact sustainability in more densely inhabited areas (Amoroso et al., 2012).

Benefits of increased walking include not only reductions in traffic congestion, air pollution and emissions, but also improvements in public and private health, community relations and positive sense of place, as well as improvements in economic and real estate performance (Hall Ram, 2018a). Walkability can be defined as the extent to which a built environment enables walking (Kelly et al., 2011) and is pedestrian friendly (Gebel et al., 2009; Moura et al., 2017). Some studies emphasize different environmental features that a pedestrian facility has to own, including areas being traversable, compact, safe, as well as the places have to be lively, enhancing sustainable transportation options, and encouraging outdoor exercise and leisure (Forsyth, 2015; Saelens and Handy, 2008; Hall and Ram, 2018b). In this context, it becomes fundamental to investigate on the direct users of the facilities about their perceptions and preferences concerning the service quality characterizing pedestrian environment. The use of pedestrian perceptions to explain the service quality has been less studied (Vallejo-Borda et al., 2020a). The relationship between pedestrian perceptions and service quality is still nascent (Bellizzi et al., 2019; Bivina and Parida, 2019; Jahan et al., 2020; Vallejo-Borda et al., 2020b). These studies are based on the collection of pedestrian perceptions in terms of rating expressed on evaluation scales.

On the other hand, some studies investigate pedestrian perceptions adopting the Stated Preferences (SP) approach, according to which actual or potential users are asked to rate or rank the attractiveness of existing or hypothetical streets (Adkins et al., 2012; Borst et al., 2008; Kaparias et al., 2012; Kelly et al., 2011; Lusk et al., 2018). The importance (utility) of the various service attributes is estimated based on the respondents' preferences. As an example, some of these studies found that wider sidewalks are generally preferred (Kim et al., 2011; Talavera-Garcia and Soria-Lara, 2015) and lateral separation from traffic increase streets' attractiveness (Adkins et al., 2012). The presence of trees is appreciated (Lusk et al., 2018; Talavera-Garcia and Soria-Lara, 2015). The existing literature confirms that the SP method is suitable for analysing pedestrian perceptions. SP scenarios are typically presented in text format showing attributes and their levels, but sometimes photos or videos are adopted (Kasrain et al., 2020).

This paper wants to provide a contribute in the literature of the studies proposing SP experiments for investigating on pedestrian preferences. For facilitating the users in expressing their opinions, we adopted also photos representing the characteristics of the alternative pedestrian environments proposed to the users to make a choice. After a deep study of the literature review, we selected four attributes to introduce in the SP experiment: width of the pedestrian path; pavement of the pedestrian path; equipment present along the pedestrian path; environment where the pedestrian path develops. Interesting findings emerge from the observations of the choice of the various alternatives made by the users. In order to synthetize the findings emerged from the analysis of the preferences expressed by the users, a Multinomial Logit (MNL) model was calibrated.

We found that the environment where the pedestrian path develops is the most important aspects for the users.

The rest of the paper is organized as follows: section 2 explains the design of the SP survey; section 3 describes the methodology and includes the data analysis and the calibration of the MNL model; in the last section the results are discussed and some final remarks are presented.

2. STATED PREFERENCE SURVEY DESIGN

The Stated-Preferences approach is a particular type of survey where two or more hypothetical scenarios are proposed to the interviewee. The interviewee is asked to choose the scenario they prefer most or to rank the scenarios according to their personal level of preference.

The SP survey planned in this work was referred to the detection of the perceived degree of comfort of a pedestrian path. The comfort attributes of a pedestrian path are countless. From the analysis of the literature, four most recurrent attributes have been identified:

- width of the pedestrian path;
- pavement of the pedestrian path;
- equipment present along the pedestrian path;
- environment where the pedestrian path develops.

Each attribute (or variable) varies on two levels or categories. Specifically, the categories relating to the width attribute are narrow path (pedestrians only) and wide path (interference with bicycles, scooters, hoverboards, authorized vehicles). The pavement can be traditional (asphalt, concrete, dirt path) or specific for pedestrian paths (coloured asphalt, rubber, beaten and/or stabilized ground). Along the route there may be more or less equipment, distinguishing between a poorly equipped path (lighting, baskets, benches) or an equipped path (lighting, waste baskets, benches and/or seats, beverage and food distributors, Wi-Fi and charging stations, protection from atmospheric agents).

The environment can be unpleasant (dirt, untreated green spaces, dilapidated building facades, scarce presence of commercial activities) or pleasant (clean, well-kept green spaces, decent building facades, presence of commercial activities).

After establishing the levels of each attribute, hypothetical scenarios were constructed. A scenario is given by a set of level attribute combinations. When all possible scenarios are considered, the survey project takes the name of Full Factorial Design. Specifically, we have considered 4 attributes at 2 levels, for which the Full Factorial Plan consists of 16 scenarios (2^4).
Often the Full Factorial Plan is too numerous or presents irrelevant scenarios, so a reduction in the total number of scenarios is implemented.

The Fractional Factorial Plan is a plan reduced through appropriate exclusions of scenarios in order to lose the least possible amount of information (variance explained) considering only the main effects of the attributes and neglecting some or all interactions. In our case, four scenarios have been eliminated, which correspond to cases in which we have traditional flooring and an equipped path. In fact, an equipped path is not compatible with an ordinary sidewalk with poor quality pavement. In total, twelve scenarios were included in the survey (Table 1).

Once the scenarios have been defined it is necessary to combine them in order to identify the set of choices. The scenarios were combined in pairs, obtaining 64 sets of choices. In this work, a set of choices has been named “card”.

Two combinations were discarded as one scenario was clearly better than the other, in order to avoid too expectable choices.

Scenario		Width	Pavement	Equipment	Environment
1	a	narrow	traditional	poorly equipped	pleasant
2	b	narrow	traditional	poorly equipped	unpleasant
5	c	narrow	specific	poorly equipped	pleasant
6	d	narrow	specific	poorly equipped	unpleasant
7	e	narrow	specific	equipped	pleasant
8	f	narrow	specific	equipped	unpleasant
9	g	wide	traditional	poorly equipped	pleasant
10	h	wide	traditional	poorly equipped	unpleasant
13	i	wide	specific	poorly equipped	pleasant
14	l	wide	specific	poorly equipped	unpleasant
15	m	wide	specific	equipped	pleasant
16	n	wide	specific	equipped	unpleasant

Table 1 – Fractional Factorial Plan

The interviewee had to administer a block consisting of 8 cards. For each card the interviewee was asked to choose one of the two scenarios. The interviewee's task was facilitated by the inclusion of images relating to the different categories of the attributes considered in the survey form (Figure 1).

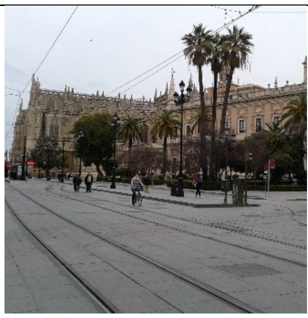
Which of these alternatives would you choose?			
A ☐		B ☐	
Width **Narrow path** (pedestrians only)		Width **Wide path** (interference with bicycles, scooters, hoverboards, authorized vehicles)	
Pavement **Specific for pedestrian paths** (coloured asphalt, rubber, beaten and/or stabilized ground)		Pavement **Traditional** (asphalt, concrete, dirt path)	
Equipment **Poorly equipped path** (lighting, waste baskets, benches)		Equipment **Poorly equipped path** (lighting, waste baskets, benches)	
Environment **Unpleasant** (dirt, untreated green spaces, dilapidated building facades, scarce presence of commercial activities)		Environment **Pleasant** (clean, well-kept green spaces, decent building facades, presence of commercial activities)	

Fig. 1 – Example of card

3. METHODOLOGY

3.1 Data analysis

The survey was carried out in November and December 2019 by interviewing a sample of 240 people along a pedestrian path located in the University Campus of Rende (Italy). The sample is divided almost equally between males (51%) and females (49%). As the survey was carried out on the University campus, most of the interviewees are students (99%) aged 25 or under.
The SP survey made up of 64 cards was divided into 8 blocks each containing 8 cards.

Each pedestrian interviewed answered only one block, so for each block we collected the answers of 30 respondents.

From the preliminary analysis of the data collected, it emerged that for each pair of scenarios where the possibility of choosing between pleasant and unpleasant environment appears, most of the pedestrians have chosen the scenario characterized by pleasant environment. As can be seen from the two bar diagrams in Figure 2, there are few (or even zero for card *ab*) pedestrians who, other things being equal, choose a path with an unpleasant environment.

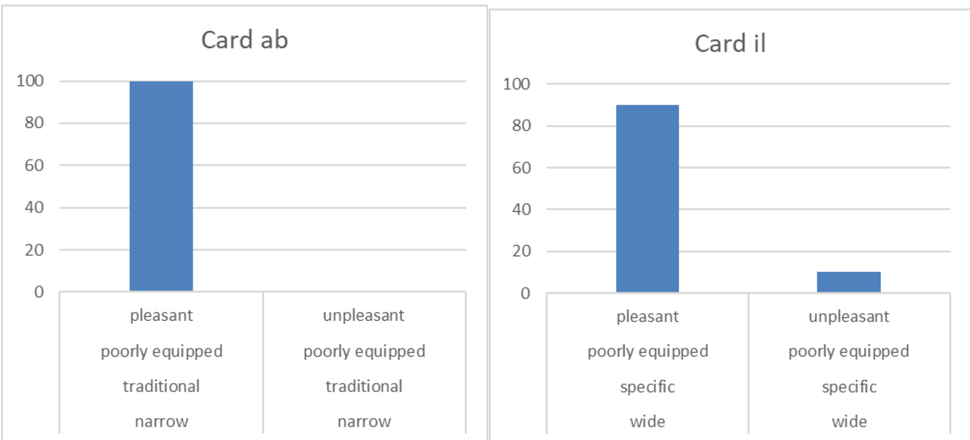


Fig. 2 – SP results: difference between pleasant and unpleasant environment

When comparing scenarios that also have other attributes that may vary in addition to the environment, most users continue to choose scenarios where the environment is pleasant.
For example, observing the card *ad* in Figure 3, it can be seen that the scenario with a pleasant environment and traditional pavement is chosen by 77% of pedestrians, while that with an unpleasant environment and specific pavement only by 23%. In the *af* card, the scenario with a pleasant environment, traditional flooring and poorly equipped path is chosen by 83% of the interviewees, while the scenario with specific flooring, equipped path and unpleasant environment is chosen only by the remaining 17%.

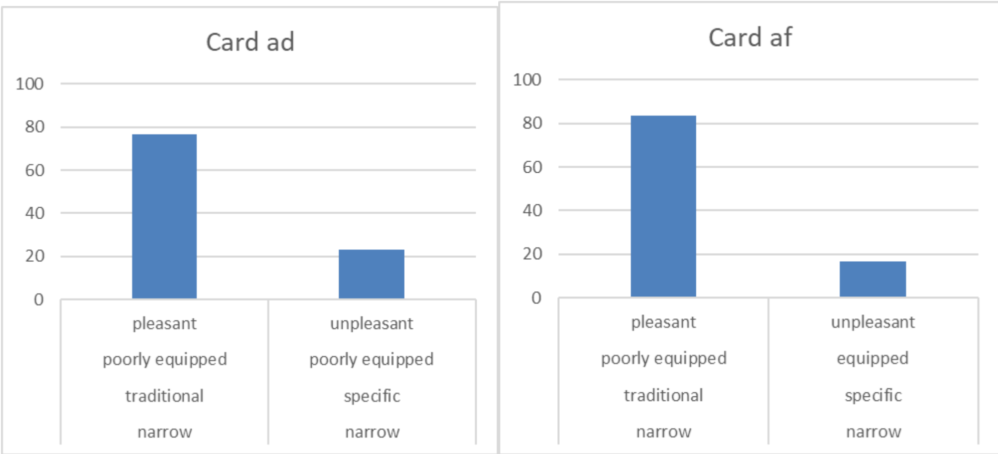


Fig. 3 – SP results: difference between pleasant and unpleasant environment in relation to other attributes

For the cards where two scenarios with the same characteristics are compared, except the pavement, the one preferred by most of the interviewed pedestrians is the scenario with specific pavement. For example, in card *ac* and card *gi* (Figure 4) the scenario with specific pavement was chosen by almost 80% of the interviewed pedestrians. The scenario with specific pavement is the most chosen one even when other attributes such as equipment and width are considered. For example, in Figure 5, in card *ai* the most chosen scenario is that with specific pavement (73%), even if the scenarios are different regarding the width. When the two scenarios differ also in terms of environment, as well as pavement, the most chosen scenario is always the one that presents the pleasant ambient alternative, regardless of the pavement. For example, in card *gl* in Figure 5, the most chosen scenario is the one in which there is traditional pavement and a pleasant environment (93%).

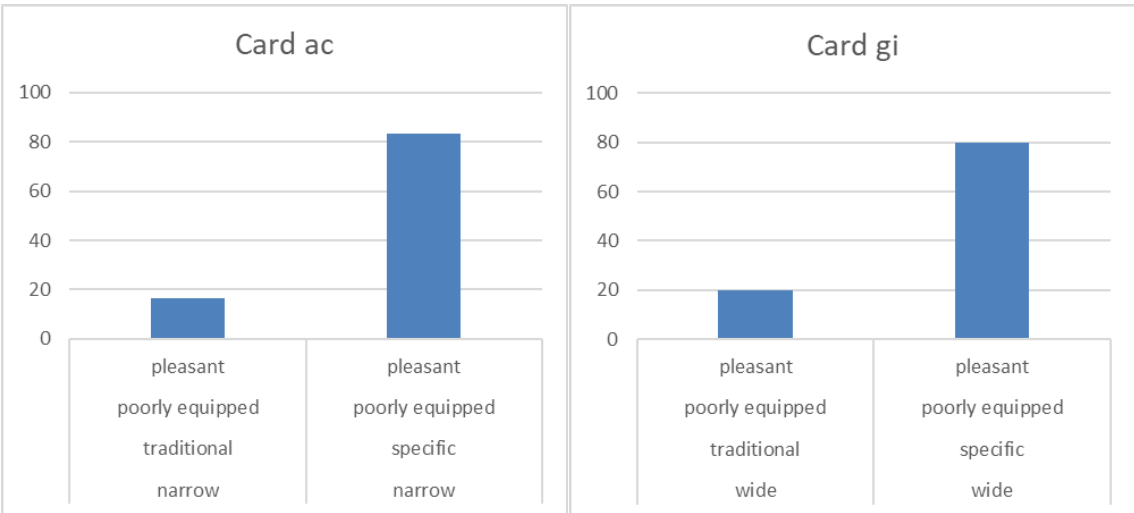


Fig. 4 – SP results: difference between traditional and specific pavement

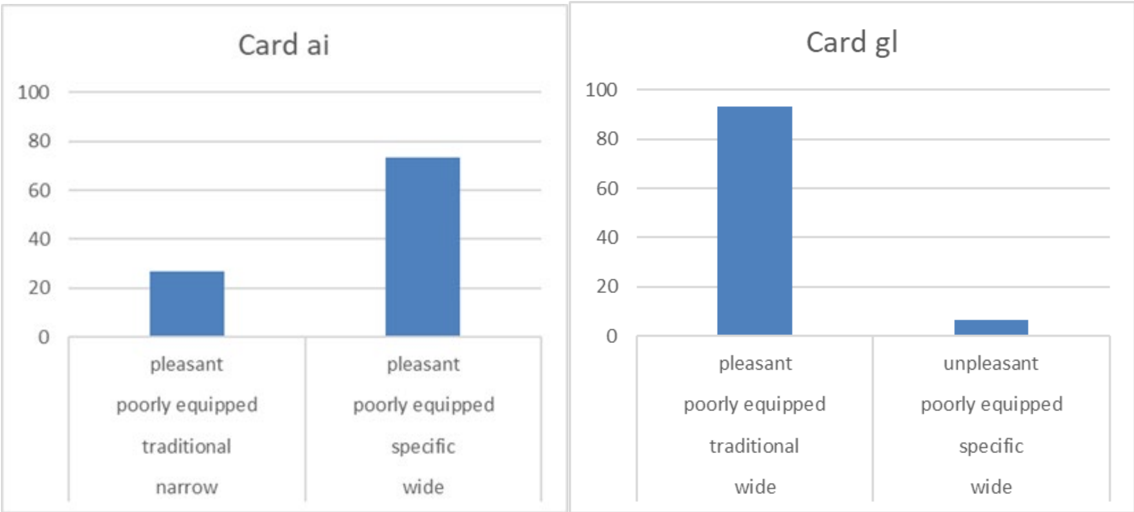


Fig. 5 – SP results: difference between traditional and specific pavement in relation to other attributes

By comparing scenarios with the same characteristics but different equipment (card *ce* in Figure 6), the equipped path is the one chosen by most of the interviewees (about 83%). The equipped path continues to be the most chosen one (80% of the respondents) when the environment is pleasant and when the pavement is specific, as reported in card *gm* (Figure 6). As can be seen from the graphs shown in Figure 7, the width of the path does not seem relevant with respect to the equipment attribute.

The width attribute is the one with the most variability. From the analysis of the results of the survey, it is clear that for some pairs of scenarios the most chosen scenario is the one with the wide path (card *ci* in Figure 8), for others the narrow path (card *ag* in Figure 8).

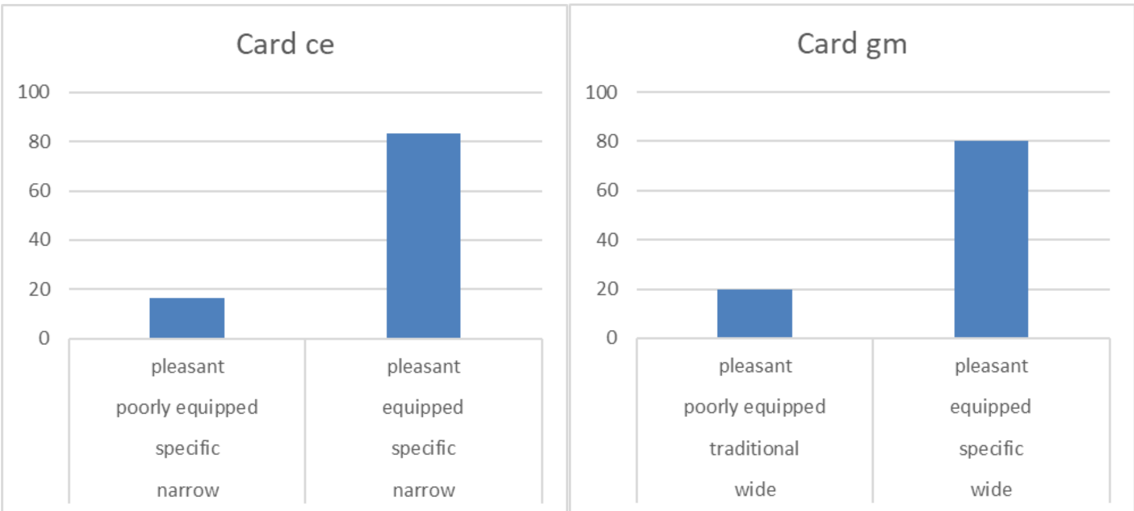


Fig. 6 – SP results: difference between poorly equipped and equipped path

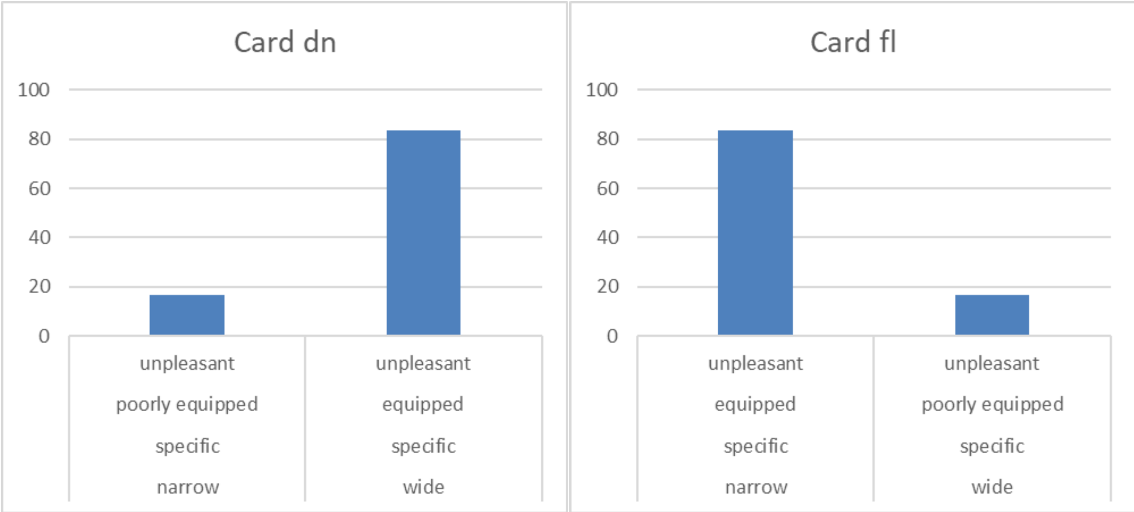


Fig. 7 – SP results: difference between poorly equipped and equipped paths in relation to other attributes

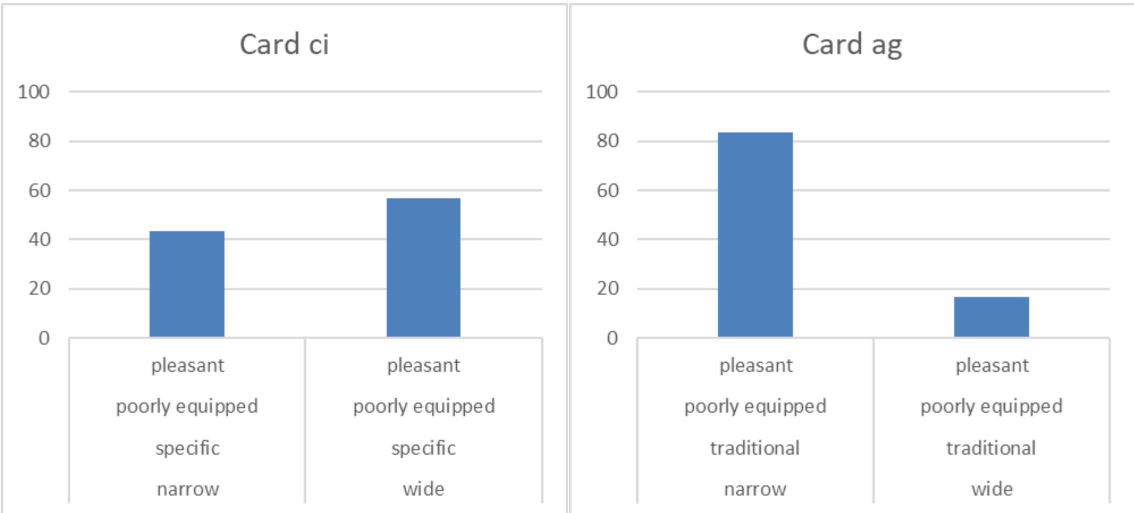


Fig. 8 – SP results: difference between narrow and wide path

Looking at the results related to the cards, where also other attributes vary, the width attribute seems to be the least relevant and the choice of scenario seems to be guided by the other variables.

From this preliminary statistical analysis, the environment where the walkway is located seems to be the most important aspect of evaluation for pedestrians.

3.2 Multinomial Logit model

A Multinomial Logit model (MNL) was calibrated for deriving the importance of each attribute in the pedestrians' evaluation. The four attributes (width, pavement, equipment and environment) were included in the model elaborated through NLogit software (Greene, 2016).

The results are reported in Table 2. The coefficients have the correct sign. Only the variable “width” is not statistically significant. The other three variables have a high statistical significance.

Variable	Standard coefficient		Error	z	Prob. |z|<Z*	Confidence interval	
Width	0.02365		0.07200	0.33	0.7425	-0.11747	0.16477
Pavement	0.60991	***	0.09706	6.28	0.000	0.41967	0.80015
Equipment	0.49662	***	0.09064	5.48	0.000	0.31897	0.67428
Environment	1.93261	***	0.09334	20.71	0.000	1.74968	2.11554
***, **, * ==> Significance at 1%, 5%, 10% level							

Table 2 – MNL output

The results of the model seem to confirm what was observed in the statistical analysis of the data. “Environment” is the variable with the highest coefficient. This means that, in this study, the environment of the walkway is the most important attribute for the pedestrians. “Pavement” and “equipment” variables are also relevant but the coefficients are lower.
In particular, the coefficient of “pavement” is higher than that of “equipment”. Even this result goes to confirm what observed analyzing the data. The variable “width” is not significant. This means that in this study the width of the path is not an important element in the pedestrians’ evaluation.

4. DISCUSSION AND CONCLUSIONS

The proposed analysis provides important points for discussion. “Environment” is the variable that most strongly affects the scenario selection in the set of choices. Among the variables included in the model, the environment can be considered as the most important aspect for pedestrians. This result is also amply confirmed by other studies in the literature (Motamed and Bitaraf, 2016; Vallejo-Borda et al., 2020b). In particular, “environment” is one of the most relevant attribute especially when its definition includes also the concept of security (Bivina and Parida, 2019).

The results also show that type of pavement has less importance than environment, but it still relevant in the evaluation of quality. In the literature, the pavement as structural element is poorly treated. Many studies consider the condition of the pavement in general as variable (Asadi-Shekari et al., 2013; Moura et al., 2017; Banerjee et al., 2018).

The variables that refer to the equipment along the walkway are often present in studies on the quality of pedestrian paths. As reported by Sarkar (2003), the presence of good furniture improves pedestrian comfort.

In the present study, the variable “width” does not result statistically significant. This means that having a more or less wide path does not influence the pedestrian’s evaluation. In other studies, instead, width is a significant variable (Kim et al. 2011; Talavera-Garcia and Soria-Lara, 2016). Streets with more lanes and streets where automobiles and bicycles are mixed have higher pedestrian numbers than pedestrian-only streets (Sung et al., 2015).

Regarding the methodology, the SP experiment seems to be suitable for simulating the pedestrians’ expectations on walkways. Considering hypothetical scenarios, respondents are faced with an unknown situation, so that their answers are not influenced by habit and knowledge of the path. In addition, the choice of including images representative of the different levels of the variables contributed to reducing any errors in understanding the question.

Ultimately, the results give indications regarding territorial and transport policies to be pursued in future years for increasing pedestrian mobility. Environment where the pedestrian path is inserted is the aspect needing more attention. It is clear that pedestrians prefer to walk in a pleasant and clean environment, with well-kept green spaces, decent building facades, presence of commercial activities. The objective has to avoid the production of an unpleasant environment, characterized by dirt, untreated green spaces, dilapidated building facades, lack of commercial activities.

The analysis provided satisfactory results, and in future studies it will be possible to continue to increase the proposed methodology. Other aspects could be included in the survey. As an example, an attribute relating to the presence of trees along the walkway could be inserted among the physical characteristics of the path. In fact, it was observed that pedestrians like to walk along tree-lined paths because the trees offer protection from the sun’s rays and heat.

Another potential important aspect could be the presence of restaurant and bar activities.

Other studies, in fact, have shown that the presence of these activities makes the walkway more pleasant for the pedestrian.

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BIG DATA EN EL TRANSPORTE
BIG DATA ON TRANSPORT

A PYTHON PACKAGE FOR PERFORMING PENALIZED MAXIMUM LIKELIHOOD ESTIMATION OF CONDITIONAL LOGIT MODELS USING KERNEL LOGISTIC REGRESSION

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ABSTRACT

In the last few years, Machine Learning (ML) methods have acquired great popularity due to their success in numerous applications such as autonomous cars, image and voice recognition systems, automatic translation systems, etc. This success has led to an increase in the use of ML methods and the extension of their applications to areas such as transport planning.

One of the main tasks within transport planning is the analysis of transport demand. To do so, it is necessary to analyse the way in which users make their decisions about the trips they make and, therefore, be able to predict the number of passengers on the transport network in relation to respect to interventions made on the transport system. Consequently, transport policies and plans can be evaluated according to the behaviour of the passengers. Discrete choice models based on random utility maximization have been developed over the last four decades and currently they have acquired a high degree of sophistication, becoming the canonical tool for transport demand analysis. Nowadays, the use of ML methods could provide an alternative to discrete choice models, as they offer a high level of accuracy in their predictions. In addition, the analyst is relieved from the need of specifying the functional expressions for the utility functions beforehand.

A Python software package called PyKernelLogit was developed to apply a ML method called Kernel Logistic Regression (KLR) to the problem of predicting the transport demand. This package allows the user to specify a set of models using KLR and the estimation of those using a Penalized Maximum Likelihood Estimation procedure. Moreover, this tool also provides a set of indicators for goodness of fit and the application of model validation techniques. Finally, it allows to obtain the willingness to pay or value of time indicators commonly used in transport planning.

1. INTRODUCTION

The efficiency and reliability of any public transport system depends on the design, management and operation of its infrastructure. These factors have a direct impact on the economic activity of the population, on their fidelity, as well as on the environment (such as pollution). There are two main strategies for improving a public transport system. On the one hand, the reliability of the infrastructure and its operations has to be improved. On the other hand, it is necessary to define an offer of transport services which is oriented to its potential demand. To achieve the second objective, it is crucial to analyse the transport demand, i.e. it is necessary to analyse the way in which passengers choose their mode of transport and thus predict the number of passengers in the transport network. Therefore, policies and plans can be established and evaluated according to the needs of the passengers.

Traditionally, process-driven models are used to predict passenger behaviour. Discrete choice models based on random utility theory describe how a rational-decision maker chooses an alternative within a set of options depending on the characteristics of each of them and the specific peculiarities of each decision-maker. The choice process involves some latent (unobservable) functions known as *utility functions*, which measure the interest of each alternative for a decision-maker. Random utility theory supposes that any decision-maker would choose the alternative that maximizes his or her utility. The utility associated with each alternative is composed of two parts: A deterministic part (also called the *systematic part*) which depends on the attribute vector of the alternative; and a *stochastic part*, whose probability distribution determines the resulting model. The Multinomial Logit (MNL) model is the most widespread example and assumes an extreme value Gumbel distribution. These models are generally estimated using a Maximum Likelihood Estimation (MLE) methodology that allows an asymptotic distribution of the estimators to be determined and to test assumptions about the value of the parameters.

The continuous technological evolution has allowed the development of new intelligent systems and Internet of Things (IoT) devices which automatically gather information about passengers on the transport system. Consequently, the amount of information used by these models has significantly increased, and the models are becoming more complex. For this reason, there is a need for new alternatives that complement the classical demand modelling methods, which are based on Random Utility Models (RUM). In this context of massive data acquisition, new models are needed, such as data-driven models. These models build relationships between input and output data, without worrying too much about the underlying processes, using statistical and Machine Learning (ML) techniques.

In the last years, the transport community has been evaluating new proposals to predict the passenger behaviour which are based on ML. Preliminary studies have revealed a significantly higher predictive performance of ML methods, which encourages further research. In ML, the *radial basis function kernel*, or RBF kernel, is a popular kernel function used in various kernel-based machine learning algorithms, such as support vector machine (SVM) classification. The combination of MNL models with radial basis functions is known in the ML community as Kernel Logistic Regression (KLR) (Zhu & Hastie, 2005). Martín-Baos et al. (2021) propose to use the KLR method as a way to specify non-parametric utilities in RUM. In KLR the parameter estimation problem is based on a Penalized Maximum Likelihood Estimation (PMLE) in which the goodness of fit criterion balances empirical risk and complexity. The main advantage of the KLR method over the RUM is that it does not require the modeler to specify a functional expression of the utilities in advance, being enough to choose certain hyperparameters such as the kernel function.

At the present moment, there are several packages for different programming languages which allows to estimate a wide variety of RUM models, such as logit models. Nonetheless, these packages do not allow to estimate discrete choice models based on KLR. In this work a Python package for estimating discrete choice models based on RUM and KLR is described. In order to avoid re-codifying functions that already exist in other software packages, it has been decided to take as a baseline a current open source package for estimating a wide variety of RUM models and to use it as a basis for aggregating the KLR models. Furthermore, it is sought to implement in this library some functions to estimate some indicators such as the Willingness to Pay or the Value of Time. The developed software package has been called PyKernelLogit.

2. RELATED WORKS

Discrete choice models based on Random Utility Theory have dominated travel behaviour research during the last decades (M. Ben-Akiva & Bierlaire, 1999; M. E. Ben-Akiva et al., 1985; McFadden, 1978; Train, 2003). For this reason, during the last years, a large number of software packages have emerged to estimate this type of discrete choice of models. These tools are usually based on the estimation of logit models and their variants, such as Nested Logit models and more recently Mixed Logit Models, among others. The following lines describe the most popular software packages which are currently available for practitioners.

2.1. Biogeme

Biogeme (Bierlaire, 2020) is an open source multi-platform package which is specially designed to estimate discrete choice models. Nonetheless, it can also be used for the estimation of general parametric models using the maximum likelihood procedure. Biogeme has been developed by Michel Bierlaire, which is a professor in the Transportation and Mobility Laboratory at the Ecole Polytechnique Fédérale de Lausanne, Switzerland.

The last version of the Biogeme package, which is called PandasBiogeme, was released in the year 2018. This version was coded mainly in Python 3 and relies on the Pandas Data Analysis Library for data management. The most compute-intensive software parts were coded in C++, for the sake of efficiency. This package can be easily installed using the Python Package Index (PIP) package manager.

Biogeme allows to define the utility functions using traditional mathematical operations which makes the utility specification very straightforward. It also uses a dictionary to describe the availability conditions of each alternative, i.e. supports datasets where the choice set may vary across observations. Biogeme supports a wide range of choice models, which are listed in Table 1. Biogeme also allows to calculate some economic indicators which are relevant in the context of discrete choice models, such as willingness to pay, value of time, market shares, revenues, and elasticities using a simulation technique which is called *stratified random sampling*. Finally, this package also allows to estimate models with latent variables, i.e. variables that are not directly observed but can be inferred from other observed variables.

2.2. PyLogit

PyLogit (Brathwaite & Walker, 2018) is a Python package intended to be used for performing maximum likelihood estimation of conditional logit models and other similar discrete choice models. This package can be installed using the PIP or Anaconda python package managers and the source codes are available in a GitHub repository.

PyLogit takes as input a long format dataset, which is composed of one row per individual per available alternative. The main advantage of the long format dataset is that it allows to calculate the utility functions $V_{ij} = x_{ij}\beta_i$ directly using a matrix dot product. PyLogit also supports different choice sets per individuals and model specifications admit alternative specific attributes, subset specific attributes or generic attributes.

An important difference between PyLogit and other packages, such as PythonBiogeme or mlogit, is the need to pre-calculate all variables to be used in the model. In other words, PyLogit does not perform variable creation, it only focuses on the model estimation using previously pre-computed variables. Hence, the user must define all the variables to be used in the model before executing the estimation procedure. Once the variables have been defined, the model can be specified and estimated. The specification of the utility functions is less intuitive than in PandasBiogeme because they are defined using a list for each variable indicating the alternatives which are affected by that variable. PyLogit also supports a wide range of choice models which are listed in Table 1.

2.3. ChoiceModels

ChoiceModels (Urban Data Science Toolkit, n.d.) is a Python package used for discrete choice modeling, as part of the Urban Data Science Toolkit, an open source portfolio developed and maintained by Berkeley Urban Analytics Lab.

This library integrates several open source packages such as PyLogit. ChoiceModels is a kind of wrapper that allows to manage in an easy way the data before applying the choice model. In addition, this package also provides a tool for Monte Carlo simulation of choices given the probability distributions from fitted models. However, its main limitation is that it only integrates Multinomial Logit Models, losing the other powerful models which are provided by PyLogit.

2.4. mlogit

mlogit (Croissant, 2019) is a R package which allows to estimate random utility discrete choice models using maximum likelihood procedure. The package can be installed directly in R from the CRAN package repository.

In mlogit the utility functions are written using an extended model of the R *Formula* package, which allows to write these expressions using a notation which is similar to the one used in ChoiceModels with Patsy, making it very intuitive. It allows to define alternative specific variables with specific and generic coefficients and individual specific variables on the utility function. Nevertheless, one of the major limitations of this package is that it does not integrate support for varying choice sets over individuals.

2.5. Other alternatives

There are also other alternatives for discrete choice modeling. However, they have not been analysed in detail because they are not open source, free to use or widely popular between practitioners. Kenneth E. Train personal webpage contains several Matlab, R and Gauss codes for estimating Mixed Logit models. It should be highlighted the software piece called *Mixed Logit Estimation by Hierarchical Bayes* which was coded in Matlab to elaborate Chapter 12 of Train (2003). Finally, there are also some proprietary and commercial packages which can be used for discrete choice model estimation problems, such as nlogit, Stata, SPSS, etc.

2.6. Comparative of the different packages

To summarise the different software packages, Table 1 compares the discrete choice models which can be estimated by each of the different software packages and Table 2 summarises the key features of each alternative.

Supported models \ Package	Biogeme	PyLogit	ChoiceModels	mlogit
Multinomial Logit	✓	✓	✓	✓
Probit	✓ (only binary)	✗	✗	✓
Nested Logit	✓	✓	✗	✓
Cross-Nested Logit	✓	✗	✗	✗
Multivariate Extreme Value	✓	✗	✗	✗
Models with nonlinear utility functions	✓	✗	✗	✗
Models designed for panel data	✓	✗	✗	✗
Heteroscedastic models	✓	✗	✗	✗
Multinomial Clog-log	✗	✓	✗	✗
Multinomial Scobit	✗	✓	✗	✗
Multinomial Uneven Logit	✗	✓	✗	✗
Multinomial Asymmetric Logit	✗	✓	✗	✗
Mixed Logit	✓	✓	✗	✗

Table 1 – Discrete choice models that can be estimated by each package

Package	Programming Language	Active?	Open Source?	Data preprocessing	Different choice sets per individual?	Allows to calculate Indicators?
Biogeme	Python 3 (implemented in C++)	Yes	Yes, but unknown license	Yes, using Pandas package and internal methods	Yes	Yes, willingness to pay, value of time, market shares, revenues, and elasticities
PyLogit	Python 2 and Python 3	Yes	Yes, BSD-3-Clause license	Yes, using Pandas package. Datasets must be converted to long format.	Yes	No
ChoiceModels	Python 2 and Python 3	Yes	Yes, BSD-3-Clause license	Yes, using Pandas package	Yes (only with PyLogit equation format)	No
mlogit	R	Yes	Yes, GPLv2	Yes, datasets must be converted to long format.	No	No

Table 2 – Comparative of the discrete choice model packages

3. PYKERNELLOGIT PACKAGE

The PyLogit package provides a good set of characteristics, integrates a variety of discrete models and its source code are available with an open-source license, therefore, it has been decided to extend this package to incorporate KLR models, which has led to the creation of the PyKernelLogit Python package. Figure 1 summarizes the main functionalities and dataflow necessary to estimate MNL and KLR models on PyKernelLogit. All the necessary functionalities for the estimation of KLR models have been integrated over the previously existing functionalities of PyLogit for the estimation of MNL models. In the following lines, the functionalities involved in the specification and estimation of a KLR model are described.

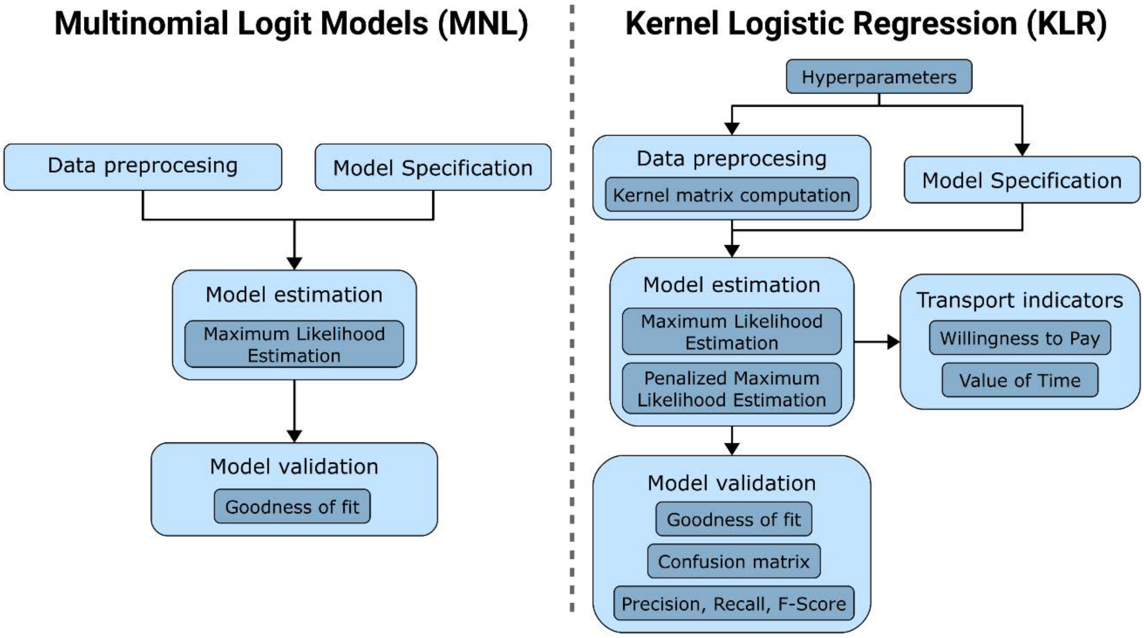

Fig. 1 – Comparison of MNL and KLR models on PyKernelLogit

3.1. Specification of the Kernel Logistic Regression Model

The KLR model builds some *latent functions*, $V_i(\mathbf{x})$ for all the alternatives i in the choice set C, which are equivalent to the systematic part of the utility functions in RUM, but in KLR they are considered as black box functions. The main problem is to find for each alternative i, its latent function $V_i : \boldsymbol{X} \mapsto \mathbf{R}$. KLR search for functions $V_i(\mathbf{x})$ within function spaces which are named *Reproducing Kernel Hilbert Spaces* (RKHS). The RKHS space is a vector space which is univocally generated by the so-called *kernel function* $k(\mathbf{x}, \mathbf{x}')$, and its associated RKHS space is denoted by $\mathcal{H}_k$. The family of functions $\{k(\mathbf{x}, \mathbf{x}')\}_{x' \in \mathcal{X}}$ constitutes a basis of the vector space. Any element from $\mathcal{H}_k$ can be represented as a linear combination of the basis elements, in particular, from $V_i(\mathbf{x}) \in \mathcal{H}_k$, the expression of the utilities is given by

$$V_i(\mathbf{x}, \alpha_i) = \sum_{n=1}^{N} \alpha_{in} k_i(\mathbf{x}_n, \mathbf{x}) \qquad (1)$$

KLR provides estimates of the class probabilities based on these utility functions $V_i(\mathbf{x})$

$$P(i|V, C) = \frac{\exp(V_i(x))}{1+\sum_{i=1}^{I-1} \exp(V_i(x))}. \qquad (2)$$

It should be noted in Eq. (1) that the non-parametric utilities defined by the KLR model are linear in their parameters. In the MNL models the deterministic part of the utility V_{in} can be defined using the linear function $V_i(x_{in}, \beta_i) = \beta_i^T x_{in}$. Therefore, the methods defined in PyLogit to estimate a MNL model can be also used to estimate the KLR model, but the vector $\mathbf{x}$ should be substituted by the kernel function $k(\mathbf{x}, \mathbf{x}')$.

Hence, instead of estimating the $\boldsymbol{\beta}$ vector of parameters, the program is going to estimate $\boldsymbol{\alpha}$. But first, it is necessary to pre-compute the Gram matrix (or kernel matrix) $\mathbf{K}^{(\mathrm{i})}$, which is defined as

$$\mathbf{K}^{(\mathrm{i})}_{\mathrm{n}',\mathrm{n}} = \mathrm{k_i}(\mathbf{x}_{\mathrm{in}'}, \mathbf{x}_{\mathrm{in}}). \tag{3}$$

Intuitively, the Kernel matrix represents how similar is the decision-maker n' with respect to the decision-maker n for the alternative i. PyKernelLogit allows to compute the kernel matrix for any input dataset. The software package allows to specify many different types of kernel functions, such as the Radial-basis function, the Rational Quadratic kernel, the Matern Kernel, etc. It also allows to specify compound kernels, which are kernel functions composed of a set of other kernels. Figure 2 shows a sample kernel matrix computed using a Radial-basis function for a dataset with 453 observations. PyKernelLogit provides the possibility to specify a reference dataset $\mathbf{Z}$ to be used when computing the kernel matrix. If no reference matrix is provided, then the kernel matrix would be a square matrix which contains the similarity between any two observations from the dataset. Nevertheless, as this approach is computationally heavy, sometimes it is required to use a resampling method to select a subset of the observations as the reference matrix $\mathbf{Z}$ or to generate this reference matrix artificially, for example using a grid over the domain of the data. If $\mathbf{Z}$ is specified, then Eq. (3) becomes

$$\mathbf{K}^{(\mathrm{i})}_{\mathrm{n}',\mathrm{n}} = \mathrm{k_i}(\mathbf{z}_{\mathrm{in}'}, \mathbf{x}_{\mathrm{in}}). \tag{4}$$

	K_i_1	K_i_2	K_i_3	K_i_4	K_i_5	...	K_i_449	K_i_450	K_i_451	K_i_452	K_i_453
0	1.000000	0.859819	0.884954	0.993861	0.976290	...	0.757557	0.929142	0.980138	0.673098	0.725472
1	0.859819	1.000000	0.992509	0.888991	0.862176	...	0.969062	0.985683	0.929744	0.893956	0.927796
2	0.884954	0.992509	1.000000	0.902722	0.904262	...	0.933217	0.986216	0.954549	0.837235	0.878386
3	0.993861	0.888991	0.902722	1.000000	0.956273	...	0.805321	0.951511	0.979215	0.732930	0.782034
4	0.976290	0.862176	0.904262	0.956273	1.000000	...	0.736968	0.918418	0.984070	0.626018	0.681269
...	...	...	...	...	...	...	...	...	...	...	...
448	0.757557	0.969062	0.933217	0.805321	0.736968	...	1.000000	0.932803	0.831198	0.972509	0.986445
449	0.929142	0.985683	0.986216	0.951511	0.918418	...	0.932803	1.000000	0.972541	0.856337	0.897445
450	0.980138	0.929744	0.954549	0.979215	0.984070	...	0.831198	0.972541	1.000000	0.732485	0.784137
451	0.673098	0.893956	0.837235	0.732930	0.626018	...	0.972509	0.856337	0.732485	1.000000	0.995798
452	0.725472	0.927796	0.878386	0.782034	0.681269	...	0.986445	0.897445	0.784137	0.995798	1.000000

Fig. 2 – Kernel matrix $\mathbf{K}^{(\mathrm{i})}$

Once the kernel matrix has been created, PyKernelLogit allows to automatically define the kernel model specification, which was presented in Eq. (1), using the PyLogit syntax.

The user can select in the model specification if the same vector of parameters to estimate $\boldsymbol{\alpha}$ is going to be used for all the alternatives or, otherwise, if one vector of parameters $\boldsymbol{\alpha}_i$ is going to be used for each alternative i. Once the model has been specified, the choice model can be created an estimated.

3.2. Estimation of the Kernel Logistic Regression Model

PyKernelLogit extends the estimation capabilities of PyLogit by implementing a Penalised Maximum Likelihood Estimation (PMLE) procedure. In order to estimate the KLR model the following optimization problem must be solved

$$\underset{\boldsymbol{\alpha}}{\text{Minimize}} \sum_{n=1}^{N} \sum_{i=1}^{I} L\big(y_{in}, V_i(\mathbf{x}_{in}, \boldsymbol{\alpha}_i)\big) + \lambda \sum_{i=1}^{I} R_i(\boldsymbol{\alpha}_i) \quad (5)$$

where L(·) is a loss function that measures the discrepancies between the observed and the predicted classifications and λ is a regularization parameter in charge of controlling the trade-off between the goodness of fit and the complexity of the model. Finally, $R_i(\cdot)$ is the penalty function of the α_i parameters. PyKernelLogit integrates two of the most relevant penalty functions $R_i(\cdot)$ proposed in the literature, which are the LASSO and the Ridge regression (Castro, 2013).

The estimation of the KLR model is computationally heavy if the number of observations is high enough (Ouyed & Allili, 2018; Zhu & Hastie, 2005). The implementation of the PMLE procedure reduces significantly the estimation time. Nevertheless, PyKernelLogit allows to use different optimisation algorithms, so it has been tested the use of tree canonical methods for solving the PMLE problem defined in Eq. (5). The selected methods are:

- Newton-CG. This method, also known as the truncated Newton method, uses the nonlinear conjugate gradient algorithm by Polak and Ribiere to compute the search direction (Nocedal & Wright, 2006). This method is suitable for large-scale problems.
- BFGS. This method uses the quasi-Newton method of Broyden, Fletcher, Goldfarb, and Shanno (Nocedal & Wright, 2006). It uses the first derivatives only. BFGS has proven good performance even for non-smooth optimizations.
- L-BFGS-B. It is an optimization method based on quasi-Newton methods that approximates the Broyden, Fletcher, Goldfarb, and Shanno (BFGS) algorithms using a limited amount of computer memory (Byrd et al., 1995). It is a popular algorithm for parameter estimation in ML, because it is optimized for functions with a large number of parameters or with a high degree of complexity.

A KLR model has been estimated for all the combinations of penalty functions and optimisation algorithms previously described. The estimation was executed using a 5-Fold cross-validation procedure on a choice model problem.

Table 3 shows the mean value for the CPU time, the objective function (the log-likelihood) and the precision value obtained using the different combinations of penalty functions and optimization algorithms. The best recommendation based on the results obtained is to use the L-BFGS-B algorithm and the Ridge regression model. Nevertheless, if the number of variables to estimate is not considerably large, the BFGS algorithm can also be applied.

Estimation model	Algorithm	CPU time (seconds)	Objective function	Precision (%)
Maximum likelihood	Newton-CG	8.63	-265.5857	66.65
	BFGS	5.65	-265.9253	65.54
	L-BFGS-B	0.80	-273.1642	66.20
LASSO	Newton-CG	0.59	-342.8578	67.09
	BFGS	3.55	-307.6523	67.53
	L-BFGS-B	0.46	-312.3938	67.31
Ridge	Newton-CG	6.32	-291.4132	67.31
	BFGS	0.33	-291.4132	67.31
	L-BFGS-B	0.07	-291.4136	67.31

Table 3 – Comparison of different penalty functions and optimization algorithms

3.3. Model validation and assessment

PyKernelLogit allow to obtain several metrics for assessing whether a model is good enough for a specific application. One of them is the goodness of fit of the model (Train, 2003), which is a statistic that describes how well a model, with its estimated parameters, performs compared with a model in which all its parameters are zero (which is usually equivalent to having no model at all). Once the model is estimated, PyKernelLogit provides the likelihood ratio index (also called McFadden R square), which is defined as

$$\rho^2 = 1 - \frac{LL(\hat{\beta})}{LL(0)}. \qquad (6)$$

However, goodness of fit metrics cannot assess how the model predicts on new data points, for which it has not yet seen the true value of the dependent variable (the alternative chosen).

For this reason, PyKernelLogit integrates some other model validation techniques. One of these techniques is the confusion matrix (Géron, 2019). Once the model has been estimated using training data, the confusion matrix can be computed over the test data for which the true values are known. Each column of the confusion matrix represents the instances in a predicted class while each row represents the instances in an actual class. Using this matrix, it easy to identify if the model is confusing two classes.

The confusion matrix gives useful information, although sometimes it is preferred a more concise metric. Another interesting way of assessing the performance of a model is to look the accuracy of the positive predictions, which is called *precision*. This metric has an important drawback because if the model makes a single positive prediction and it is correct, then the precision will be 100%. For that reason, the precision metric is commonly used along with another metric called *recall*, or *sensitivity*. The recall is the ratio of positive instances that are correctly detected by the classifier. Finally, there is a third metric called *F-score*, which combines the precision and the recall results to compute the score. The *F-beta score* is the weighted harmonic mean of precision and recall, reaching its optimal value at 1 and its worst value at 0. The β parameter determines the weight of recall in the combined score. When $\beta < 1$, the F-score lends more weight to precision, while $\beta > 1$ favors recall. The evaluation of the precision, recall and F-Score metrics requires to compute for each class i the number of True Positives (TP), False Negatives (FN), True Negatives (TN) and False Positives (FP) instances.

The previous metrics are defined por binary classification problems, i.e. only two alternatives are considered. Nevertheless, when there are more than two alternatives in the model, the quality of the overall classification is usually assessed using two techniques (Sokolova & Lapalme, 2009):

- Marco-averaging. Each measure is the average of the individual measures calculated for all the alternatives.
- Micro-averaging. Each measure is obtained computing firstly the cumulative TP, FN, TN and FP for all the alternatives.

PyKernelLogit allows to obtain the precision, recall and F-score metrics for micro- and macro-average methods. Table 4 shows how the previous metrics have been implemented in the software package.

	Precision	Recall	F-Score
Micro-average (m)	$\frac{\sum_{i=1}^{I} TP_i}{\sum_{i=1}^{I}(TP_i+FP_i)}$	$\frac{\sum_{i=1}^{I} TP_i}{\sum_{i=1}^{I}(TP_i+FN_i)}$	$\frac{(\beta^2+1)\text{ Precision}_m \text{ Recall}_m}{\beta^2 \text{ Precision}_m+\text{Recall}_m}$
Macro-average (M)	$\frac{\sum_{i=1}^{I} \frac{TP_i}{TP_i+FP_i}}{I}$	$\frac{\sum_{i=1}^{I} \frac{TP_i}{TP_i+FN_i}}{I}$	$\frac{(\beta^2+1)\text{ Precision}_M \text{ Recall}_M}{\beta^2 \text{ Precision}_M+\text{Recall}_M}$

Table 4 – Precision, recall and F-score metrics for multi-class classification

3.4. Computation of economic indicators

Once a discrete choice model has been estimated using the PyKernelLogit package, it can be useful for the analyst to extract some indicators from this model. There are many indicators that are particularly relevant in the context of discrete choice models, such as, Willingness to Pay (WTP), Value of Time (VOT), elasticities, consumer surplus, market shares and revenues. Currently, PyKernelLogit allows the estimation of the WTP and VOT indicators.

The WTP allows to analyse the trade-off between any variable from the model and money. Let consider that c_{in} is the cost of the alternative i for a decision-maker n, and x_{in} is the value of another model variable. Now, let $V_{in}(c_{in}, x_{in})$ be the value of the utility function that is associated to an alternative i for a decision-maker n. Then, the WTP can be computed as

$$\text{WTP} = -\frac{\partial V_{in}/\partial x_{in}}{\partial V_{in}/\partial c_{in}}. \quad (7)$$

The VOT indicator is closely related with the previous one, as it reflects the price that a traveller is willing to pay to decrease the travel time in one unit. Therefore, VOT can be computed as

$$WTP = \frac{\partial V_{in}/\partial t_{in}}{\partial V_{in}/\partial c_{in}}. \quad (8)$$

The WTP and VOT indicators can be computed using a closed form expression for linear MNL models. Nonetheless, in KLR Eq. (7) and (8) does not have a closed form expression for some kernel functions and the partial derivatives must be approximated numerically. PyKernelLogit allows to calculate the WTP and VOT indicators for KLR models easily. It implements the Newton's difference quotient method to compute the partial derivatives of Eq. (7) and (8). One advantage of PyKernelLogit is the fact that it allows to compute the WTP an VOT indicators for certain values of the attributes.

3.5. PyKernelLogit package installation

PyKernelLogit source codes are available under an open-source license in a Github repository (https://github.com/JoseAngelMartinB/PyKernelLogit). In addition, a compiled version of PyKernelLogit is available for its installation on the Python Package Index (PIP) at https://pypi.org/project/pykernellogit/. The package can be installed on a computer with any operating system, provided that a Python distribution is available (preferably Python 3.7 or later), using the command:

```
$  pip install PyKernelLogit
```

Interested authors can find more detailed information on Martín-Baos, (2019).

4. CONCLUSIONS

In this work, an open source software package called PyKernelLogit has been developed for Python programming language. This software package allows to implement several discrete choice models, to apply several model validation techniques and to obtain a set of economic indicators. The package extends the capabilities of the original PyLogit package, which was able of estimating MNL models and its derivatives, and integrates the KLR models. The interest on aggregating the KLR model to the software package arises from two reasons. Firstly, KLR models are machine learning models which relieves the analyst from specifying a functional expression of the utilities beforehand through the use of the kernel functions. Moreover, KLR models have better predictive capabilities than the MNL models for non-lineal effects.

Our future work will be focus on extending the KLR model utility specifications to other discrete choice models such as Nested Logit models.

In addition, we will integrate into PyKernelLogit estimation procedure the Tikhonov regularization procedure. Finally, new features will be implemented to retrieve other economic indicators such consumer surplus, market shares, elasticities, revenues, etc.

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EVALUATION OF TRANSPORT EVENTS WITH THE USE OF BIG DATA, ARTIFICIAL INTELLIGENCE AND AUGMENTED REALITY TECHNIQUES.

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ABSTRACT

The phenomenon of "smart cities" generalizes the use of Information and Communication Technologies. The generation and use of data to manage mobility is a challenge that many cities are betting on and investing in. Through the Internet of all things (IoT) and the use of sensors and mechanisms for capturing information, the number of data analysis tools such as Big Data, Artificial Intelligence (AI), and Augmented Reality (AR) has increased.

The tools that are used to interpret events are applied to the analysis of video and photographic images and comprise of a set of programs, mathematical algorithms and protocols. The implementation of procedures could enable the automatic interpretation of image information, from the most basic such as changes in the presence of objects or people, to the identification of complex shapes and relevant event detection. With the constant use of the assisted process learning (Machine Learning), it’s possible to improve event interpretation through the customization of learning protocols.

Repetitively trained software can identify relevant events and report changes in critical scenarios that can trigger a series of protocols. The use of artificial intelligence techniques makes it possible to automate monotonous processes and improve transport management.

This article analyzes different technologies used to generate transport information and data validation. It is intended to experiment with the use of technologies in the detection of relevant facts, changes of state, and identification of events. It also measures the reliability level when detecting events, and studies the implementation of possible solutions into the transport management system, in order to assist in decision making processes.

1. INTRODUCTION

There is an increasing interest in the potential of the Information and Communication Technologies to manage and police urban transport issues. Recent advances in urban monitoring and sensoring applications have broadened the landscape of managing transport operations and infrastructures. Monitoring of transport processes is a key issue in efficient mobility. Sensoring and monitoring not only reduces the need for expert operators, thereby lowering costs, but it also allows quicker incident detection and consequently its prompt risk management.

This article aims to show a series of experiments in the field of transportation management in which Big Data, Artificial Intelligence and Augmented Reality techniques are used with different levels of interaction and integration. The experiments carried out are intended to show in an empirical way potential uses of these technologies separately and with different degrees of integration in order to try to manage specific situations of parking places management in urban sections.

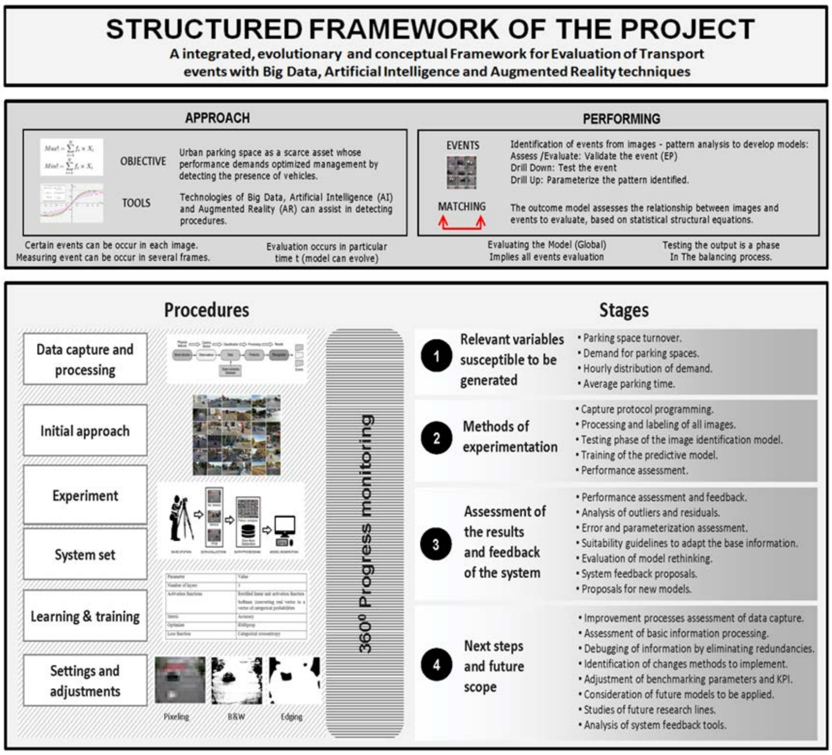

Figure 1. Structured framework of the project.

The purpose of the experiments carried out in this study is to provide better tools for managing parking spaces. Vehicles detection is considered as a challenging field in computer vision. The experiments are based on the recognition of traffic-related events, specifically the identification of changes in traffic and parking status. Artificial Intelligence protocols will be used for this purpose. Next, management and communication techniques of relevant information and assistance in decision making by the agents involved in mobility management will be used, evaluating in some cases the introduction of Augmented Reality methods. Finally, Big Data techniques have a transversal character as they are present in the implemented applications of Artificial Intelligence and Augmented Reality.

The article frames some applications in the domain of mobility, Smart Cities and urban space Management. In addition, several experiments were carried out to develop a vehicle detection system. Various smart technologies have been repurposed to inform appropriate response measures. It has been evaluated as the combination of AI and AR technologies yielded the best results.

2. AWARENESS OF THE PROBLEM

2.1. Urban parking space as a scarce asset that should to be optimized.

In urban environments, motorized vehicle trips require the reservation of space for circulation and parking, especially in areas with high demand and intensive land use. Traffic space is shared by private vehicles, but also by public transport, bicycles and pedestrians. For the authorities in charge of managing public space, it is a challenge to distribute uses for transit, private vehicles, pedestrian and parking mobility.

In urban central districts, public space is a scarce resource that is assigned to different uses. It can be considered, that much of the public areas are divided between the surface reserved for pedestrian traffic, mainly sidewalks and roads dedicated to traffic. The sidewalks are reserved for the priority transit of pedestrians, although in certain sections the circulation of bicycles and the parking of two-wheeled vehicles are allowed. In turn, there are areas of unique access to pedestrians (parks, gardens, beaches ...). The circulation routes are dedicated to the vehicles with reserved sections according to uses (bus-taxi lane, bike lane ...). A part of the road is reserved for parking vehicles on the surface with different types of regulations and different reservations.

The great demand for public space in dense urban environments pressures the specialization of land uses and its reserve for specific uses, both dedicated and by time slots. The management of such a scarce resource requires the application of different techniques and technologies that allow optimizing its use. In this sense, different technologies can contribute decisively in the management of mobility and optimization of public space uses.

The use of Big Data, AI, AR applications in the field of urban mobility can bring advances in the control of the mobility that can result in the improvement of safety conditions and the transports system efficiency.

The allocation of public space and its distribution among different users and modes of transport is one of the most important policy areas of territorial management in general and mobility in particular. The management of public space includes traffic management, integrating measures aimed at adjusting the supply of public space with the demand for mobility, taking into account the different modes of transport and their road space requirements.

The city of Barcelona has 1,362 kilometers of roads. The basic network comprises 27.5% of the streets of the city, which absorb 82.04% of circulation. The City Council has carried out, in recent years, pacification projects, especially in the central areas of the different neighborhoods. The measures implemented consist of reconverting areas for pedestrians, widening sidewalks, raising roadways and creating unique platforms, as well as reducing the accessibility of motor vehicles and speed of traffic to ensure the safety conditions.

From the data of the statistical yearbook of Barcelona, table 1 shows the evolution of the surface of sidewalks, road and the length of the streets. It can be observed how the extension of surface area for pedestrians has expanded in recent years, while that for cars has decreased (AJUNTAMENT de BARCELONA 2015; 2018).

Public Road	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Street KM	1361,8	1369	1369	1368	1368	1368	1368
Total Surface of Barcelona (km^2)	102,6	102,6	102,6	102,6	101	101,3	101,3
Surface intended for the vehicle (km^2)	10,9	11,4	11,4	11,4	11,4	11,4	11,4
Surface intended for the pedestrian (km^2)	15,32	15,81	15,81	16,18	16,83	17,52	17,52

Table 1. Evolution of the distribution of space in the city of Barcelona.

The municipal forecast is that all streets that are not part of the basic network have to become part of a pacified zone. These streets have to have a different character, depending on the hierarchy they occupy within the secondary network (segregated spaces, single platform, etc.) and they have to abide by the restrictions in the speed of the vehicles and priorities of step that regulate them. According to the municipal data, currently, about 56% of the city's road network gives priority to pedestrians or is pacified.

The road network has acquired a great specialization. It has gone from a wide basic road network, to a greater segregation of the road by uses, so that the local road network or non-basic network, is hierarchies in different categories. In urban dense areas such as the City of

Barcelona, mobility management implies acting on a great variety of modes of transport. The priorities are to reduce private vehicles mobility and promote public transport. Although it is desirable to discourage the use of private vehicles, it is also important that those private vehicles that circulate can do it smoothly, without congestion.

The challenges posed by the "smart cities" and their concretion in the "smart mobility" involve the implementation of technologies such as assisted and autonomous driving, sensitization, processing and massive use of data (Big Data), geolocation, systems navigation, Artificial Intelligence (AI) and other areas that make the knowledge of the current behavior of users of motorized two-wheelers have a great future potential and opens the way to a wide field of research (VIDAL TEJEDOR, N. 2015; VIVES, A 2018).

3. USE OF BIG DATA, ARTIFICIAL INTELIGENCE (AI) AND AUGMENTED REALITY (AR) IN URBAN TRANSPORT MANAGEMENT

The Big Data, the Artificial Intelligence (AI) and the Augmented Reality (AR) tools use will reshape the urban transport management, leading to fast adoption of more efficient transport integrated systems at an unprecedented rate. Traffic professionals continuously apply management strategies in order to maximize the productive use of the infrastructures. The use of those technologies could elevate and improve the transport management experience dramatically. This article focus on use of Big Data, Artificial Intelligence (AI), and Augmented Reality (AR) has increased to help solve problems of Transportation Analysis aiding human intelligence in functioning of machine and systems.

Big data implies an exponential availability of information and its accessibility, which enhances the capacity to assess data relevance. The significance of information is proportional to its meaningfulness. Its value lies in how we use it to guide our decisions and place it in a specific knowledge framework.

Some authors have highlighted the potential that Augmented Reality has, so that they consider that a breakthrough is not only machines that think, but machines that allow us to increase our perception and how the fact that officials will have improved cognition systems can transform power relations (Anderson, R. 2020.). Thanks to the development of the Artificial Intelligence (AI) new forms appear in the convergence of machine learning and deep learning. The union of Machine Learning algorithms with artificial neural networks and deep learning are being used in numerous and several fields. Artificial intelligence is already embedded into traffic control the ability to detect the presence of pedestrian and vehicles (BENGTSSON, P. 2018).
The developments that Big Data has brought about in the efficiency processing of huge quantities of data are closely related to Artificial Intelligence and Augmented Reality applications, making possible better learning algorithms (PASTOR, R. (2018).

On the basis of the number-crunching power is the improvements of digital computers. The exponential rise in crunch power lets ordinary-looking computers tackle tougher problems of Big Data and pattern recognition.

The optimal approach to getting machines to solve difficult real-world challenges is to set them up as statistical learning machines that can benefit the most from exposure to massive amounts of data. These technologies can come to learn to solve complicated tasks by detecting patterns, and patterns between and within patterns, hidden from the vast data streams to which they are exposed. Big Data technologies have made it possible to provide a capacity to manage enormous amounts of data with which to feed the algorithms that underlie Artificial Intelligence technologies. Data crunching is at the basis of the operation of deep learning algorithms that make it possible to profoundly examine data flows, yielding systems that work to provide solutions to solve problems, but whose knowledge structures are opaque to the technicians who created the system, so that the resulting algorithms can be used with levels of significance of the results, totally unaware of the reasons that make their significance levels possible. In this way is acceptable that current and future AIs solutions are forms of intelligence feeding off Big Data and crunching statistics in ways that render their operational engines opaque to human understanding.

Artificial Intelligence (AI) applied to the interpretation of video or photographic images comprises a set of programs, mathematical algorithms and protocols that make it possible from a process assisted learning (machine learning), the possibility of interpreting events from the computer processing of images. From the customization of learning protocols, in an automatic way it is possible to interpret events in images, from the most basic ones, such as the presence of objects or people, to the identification of complex shapes.

The use of Artificial Intelligence (AI) can be a valuable tool to assist in the detection, interpretation of events, state vision, and identification of relevant facts. In this sense it can be useful in assisting in case detection, alert triggering and helping in decision making to assist in dealing with situations that demand more or less immediate responses.

There are several areas in which these technologies are used in the management of traffic. One of the main fields is vehicle identification: AI in the area of traffic management can be used mainly in traffic jam recognition and management. These systems could perform the task of tracking and locating vehicles in real time and adapt traffic management according to current or predicted conditions to accommodate lanes or fast sections for emergency services. These technologies can also be used to detect infractions, which will help municipal and traffic authorities to identify them, develop effective prevention systems and apply the corresponding penalty (JIN, J. and DENG, Y. 2017).

However, the adaptation of these technologies to cities and roads must consider safety, so it is necessary to establish systems that prioritize avoiding traffic accidents; one of the additional facilities performed by these technologies are the identification of people at risk, in order to warn or prevent reckless actions of pedestrians, crossing streets inappropriately, identifying motorcyclists who did not wear helmets properly (CHIVERTON, J. 2012) and estimating the driver's workload (MANAWADU, U. E. et al. 2018).

BARLOW,H.(1989) was one of the first to appreciate the importance of unsupervised learning as opposed to reinforced learning, so that unsupervised learning applied to big data and artificial intelligence allows to identifies "statistical regularities", or patterns in its inputs in the form of possible discrepancies that allow it to identify and deal with potential underlying patterns. This information theory-based approach embodies many modern approaches to unsupervised learning in neural networks and Bayesian learning.

4. RELEVANT VARIABLES SUSCEPTIBLE TO BE GENERATED

The purpose of the experiments carried out in this study is to provide better tools for managing parking spaces in urban sections. Vehicles identification is considered as a challenging field in computer vision. We consider the vehicle detection problem as the basis for extracting relevant variables for parking space management in urban areas sections.

We study the case of the vehicle presence identification in parking line section. Our research goal is to test a method to identify vehicles and types of vehicles presence in a street section. Once an object has been detected, the next challenge is object localization in the section. Object detection deals with finding the objects that are present in an picture. The technologies for the recognition of elements in a road section are based on the interpretation of a set of digitized data captured by different means. Based on these data, different tools can create analogies and models that simulate the presence of defined objects on a road section. One of the most common applications of Big Data, AI and ER is the use of photography to identify events. In the case of urban traffic a primary event would be to recognize the presence or not of vehicles on a section road.

Once the presence of vehicles on a stretch has been detected, we can lay the foundations for building variables such as counting vehicles, estimating speeds, identifying vehicle types, calculating parking space turnover, detecting violations and many other different variables relevant to traffic and parking management. With the above technologies we can develop accurate techniques to identify the presence or not of vehicles in a stretch and we can have a basic tool to develop traffic management devices.

A basic stage would be to have a device, in this case that answers the bionomial question: Are there or not vehicles on a specific section, with a Boolean answer.

Knowing whether there are vehicles on a road or in a parking space is relevant information for traffic management. If the information can be obtained periodically, we are able to evaluate changes in status.

So it can be used to detect presence, and count vehicles in a section (measuring capacity) or to determine the rotation of parking spaces. In this way, the dynamic management of information and its analysis can be relevant in traffic management.

Relevant variables related to parking space management that can be expected to be generated in future phases of our experiments are:

- **Parking space turnover:** number of vehicles parking in a space over a period of time.
- **Demand for parking spaces:** Usage ratio, based on the number of vehicles driving on the section and the number of vehicles that end up parking.
- **Hourly distribution of demand:** Use of parking spaces throughout the day and therefore peak and off-peak periods.
- **Average parking time:** Length of time the vehicle is parked in the space.

In order to generate all of the above variables, the basic variable to work with is to detect the presence of vehicles on a section of road. So if it is not possible to detect the presence of vehicles, it is not possible to progress to the following phases. This is why the experiment focuses on identifying the presence of vehicles on a stretch of road. Once a high level of reliability is achieved in identifying the presence of vehicles on a stretch of road, it is possible to move on to more complex phases of information generation, such as identifying parking in a spot and, from there, estimating parking times.

5. METHODS OF EXPERIMENTATION AND PROCEDURES TO DETECT PRESENCE OF VEHICLES IN A STREET SECTION

5.1 Outline of the methodology applied.

The study is forward-looking in approach. The initial objective is to produce a large number of images that will allow the building of a database in which each image will be linked to certain attributes for fields. Starting from the basic information, the learning process is conducted, following which the levels of accuracy are evaluated. Then different techniques are applied to improve the reliability of the results. Finally, the results are presented and a proposal is made for uses and future developments.

The phases of the project are:

1. **Capture protocol programming.** In order to obtain images from the installed cameras, it will be necessary to develop a computer program to capture the images. For this purpose, software will be developed with code that will implement the following operations at each programmed interval: open the browser with the IP address, capture the images for each image, label the images and store them sequentially in a database.
2. **Processing and labeling of all images:** Generation of image database. A database will be designed with the identified attribute fields of the images. Then a specialist will analyze the images one by one and will fill the database with the selected attributes.
3. **Testing phase of the image identification model.** Based on the images and the associated database, it is possible to develop the testing phase for the identification of events in the images.
4. **Training of the predictive model.** The central phase of the application of Artificial Intelligence techniques goes through the training of the model, from different treatments of the images adapted pixel matrices and chromatic treatments.
5. **Test run. Once the model is trained, it is possible to identify the degree of reliability in the identification of events.** Once the program has been run with the images to be detected, reliability tests can be performed in different scenarios.
6. **Performance assessment.** Result study to improve predictability, elimination of false positives and robustness of the system. From the statistical reliability data of the systems, different techniques can be applied to debug the results and filter out false positives, thus increasing the degree of reliability of the system.

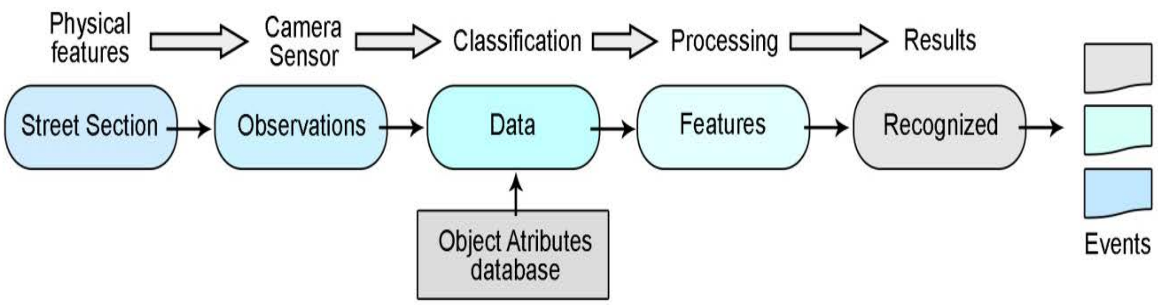

Figure 2. Process scheme of the built-in procedure from the data collection system to the handling of the data and the identifying stages.

5.2 Initial approach to vehicle presence identification.

A first exploratory experiment has been carried out, consisting of analyzing photographs from different sources related to stretches of roads. The purpose of the exercise was to assess the feasibility of assessing the presence of vehicles on different stretches of roads regardless of the origin of the information collected, so that if the experiment proved to be satisfactory, we should be able to have a generalist tool for assessing the detection of the presence of vehicles on stretches of traffic sections.

In this experiment the first level was carried out in the following way: Initially we proceeded to capture images of the Google Street View application with the intention of having a sufficiently large bank of images to start testing with the AI software. A total of 2,097 photos were captured, which were classified manually on the one hand, depending on whether vehicles were observed or not; and on the other hand, depending on whether they were in an urban or interurban environment.
The classification of the images was carried out to evaluate the degree of success of the application, being able to compare the results obtained from the analysis of the images by the analysis application with those observed by a person.

Figure 3. Sample of images used in the performance of the experiment to identify the presence of vehicles and the type of road section.

Two different experiments were carried out on two scopes of information contained in the pictures: One experiment tested whether or not vehicles were detected on the section and the second experiment tested whether the section was an urban street or an interurban road. The analysis was carried out by performing binomial tests in which two sections were performed: a first phase of model training and a second level of testing on the presence or absence of the event.

The results were found to be poor and unreliable. Therefore, it became obvious that the kind of images used did not lead to results that could be suitable as a basis for the development of any kind of application.

It was found that there are different factors causing the poor results, among others the different sizes, lighting, exposure, orientation, quality and accuracy of the images. These considerations lead to the conclusion that in order to conduct this type of experiments it is necessary to consider initially the use of images taken by the same camera, focus, ambient, exposure, orientation and zooming.

6. EXPERIMENT

6.1 Design of the experiment.

In this section, we described in detail the experiment carried out about how to detect vehicles on an urban street section from images and the usage of the technology.

The poor results of the initial approach using external images and explained in the previous section led us to the perspective that in order to have a better control of the experimentation it is relevant to generate one's own images. That is why we conducted this new experiment using raw images captured by our own devices and which are explained as follows.

The experiment consisted of selecting a section of urban section to initially analyze the phenomenon of the presence of vehicles on the stretch. Once a high reliability in the detection of the presence of vehicles is achieved, it is possible to advance in the generation of variables for monitoring the use of parking spaces by vehicles.

An ideal environment was sought in Barcelona that met the requirements: continuous presence of vehicles, among which: cars, taxis, motorcycles, bicycles, as well as the presence of pedestrians.

The photos had to be taken from a certain height in order to obtain a clear image of several lanes of traffic and thus control vehicle traffic. All these requirements were met, in the centre of the town of Barcelona, which supports a high rate of circulation compared to other parts of the city.

The place chosen was the Carrer de Provença, from a floor where the circulation of the vehicles was observed properly by the two existing lanes, as well as a two-way bike lane is observed and a pedestrian alley is available. It implies the continuous transit of pedestrians which cross the Carrer de Provença.

Figure 4 shows the elements of the set. Image capture was conducted with a Canon camera (model EOS 50D DS126211 and Canon zoom lens EF-S 17-85mm F 4-5.6 IS USM) and the storage of the images was downloaded into a DELL laptop. OpenCV, a computer-vision library was used for automatic image processing.

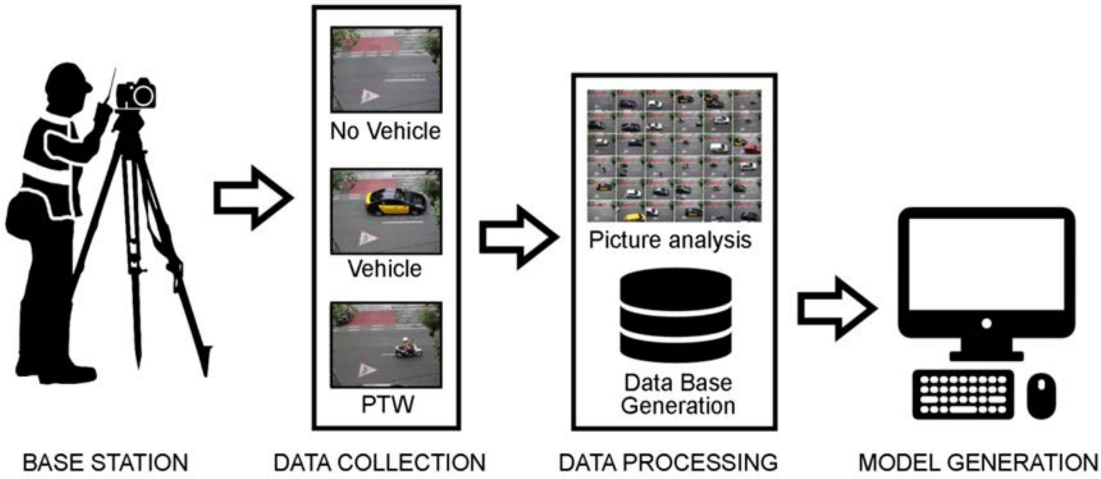

Figure 4. System Set. Design of the images capture system from a base station and data processing for the preliminary pretreatment of the data.

Once the location was chosen, several tests were taken to evaluate the chances to collect the images in the adequate environment conditions. The frame of action has been a stretch of road considering the width and the set of lanes that make up the section.

The location had adequate visibility conditions so that data collection could be performed in an automated manner without the continuous assistance of operators.

A camera was pointed at the road and pictures were taken over a period of time. The camera was connected via cable to the DELL laptop. The first realized were made from the time-lapse of the camera while was connected to the laptop, it was programmed so that every five seconds it took a picture. Once this step was done, they began to classify the photos.

For the management of the photographs, it was used as a photographic assistant the software of the Canon Reflex camera used to perform image capture. The computer used for data processing has an Intel I5-9400 processor running at 2.9 GHZ, with a RAM memory of 19 GB, and the graphics card used is a Radeon RX-580 graphics card.

Figure 5. Sample of different pictures taken for the performance of the experiment.

Each photo was analyzed by a specialist and a database was created in which the numeration of the photograph was collected and the following fields were filled in with binary data (0: negative; 1: positive): presence of vehicle, the vehicle is a car, the vehicle is a PTW, the vehicle is a heavy vehicle, the vehicle is a cab. (LIM, G.H. et al.).

Picture #	Vehicle presence	Car	PTW	heavy	Cab
#00001	0	0	0	0	0
#00002	0	0	0	0	0
#00003	1	1	0	0	0
#00004	1	0	1	0	0
#00005	0	1	0	0	0

Table 2. Fields of the dataset

The use of deep learning allows detecting an object with certain accuracy. Open source AI libraries and data flow graphs were used to develop the neural network. To create neural networks with different layers, TensorFlow and Keras (an end-to-end open source platform for machine learning by Google) as a R modules was used, which allows building a neural network based on the requirements of the model with Keras deep learning API.

Once pre-processing data was done, before training the sequential model, values for hyper parameters were chosen. Batch size (number of training examples present in a single batch), epoch's number (number of iterations passing the full dataset by the network) and learning rate (amount that the weights are updated during training) have to be fixed.

The used hyper parameters are shown in the following table:

Hyper parameter	Value
BATCH-SIZE	128
NUM_EPOCHS	100
LEARNING RATE	0.01

Table 3. List of the selected values for the hyper parameters selected for sequential training.

The API requires other general parameters to compile the Keras model that in this case are fixed as the following table summarizes:

Parameter	Value
Number of layers	3
Activation functions	Rectified linear unit activation function Softmax (converting real vector to a vector of categorical probabilities
Metric	Accuracy
Optimizer	RMSprop
Loss function	Categorical crossentropy

Table 4. Summary table of additional general parameters applied in the compilation procedure of Keras model.

About 2100 images were prepared to train. In our research, the primary target output is whether or not there was a vehicle on the section of road.

Two experiments were performed: the first one was to identify the presence of the vehicle on the stretch and the second one was to try to identify the type of vehicle.

The first experiment consisted in identifying or not the presence of a vehicle on the section. From the training phase images with and without vehicles on the section where used and then went on to a second phase to perform the testing of the training carried out previously. Once the algorithm is selected, we proceed to split the pre-processed data. A percentage of the data, typically 80% of the total, will be used as training data and the rest 20% to evaluate the model performance.

Once the model is fitted, the next step is the model evaluation phase. This will be done with the remaining data, that which was not used for the training phase, which will be referred to as model evaluation data. In other words, it will be the data to which will be applied the fitted model. On this data will be used to achieve the initial objective and evaluate it.

The metric for assessing the results of the experiments is accuracy (simply a ratio of correctly predicted observation to the total observations) and precision (ratio of correctly predicted positive observations to the total predicted positive observations), which are calculated as shown below:

	Predicted class		
Actual Class		Class = Yes	Class = No
	Class = Yes	True Positive	False Negative
	Class = No	False Positive	True Negative

Table 5. Relation of the parameters applied in the classification of the classes and results of the events.

$$Accuracy = \frac{TP+TN}{TP+FP+FN+TN} \quad (1)$$

$$Precision = \frac{TP}{TP+FP} \quad (2)$$

Where TP= correctly predicted positive values, TN= correctly predicted negative values, FP= incorrectly predicted positive values and FN= incorrectly predicted negative values.

The experiment of identification vehicles on the section was performed and a level of 64 % was matched.

The results have a level of significance that allows us to propose in the advance of performing calculations to count vehicles in a street section.

The second experiment that was carried out was to try to identify the type of vehicle. It must be taken into account that it is already part of a high determining factor and that is that the system has an accuracy level of 64% to detect or not vehicles in the section, so there is already a level of lack of precision to pass to the second experiment.

After the training phase (machine learning) and testing of the second experiment it was found that the results were not representative and therefore that the type of vehicle that circulated on the section could not be reliably identified.
Once the two initial experiments have been carried out, the conclusion is reached that for the

time being we discontinue advancing in an identification model of the typology of vehicles that are on a section of road and we focus on a model of identification of the presence/absence of vehicles in a section of urban road.

The next steps to be carried out in the following sections are the implementation of image processing adjustments and the use of augmented reality techniques, in order to improve the reliability of the model and the reduction of the volume of information to be managed.

Some adjustments were made to the images to reduce their size, decrease their resolution and switch them to black and white, so that more pictures could be taken in order to develop an experiment and obtain the most detailed results possible.

The following sections show different image debugging procedures and the application of data optimization methods to evaluate possible variations in the results obtained.

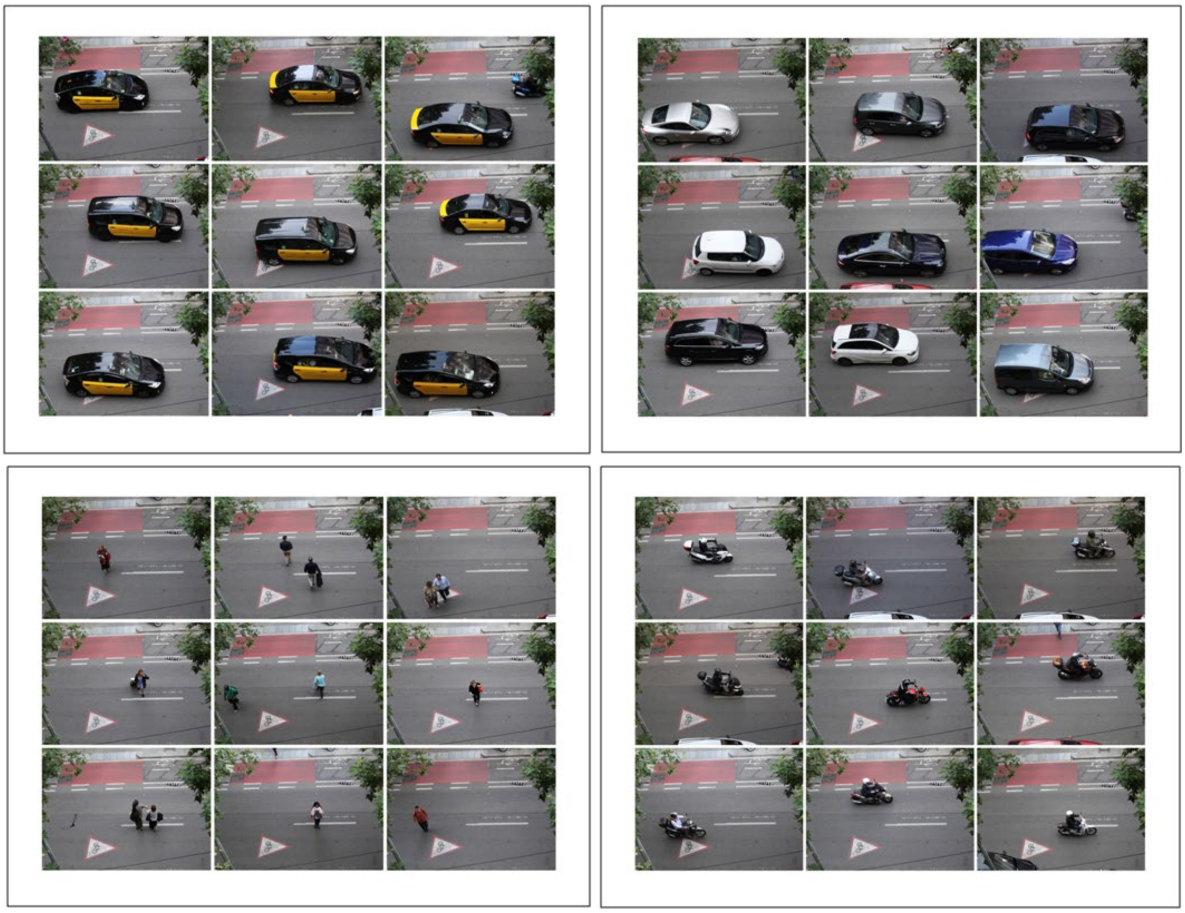

Figure 6. Different types of entities that can be identified in the information capture and analysis environment.

6.2 Reduction of image size by pixel processing.

One of the problems of working with photographs is that the more information they contain, the more accurate they are, but there is a significant increase in the size of the files, which makes them difficult to manipulate and process in the analysis and elaboration of results. (DEY, V., et al. 2010). Image pixelation allows the clustering of spectral information and enables the matrix comparison of a smaller quantity of data, which increases the processing rate of the information.

In this stage, we proceeded to apply techniques to reduce the size of the photographs by increasing the pixel size. The size of the photos has been reduced by enlarging the pixels. This is intended to manage the photos, improve the processing speed and even the data transfer if smaller photographs are available to keep the results high, the system experiences several improvements. First of all, a smaller volume of information is required, which increases the speed of data processing, analysis and transport.

It can be seen how by means of image pixelation techniques it is possible to significantly reduce the size of the images. The training phases (machine learning) and testing of the results are carried out and a reliability of 51% is found. Therefore, a significant reduction in the accuracy of the results is observed.

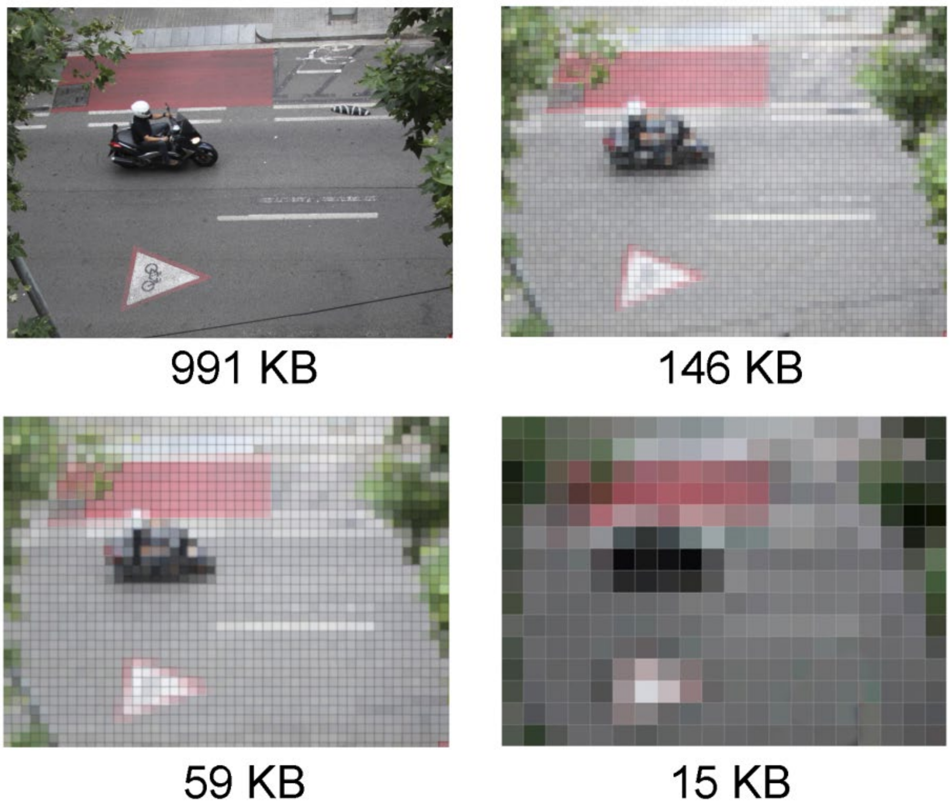

Figure 7. It can see the pixel processing with the output grid for size reduction in a ratio 65 times smaller.

6.3 Transformation of black and white photos.

We proceeded to process the images in black and white. Working with black and white images also helps to mitigate problems such as errors associated with shade and mitigates problems with bright light. The processing of the images goes through a phase of change to grayscale and then to black and white. It should be noted that the focus cannot cope with gradual illumination changes in the scene.

Vehicle detection is hampered by bright sunny conditions combined with shaded areas. Using black and white images can diminish the influence of excessive brightness and shadows "noise" in the frame. If the shadow contour is not clearly detached from the objects, the possibility of detecting moving targets is enhanced. Different algorithms for moving object detection work on detaching vehicles from their shadows to achieve better results (KILGER, M. 1992).

It is stated that the processing of the images to black and white allows reducing the size of the frames in the order of 7 times lighter in weight and thus simplifies data processing and transmission.

Once the images have been processed and rendered to black and white, the training process (machine learning) and testing of the results is carried out and a reliability of 48% is found. A significant reduction in the accuracy of the results is noticed.

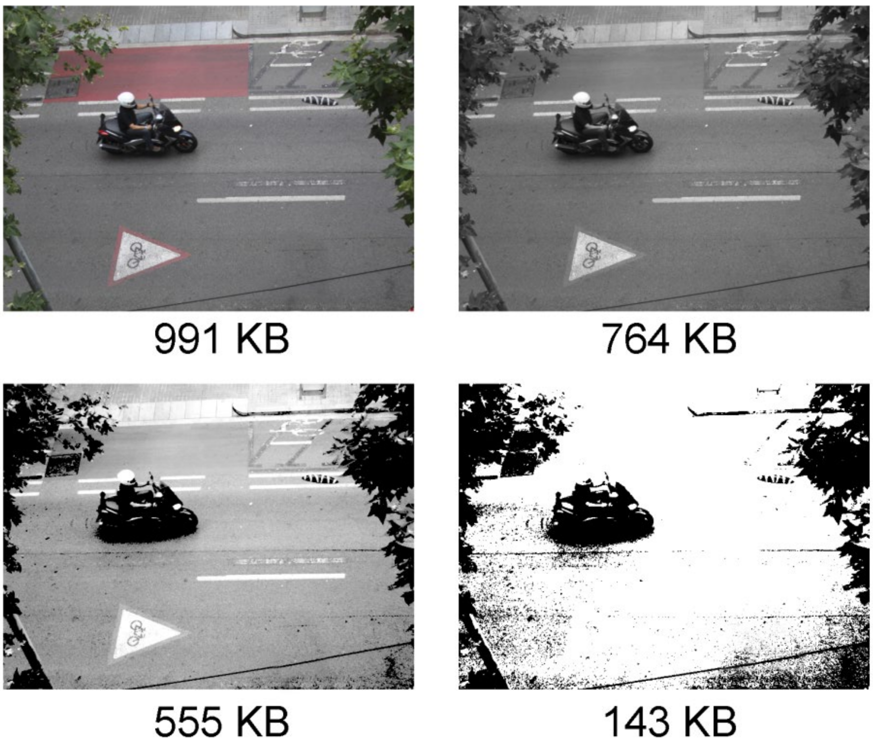

Figure 8. Sequence of frames of the processing of the color picture to grayscale, and subsequently to black and white with fading of the shadows and shines effect. It is evident a reduction in the size of the image of almost seven times the weight of the photograph.

6.4 Use of augmented reality techniques.

One technique that can be employed is to focus the analysis on the areas of the photograph where changes can occur. When working with a vehicle detection algorithm, one of the problems faced is that of redundant features not associated with the object to be detected. That is why in order to reduce the risk of presence of redundant elements it is useful to narrow down the plane of possible relevant events.

The subtraction or reduction of study areas involves analyzing a reference image shrinking the analysis area in each frame and scaring the result threshold. This is achieved by reducing the information and adjusting the binary segmentation of what is to be examined in the image, especially the detection of non-stationary objects. A photo processing technique can be applied in order to select attributes that can be mobile entities within the image and therefore, if their presence is detected in the picture, it means that there is a vehicle in the scene.

First of all, a reduction in the size of the images of more than 9 times the size was verified. After the training process (machine learning) and testing of the results, a reliability of 42% is checked. Therefore, a remarkable reduction in the accuracy of the results is registered.

The following is a sequence of images treated in order to identify features with volumetric attributes that could be related to a vehicle.

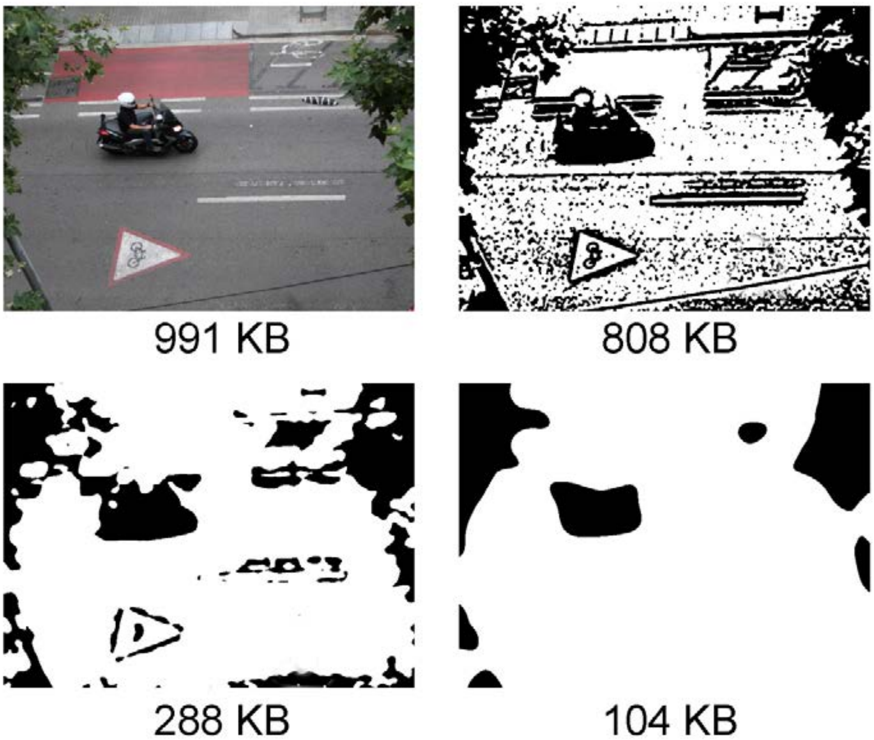

Figure 9. Transformation process of an image by reducing the information to volumes that could be identified as vehicles, and based on their presence or absence, test the detection model.

7. FUTURE SCOPE

7.1 Debugging of information by eliminating redundancies through the identification of changes.

SHANNON, C.E. (1951) emphasized how "redundancy" can be something like an opposite of information. BARLOW, H. (1961) developed an idea about redundancy reduction and pattern recognition, whose ramifications have influenced the debugging of Artificial Intelligence models, vindicating the need for interpreting the goals of the system to avoid heaps of irrelevant data that may result in crucial observations being overlooked. According to information theory, this can be achieved by eliminating redundancy through inhibition and adaptation. BARLOW, H. (1961) and ATTNEAVE, F. (1954) proposed the reduction of redundancies as a response through systems of transmission inhibition of non-relevant information. Barlow, H. suggested that at the level of the biological systems of sensory perception there are mechanisms adjusted to eliminate massive redundancy in order to avoid constantly informing about the state, so the relevant information to be reported to the system is changed in state, leaving the system to assume that everything not reported remains the same. In this way, the system reports information only when there is a change. This achieves a significantly reduction of the amount of information and it ensures that practically all the information that is managed is relevant, since by avoiding repetitions (redundancy).

If most of the data to be analyzed by the system come from events of possible changes, great savings in management and greater efficiency in interpretation are achieved. These methods have some problems and involve a training period with no objects in the plane under analysis. The movement of background objects after the training period and foreground objects without movement during the training period would be regarded as permanent foreground objects. (CHANGALASETTY, S. B. et al. 2014).

An intuitive method is to apply a Kalman filter to track changes in the background of each pixel in the image (KALMAN, R.E.1960). That tool attempts to assist in predicting future states of the system by taking the series of previous records. It’s an algorithm for identifying states of a dynamical system that relies on the known information of the previous states of the given system by comparing with the previous ones.

An additional starting stage can be performed using a customized version of the moving segregating objects. An adaptive filter-based Kalman model could implement in future steps, to analyze the changing background conditions. The foreground is refreshed at each frame using the following update equation:

$$B_{t+1} = B_t + (\alpha_1(1 - M_t) + \alpha_2 M_t)D_t \tag{3}$$

7.2 Assessment of use of logistic regression to improve machine learning and binomial event classification.

In order to work with a dichotomous outcome predictor variable, Logistic Regression algorithms allows assigning the probability between 0 and 1. In this way a binary classification is obtained, with only two possible outcomes. The regression algorithm is one of the most prevalent and common classification algorithms found valuable in machine learning. The binary options allows to plot the coordinates of the set of features with their values and then attempts the most accurate function possible that can predict the output values of the input features.

The logistic regression model has two dependent and independent variables, while the dependent variable with two values is represented by proxy variables shown in the following equation.

$$P(x) = \frac{e^{(\beta_0+\beta_1 x_1 \cdots\cdots \beta_n x_n)}}{e^{(\beta_0+\beta_1 x_1 \cdots\cdots \beta_n x_n)+1}} = \frac{1}{e^{-(\beta_0+\beta_1 x_1 \cdots\cdots \beta_n x_n)+1}} \in [0,1] \qquad (4)$$

7.3 Use of other software or analysis procedures.

In the field of study there is a continuous great amount of innovations and applications that can be implemented on the basis of images already available. In this case study it is relevant to have generated the images themselves, so that we can have our own base material. This material has been applied to carry out the present study, but as there are continuous innovations in the procedures, it is feasible to continue advancing in the improvement of the results already obtained from the use of other protocols and programs such as Wolfram, MatLab...

Advances are increasingly being made in computing power at a significantly higher level than ever before, benefiting from built-in computational intelligence based on a great depth of algorithms and knowledge that can substantially improve the results already obtained.

Futures line of research are the identification of possible innovations that may appear and the wide range of already available programs and methods that can test different domains of mathematical modeling, statistical applications, information management and data processing.

8. CONCLUSIONS

Several experiments have been carried out in order to develop tools to identify vehicles in urban areas using different technologies of Big Data, Artificial Intelligence (AI) and Augmented Reality (AR).

A first attempt has been made to identify vehicles in a stretch of road using images from different sources and it has been found that it was not an adequate approach. Subsequently It has been performed an experiment based on the shooting of our own images by locating an observation station and collecting pictures pointing to a specific segment of road.

After applying image training techniques, it was found that the most reliable results were obtained with the least treated frames, which retain the greatest amount of raw information. By applying artificial intelligence techniques on the unprocessed images, a result of 64% identification of the presence of vehicles on the section was achieved.

The subsequent experimentation carried out consisted of image processing refinements, the application of augmented reality techniques, in order to improve the reliability of the model and the reduction of the volume of data to be handled. To this end, the black and white photos were processed, the images were pixelated to reduce the information and size, and an attempt was made to identify the volumetry of moving objects. The summary of the results obtained is as follows:

Picture treatment	Recognition Accuracy
Raw	64
Pixel processing	51
Black & White	48
Edging	42

Table 6. Comparison table recognition accuracy (%).

It should be noted that there has been significant advances in the use of images own collected in a controlled environment, because it allows to work with data that are easier to be treated and adjusting the parameters to improve the result. The tests of different treatments of the images were carried out, obtaining mixed results. There were satisfactory results for the detection of the vehicle's presence, but in the application for the determination of the type of vehicle, the results were not reliable.

In global terms we must validate as adequate the concept of the experiment, the location and the methodology adopted. We can also consider the results as satisfactory and encouraging as a starting point for further progress in improving reliability.

Next challenges of using these technologies in the transportation sector will be to expand the fields of analysis to different areas such as pollution reduction, road safety, improved accessibility and seamless mobility.

Future lines of progress in the research could be considered such as the application of techniques for filtering the information by eliminating redundancies through the detection of modifications in the images; exploring the implementation of mathematical models to increase machine learning and binomial events, as well as examining the application of other software or analysis protocols.

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URBAN POPULATION DYNAMICS DURING THE COVID-19 PANDEMIC BASED ON MOBILE PHONE DATA.

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ABSTRACT

Because of the fast expansion of the COVID-19 pandemic in 2020, many countries established lockdowns, implementing different restrictions on people's mobility. Analysing the effectiveness of these measures is crucial to better react to similar future scenarios. This research uses anonymous mobile phone data to study the impact of the Spanish lockdown on the daily dynamics of the Madrid metropolitan area. The analysis is focused on a reference week prior to the lockdown and on several weeks of the lockdown in which different restrictions were in place. For this timeframe, population distribution is compared during the day and at night and presence profiles are obtained throughout the day for each type of land use. In addition, a multiple regression analysis is carried out to determine the impact of the different land uses on the local population. The results in the reference week, pre-COVID-19, show how the population in activity areas increases in each time slot on a specific day and how in residential areas it decreases. However, during the lockdown, activity areas cease to attract population during the day and the residential areas therefore no longer show a decrease. Only basic essential commercial activities, or others that require the presence of workers maintain some activity during lockdown.

1. INTRODUCTION

The COVID-19 pandemic has abruptly changed the way in which citizens interact, move or make use of different urban activities. The change has been radical particularly in the initial phases of the pandemic, with the adoption of the most severe measures and the lockdown, which has led to the closure of most activities and changes in habits when carrying out the most basic activities. Without any warning, cities were forced to slow down, reduce and even stop much of their activity for months. Knowing how the pandemic has transformed urban dynamics and what the patterns of these dynamics are in the phases of lockdown and subsequent restrictions is essential for decision-making, establishing new measures or evaluating their effectiveness in preventing and controlling the spread of the pandemic and in understanding the city's resilience to these measures to contain severe outbreaks.

New geolocation technologies offer significant possibilities to study population mobility and the possible spread of contagious diseases are well known (Sirkeci and Yucesahin, 2020, Ferretti et al., 2020). Mobile phone data had only been rarely used in epidemiological research, but their enormous potential has been demonstrated during the COVID-19 pandemic to estimate the effectiveness of the control measures in many countries (Oliver et al., 2020b).

This research aims to study the impact of the pandemic on the dynamics of the city throughout the day and its spatial relationship with land uses, an aspect that the authors believe has not as yet been discussed in depth. The presence of the population in each area of the metropolitan area of Madrid (Spain) is calculated throughout the day using information from mobile phones. This daily distribution of the population is analysed for a typical week, and then compared with the daily distributions in the weeks of confinement decreed due to the state of emergency in Spain. During this lockdown period, we also analyse the effects of the different phases, where measures to restrict the mobility of the population and the opening of the different activities have been tightened or eased.

In order to analyse urban dynamics, mobile phone data were crossed with the distribution of land uses within each transport zone. Typical hourly activity profiles have been obtained for each land use and multiple regression models (OLS) have been calculated for four major moments in time (morning, afternoon, evening and night). The analyses carried out show the level of activity throughout the day that each type of land use has maintained according to the degree of restrictions imposed.

Madrid metropolitan area as a case study is also of special interest, given the high impact that the disease has had. Spain has been one of the countries most affected by the pandemic, with rates of confirmed cases and deaths among the highest in the world (Johns Hopkins University, 2020). Madrid, the most affected metropolitan area in Spain, was also one of the first affected areas in Europe to establish a lockdown and has also witnessed various phases in the application of the measures, which allows us to evaluate the impact of different types of measures and serves as a reference in the evaluation of the same.

2. CASE STUDY, DATA AND METHODOLOGY

2.1 Study Area and Phases

The study area consists of the municipalities included in the Morphological Urban Area (MUA) (ESPON, 2014) of Madrid that are located within the Region of Madrid. With an extension of 202,478.46 Ha, the study area enables us to analyse Madrid's behaviour on a metropolitan scale, and study in detail what happens in each of the 1,062 transport zones into which it is divided (Figures 1 and 2). Just over 5.7 million people reside in the metropolitan area of Madrid according to the 2019 census.

When it comes to the time frame, the research analyses the impact of the COVID-19 pandemic on the distribution of the population in the study area over 6 weeks (March 23 - May 10, except Easter). In these weeks, the Government of Spain had activated the State of Alarm prior to the adoption of the Transition Plan to the New Normal. They were the weeks of greatest restrictions, with various measures to regulate activities in the different phases. Additionally, the analysis extends to the week of February 14-20, 2020, taken as a reference (W0), representing the distribution of the population in a normal week, prior to the pandemic.

The weekly analysis allows us to study the impact of the different measures decreed by the government on mobility and the degree of confinement of the population.

To understand the results obtained, the phases of the lockdown decreed by the Government of Spain and the most important measures established in each of them (Table 2) must be defined. Table 1 shows the dates of the study weeks, relating them to the phases and measures indicated in Table 2.

Study weeks	Dates	Corresponding phase
W0	14-20 February	Reference week. Normal activity prior to COVID-19.
W1	23-29 March	Second week after the Declaration of the State of Alarm
W2	30 March - 5 April	First week of Extension of State of Alarm 1
W3	13-19 April	First week of Extension of State of Alarm 2
W4	20-26 April	Second week of Extension of State of Alarm 2
W5	27 April - 3 May	First week of Extension of State of Alarm 3
W6	4-10 May	Second week of Extension of State of Alarm 3 and first week of Transition Plan to New Normality: Phase 0

Table 1. Study weeks, dates and correspondence with the State of Alarm phases

Phase	Dates	Summary of measures
Declaration of a State of Alarm	14-28 March (2020)	● Suspension of face-to-face classes in all learning centers. ● Prohibition to circulate in the streets, except for: Buying food or medicine, going to health centers, going to or coming from the workplace, going to banks or insurance companies, taking care of the elderly or children. ● Recommendation of teleworking. ● Closure of most premises, shops and businesses. Exceptions: Food stores, pharmacies, medical centers, gas stations, and others. ● Closure of museums, libraries and leisure or sports centers. ● The public transport service is maintained.
Extension of State of Alarm 1	29 March - 12 April (2020)	This is the phase with the greatest restriction of activities. The measures adopted during the State of Alarm also include: ● Suspension of non-essential face-to-face work activity. Fundamentally, the following are considered essential activities: health, food and fuel distribution, public maintenance services, cleaning and waste collection, state security, postal services, funeral services and media.
Extension of State of Alarm 2	13 - 26 April (2020)	Measures relating to those defined in the previous phase: ● People are allowed to return to their workplaces for non-essential activities where teleworking measures cannot be implemented. ● Circulation of private vehicles is allowed to carry out the permitted activities.
Extension of State of Alarm 3	27 April - 10 May (2020)	Measures relating to those defined in the previous phase: ● Children under 14 years of age may go out with someone one hour a day but must not go further than one kilometer from home. ● From 2 May: Those defined by the Transition Plan to the New Normal.
Transition Plan to the New Normality: De-escalation - Phase 0	2 - 10 May (2020)	On April 28, a 4-phase Transition Plan to the New Normal was established. On May 2, Madrid enters Phase 0 of the plan, allowing: ● Departure for minors, individual non-contact sports activities and walks, once a day and at regulated hours. ● Opening of establishments by appointment for customer's service.

Table 2. Phases, dates and measures adopted by the Spanish Government

2.2 Data

This research is based on the datasets described below:

1. **Mobile phone records**. The data used for the extraction of mobility indicators consists of a set of anonymized mobile phone records corresponding to the defined weeks of study, obtained through a collaboration agreement with one of the three main Mobile Network Operators (MNOs) in Spain, with a market share of more than 20%. The records include Call Detail Records (CDRs), produced every time a mobile phone interacts with the network through a voice call, a text message or an Internet data connection, as well as passive events coming from network probes. Among other information, each record contains an anonymized identifier of the user, a timestamp and the position of the tower to which the device is connected at that particular moment. This provides an indication of the geographical position of the user at certain moments along the day. The temporal resolution of the records depends on the frequency of use of the mobile device; most users typically generate a register at least every 15-20 minutes.

2. **Land Use data**. Land use data provided by the Directorate General for Cadastre in Spain (Cadastre), by built entity of the study area. The databases define the surface area [m^2] of each type of land use. The data set used corresponds to the update of January 24, 2020. Figure 1 represents the transport zones of the study area according to a classification of predominant land uses.

3. **Population Data**. Census data for 2019 at the census section level, obtained from the National Institute of Statistics. The data has been aggregated at the transport zone level, and it has been used as the sampling frame for expanding the sample of the MNO customers. Figure 1 shows the population distribution in the study area.

4. **Territorial boundaries**. The demarcation of the Morphological Urban Area (MUA) of Madrid has been obtained from the ESPON DATABASE project. The transport zones defined in Madrid have been obtained from the Open Data Portal of the Consorcio de Transportes de la Comunidad de Madrid.

5. **Data on State of Alarm phases and measures**. They come from the Royal Decree of the Ministry of the Presidency of the Government of Spain published in the Official State Gazette.

To extract meaningful mobility indicators, the sample is expanded to the total population of the study area. The expansion factor is calculated as the ratio between the number of residents of the district according to the census information and the sample of users with their home location at the given district.

In the present study the mobile phone records were used to build OD matrices with origin and/or destination in the 1,062 zones of the study area. The matrices were segmented by day and start time of the trip, considering 24-time segments.

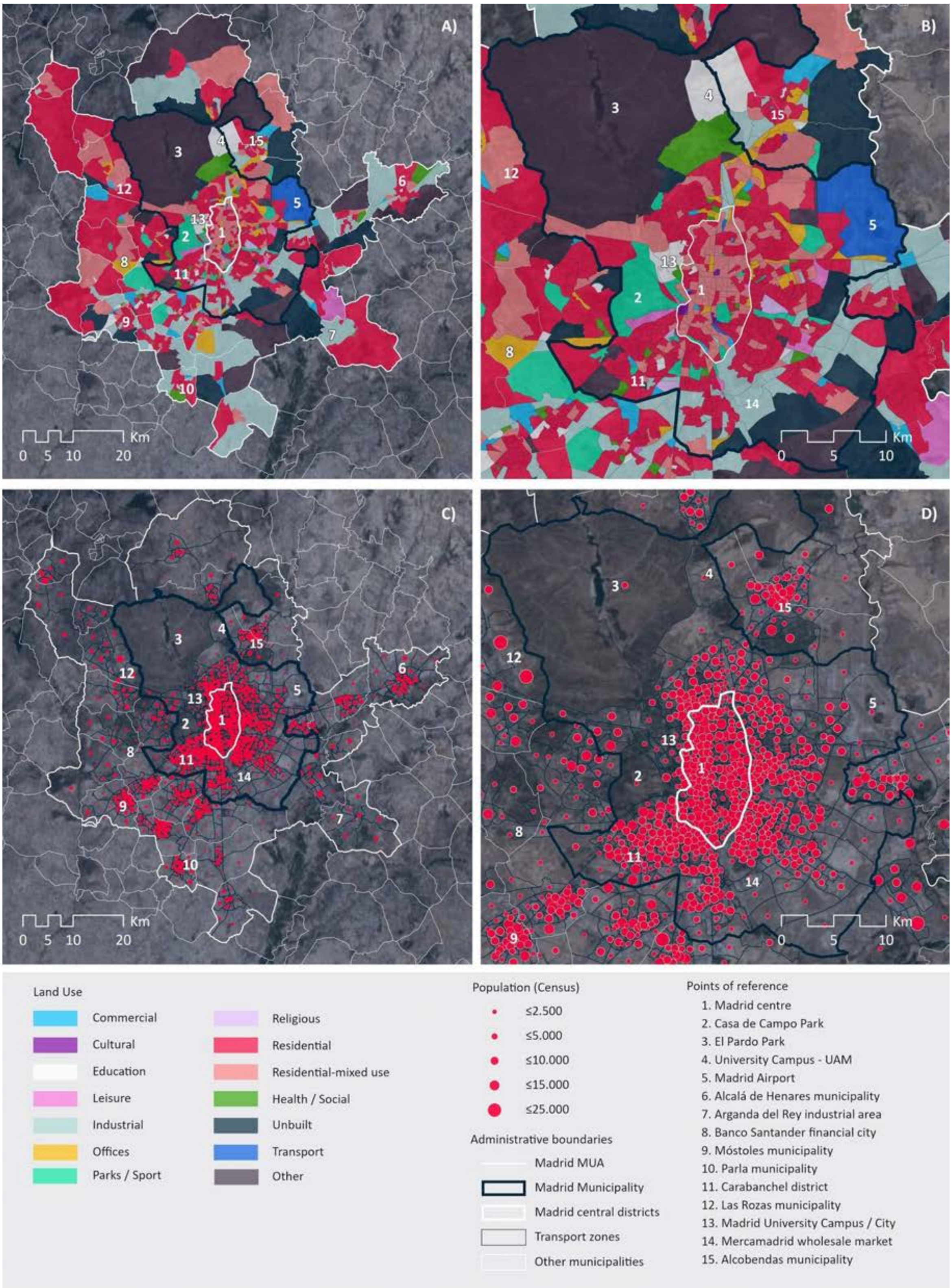

Figure 1: Land Use and Distribution of population (in the reference week at night) in the study area

2.3 Study of the spatial distribution of population according to time slot

Because of the different activities carried out, population distribution in the study area varies throughout the day. For analysis purposes, the number of people present in each transport zone for each hour and week was estimated from the O-D matrices. The following criteria were considered:

1. A single matrix of hourly trips per week was obtained, in which the average number of trips for each O-D pair is the average of the trips made between Monday and Thursday of that week.
2. It was considered that the number of people in the census corresponds to the number of people present in each transport zone at 02:00, when the lowest number of trips generated in W0 in the study area is observed.
3. The number of people present in each transport zone per hour was estimated as those indicated in the census (situation 02:00 hours) plus the sum of average weekly trips of people attracted to that transport zone, between 02:00 and the corresponding time, minus the sum of average trips for the week generated in that transport zone for the same time period.

Firstly, we explored the data through video-visualization, which represents the evolution of the population density [people/km^2] for each time slot in the reference week (W0) and the week of greatest restrictions (W2).

Secondly, bivariate Ordinary Least Squares (OLS) analyses were performed in order to compare the different population distributions according to time slots for each of the study weeks: Morning (08:00 to 14:00), Afternoon (14:00 to 19:00), Evening (19:00 to 22:00) and Night (22:00 to 00:00). The coefficient of determination indicates the degree of overlap between population distributions, while the regression residual maps show where differences (positive or negative) between time slot distributions emerge. This analysis was focused on differences between the reference time slot (night) and the rest of the time slots for each of the study weeks. These differences are expected to be especially high in the reference week W0 (people move within the city without restrictions) and particularly low during the week of strictest home confinement W2 (most people stay at home).

2.4 Analysis of temporal profiles according to predominant land use

Population presence according to predominant land use were calculated for each time slot and study week and represented through different temporal profiles. The total number of people present in a zone was assigned to the predominant land use in the zone, and then the total number of people according to land use was added up for each time slot in order to obtain the specific temporal profile of each land use in each study week.

With the aim of performing this temporal analysis, the percentage of built-up area pertaining to each land use in each transport zone was calculated based on cadastral data. Firstly, three main types of transport zones were distinguished: residential (when more than 66.6% of built-up area in the zone is residential), activity (when more than the 66.6% is non-residential, e.g. offices, industry, retail or education) and mixed residential (all other cases).

Secondly, activity (non-residential) areas were classified in 10 types: offices, industry, retail, health, education, culture, entertainment, large transport terminals, parks and others.

3.RESULTS

3.1 Spatial distribution of population according to time slot

The visual analysis of the spatial distribution of population according to time slope in weeks W0 and W2 shows a very clear picture of the impact of the measures restricting mobility and performance of activities established with the decree of the State of Alarm. During the lockdown week (W2), the population variations with respect to night-time distribution are minimal, which is also shown in the animated graph that represents the evolution of the population in each type of urban area according to the basic classification of predominant land use: residential, mixed residential and activity. However, a more detailed visual inspection reveals more significant changes in specific areas of the city, where activity registers a particularly sharp decline (for example in educational, financial or office areas) or where it remains at outstanding levels (some areas of logistics or health). Figure 2 shows a screenshot of the video-visualization, which is attached as supplementary material in this paper.

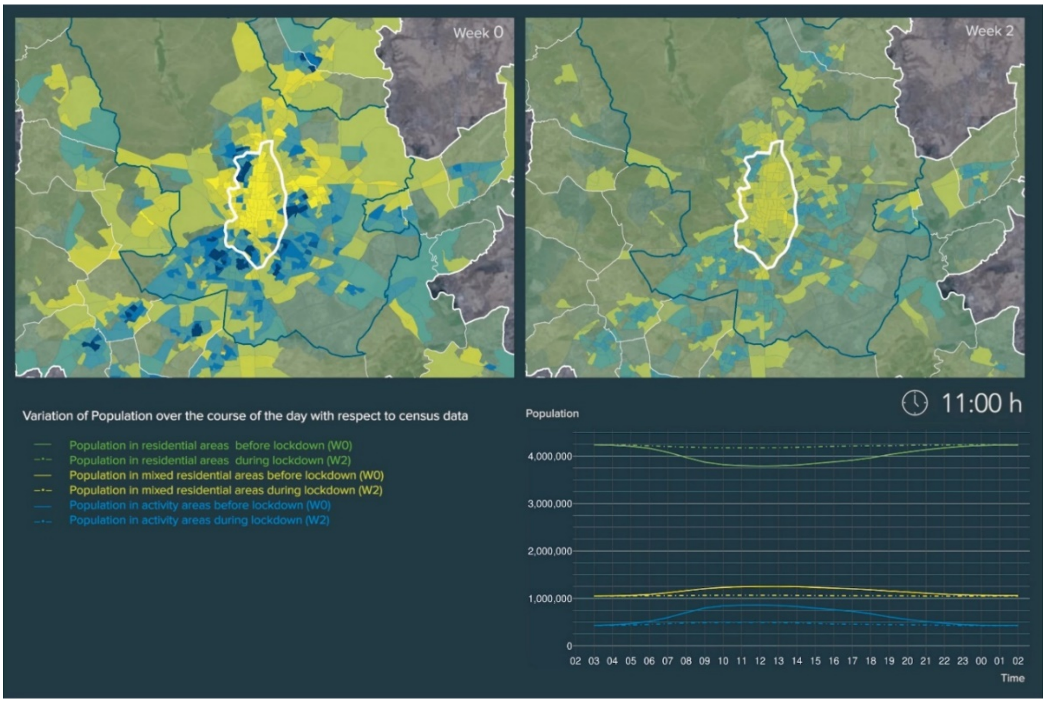

Figure 2: Layout of the video-visualization representing the variation of population density according to time slot for the reference week (W0) and the second week of the

lockdown (W2).

The first visual approximation is complemented by the weekly bivariate analysis between large time slots, allowing us to obtain a numerical indicator for comparing the different scenarios. Taking night-time as the base period, the differences in distributions of the population throughout the day can be analysed from bivariate correlations (Table 3). Madrid and its metropolitan area have a high mix of land uses, meaning that the coefficients of determination are high in all cases. The biggest differences are between night-time (residence) and morning (activities). On the contrary, between Night-time - Afternoon and, especially, between Night-time - Evening the correlations are very high, because many people have already returned to their areas of residence. The confinement situation makes the correlations between night-time and the rest of the time slots practically equal to 1.

Week	Morning 08:00 to 14:00	Afternoon 14:00 to 19:00	Evening 19:00 to 22:00	Night 22:00 to 00:00
W0 Night (22:00 to 24:00)	0.711***	0.814***	0.978***	1
W1 Night	0.987***	0.996***	0.999***	1
W2 Night	0.994***	0.998***	0.999***	1
W4 Night	0.984***	0.996***	0.999***	1
W6 Night	0.976***	0.993***	0.998***	1

*** P Value < 0.001

Table 3. Relationships in the distribution of population according to time slot (r^2)

A very different spatial behavior between night-time and morning in weeks W0 and W2 (Figure 3) is shown by the mapping of the correlation residuals. In a normal situation (W0), the morning activity spaces become highly active (positive residual in yellow), such as office areas (Points of interest 1 and 8) and mixed areas of the center, industrial areas (Points 4, 7 or 9), large facilities, university campuses (Point 2) or hospitals, as well as transport terminals, such as railway stations or the airport (Point 3). Whereas residential areas have high negative residues (blue color).

During the week of greatest restrictions (W2) the intensity of the residuals is very low. Some equipment areas are shut off (for example, Ciudad Universitaria - Point 2) and the intensity of activity is significantly reduced in the central office spaces (Points 1 and 8). On the other hand, some industrial spaces on the periphery now show the greatest deviations (Points 4, 7 and 9), together with strategic logistics facilities, such as Mercamadrid (Point 5).

Mercamadrid is the largest wholesale market in Spain, and presents an even greater deviation than in the reference week (W0), which is related to the fact that supermarkets increased sales during the first weeks of the state of alarm.

Finally, attention should be drawn to the activity detected in specific points of the city, such as the Feria de Madrid-IFEMA (6), which was converted into the largest emergency hospital in Madrid during the State of Alarm.

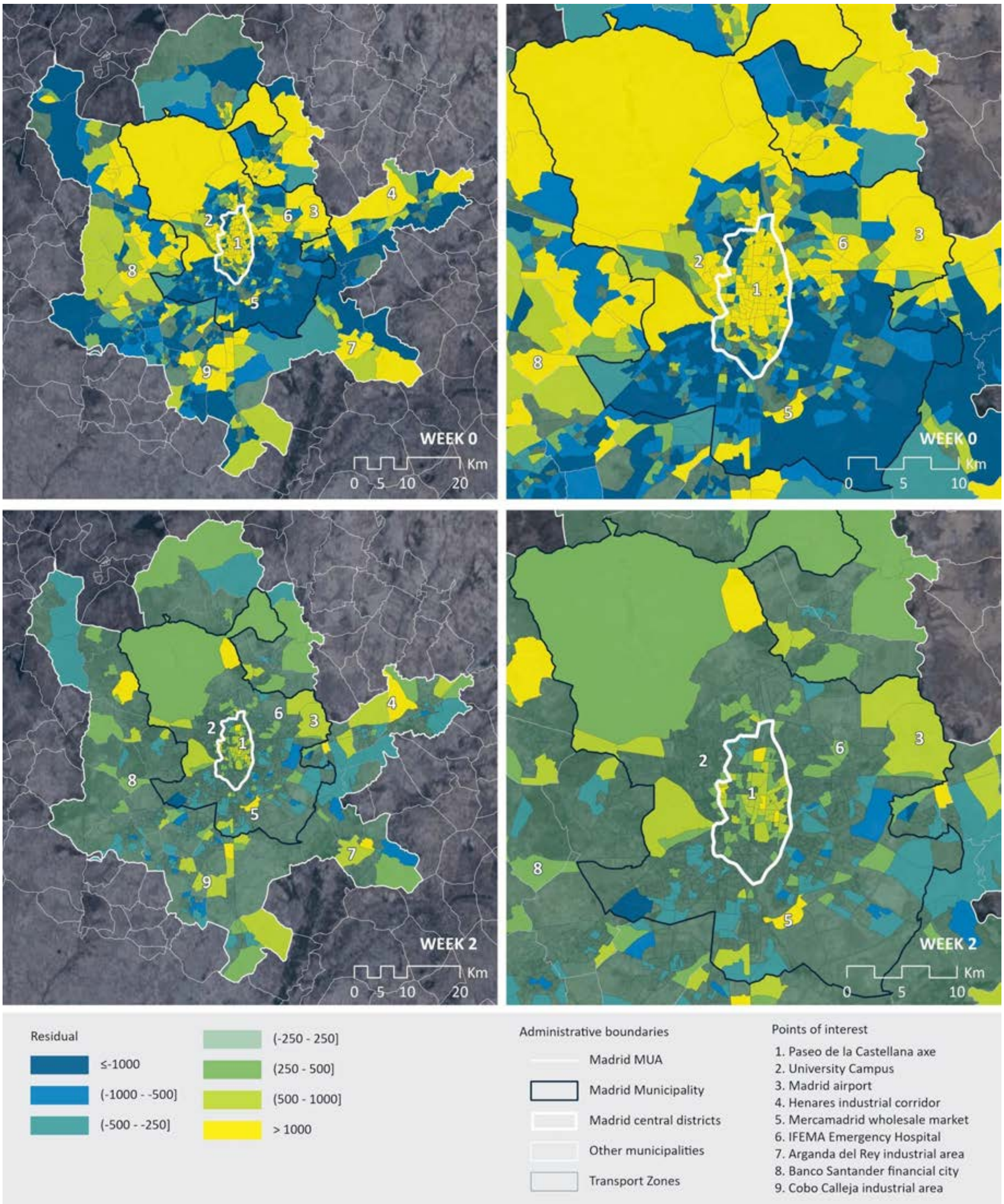

Figure 3: Residuals in the bivariate correlations of the distribution of population at night and in the morning

On the contrary, residential areas tend to lose a large part of their population during the hours of activity during the reference week (W0), while these losses have decreased substantially between night and morning in the week with the highest restrictions (W2).

3.2 Temporal profiles according to predominant land use

Population distribution according to land use and time slots for the reference week (W0) is shown in figure 4a. Most of the population can be found in residential areas during all time slots. Although residential use is dominant in these transport zones, other activities, mainly commercial, services and equipment can also be found. Many of these areas therefore maintain a high population presence also during working hours (morning and afternoon).

Temporal profiles according to large types of land use and their behavior during the weeks of the pandemic are very different from the reference week (Figures 4). In week W0, the departure of the population from residential areas does not compensate for arrivals. The areas of activity show an opposite profile, with very important gains in the morning and falling during the afternoon. The mixed areas have an intermediate situation. However, during the pandemic, the three curves have tended to flatten significantly. Data also show the evolution of the different phases.

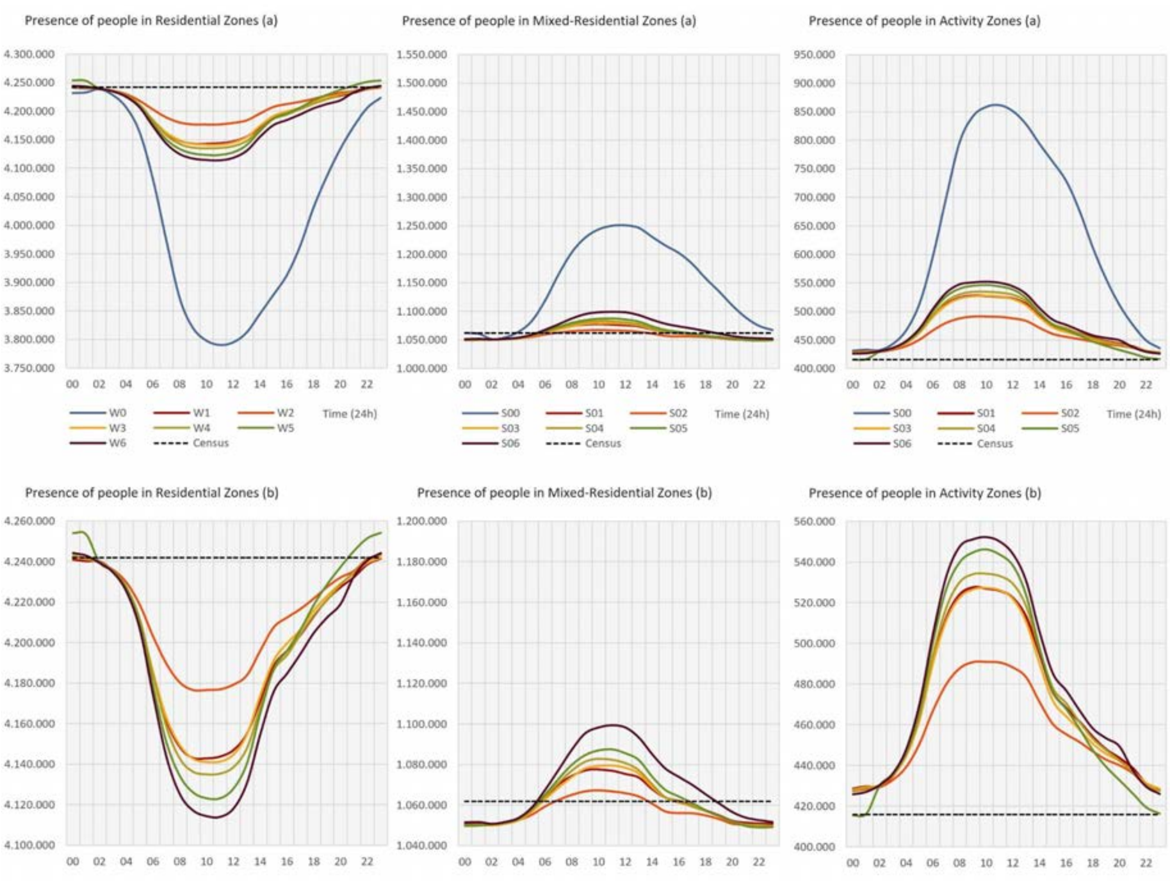

Figure 4: Population distribution profiles throughout the day during the study weeks (W1-W6), including the reference week W0 (a) and without it (b).

The temporal distribution of the population in the activity areas shows different profiles and different behaviors during the study weeks according to the characteristics of their activity (Figure 5). For instance, during the reference week (W0), the curves of office or industrial activities are very similar, however their behavior is different during the pandemic.

Office workers have been able to implement teleworking to a greater extent, so that the presence of the population in these spaces has been reduced very significantly, to the point of practically flattening the profiles.

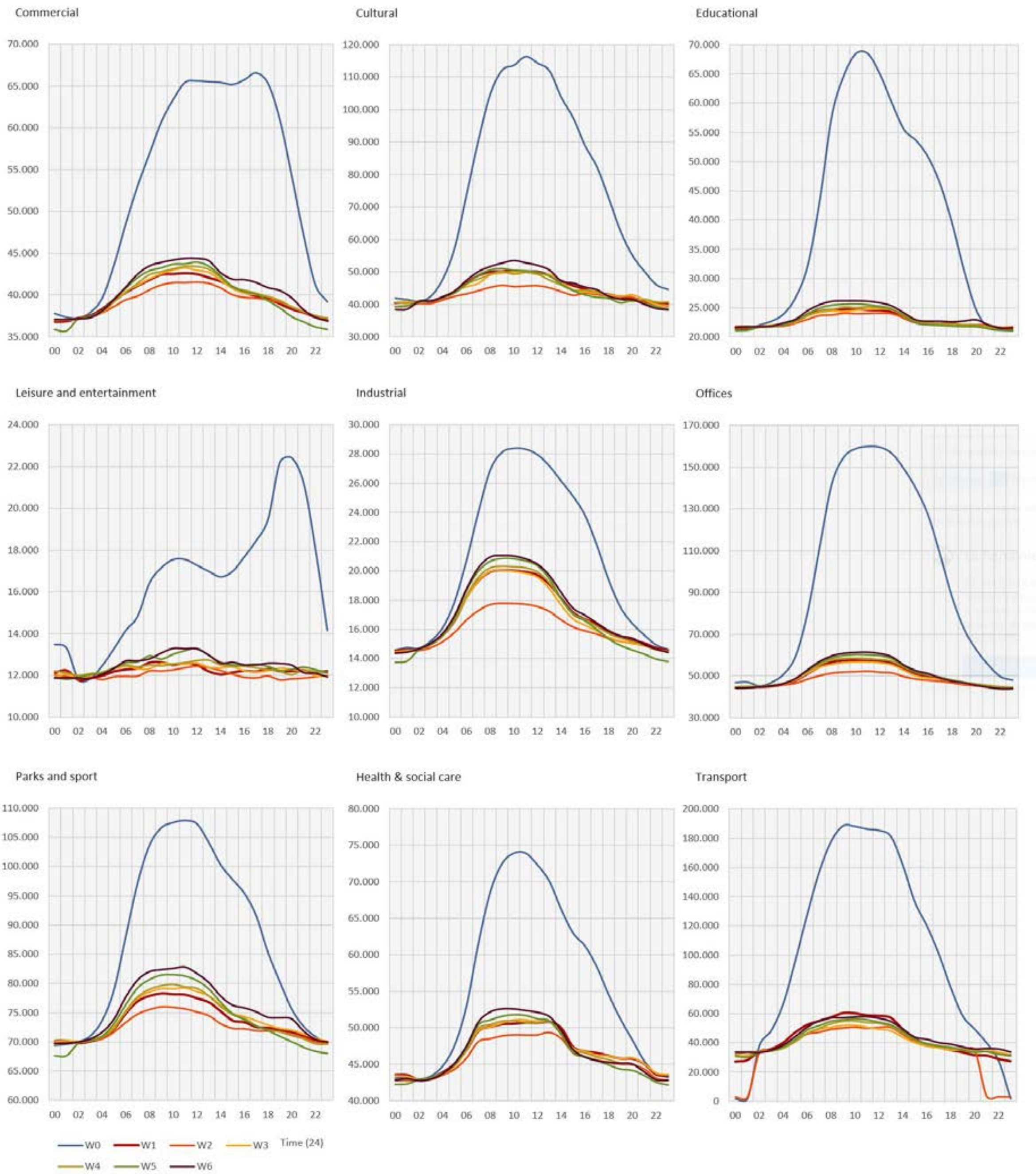

Figure 5: Population distribution throughout the day in the different activity areas during the study weeks (W0-W6).

4.CONCLUSIONS

The first visual analysis allowed us to explore the variation in population in the different urban areas throughout the day, comparing the reference week prior to the lockdown (W0) with that with the greatest restrictions on mobility (W2), showing very significant changes.

The second analysis, based on the study of bivariate correlations of population distributions between large time slots, allowed us to obtain a numerical indicator to globally compare the impact of the lockdown measures in the different study weeks. The city of Madrid presents a high mix of land use, so that even in a reference week (W0) the correlations between the strips are very high. However, while in week W0 the correlations between morning and night decreased, due to the differences between residential and activity spaces, correlations were practically 1 during the lockdown, showing a similar distribution of the population in all time bands at night. The mapping of the residuals of these correlations showed that the few active zones during the morning hours were mainly logistics and industrial areas (positive residues).

In addition, the hourly population distribution profiles for the dominant land use in each zone also showed a radical change with respect to the reference week (W0), especially in the weeks of greatest restrictions (W2). These profiles are simplified, since they consider only the dominant use, when in most areas there are several uses of the land. However, the results explicitly showed the drastic reduction in population in activity spaces in the morning and afternoon, while residential spaces conserve the population in those time bands. All profile curves tended to flatten significantly, but once again the activities related to industry, commerce or health maintained more active profiles, compared to very subdued educational, leisure or office areas.

The different analyses carried out provide helpful information for pandemic management and post-recovery planning. First, they enable us to improve our knowledge of urban dynamics during each of the confinement phases and the degree of restricted mobility of the population. Changes in population density according to mobility restrictions help to assess the level of follow-up of the measures. Second, they help us to determine in which spaces and activities a greater presence of the population is concentrated during the weeks with restrictions and those when the restrictions are lifted. This is of interest to identify the areas of the city, the activities and the population groups associated with them, which remain functional and, consequently, pose a greater risk of virus transmission. In addition, once the restrictions are lifted, these analyses will show the pace of the city's recovery and the different recovery speeds of each urban activity.

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UNDERSTANDING THE USER CHARACTERISTICS FOR SUBSTITUTING TRIPS BY TELEWORKING AND ONLINE SHOPPING

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ABSTRACT

This paper explores the user profile, spatial aspects, and mobility patterns affecting the adoption of teleworking and shopping online as a replacement for the working and shopping trip. The study is based on an EU-wide survey on mobility patterns and preferences with 26.500 respondents. The questionnaire combined socio-economic, mobility behaviour and the use of ICT in mobility-related issues, as well as teleworking and online shopping.

The methodology used combines classical statistical inferences and a classification Machine Learning (ML) algorithm to find the most important factors affecting the typology of the users adopting these tools.

The results suggest that while the new consumption patterns are high on average, the new working arrangements still have a margin to improve. Furthermore, there are significant differences among countries and between different socio-economic profiles. Online shopping was already prevalent, but teleworking was still limited (given that the survey was conducted in 2018, i.e., before the COVID-19 pandemic).
The findings of this work can be useful for the analysis of policies to encourage the uptake of new technologies in transport and mobility. Also, they can be a good reference point for future studies on the ex-post analysis of the impacts of the pandemic on mobility.

1. INTRODUCTION

Work and shopping constitute two of the main trip purposes for urban mobility and are responsible for the largest share of passenger transport activity (Eurostats, 2020).

Teleworking and e-commerce are two technology-enabled options that can modify individual daily mobility patterns and potentially reduce total transport demand and its associated impacts (energy consumption, CO2 and pollutant emissions, congestion, etc.).

The objectives of this paper are, on the one hand, exploring the main characteristics of individuals adopting teleworking and online shopping as a substitution of the trip to the workplace and to the traditional shop (socio-demographic, mobility-related characteristics, and the use of ICT). On the other hand, our target is to find the main election drivers by analysing the factors affecting the uptake of teleworking and online shopping.

2. METHODOLOGY

We used the second wave of the EU survey on issues related to transport and mobility, carried out in 2018, which applied a CAWI (Computer Aid Web Interview) methodology (Scarcella & Fiorello, 2017). The sample includes 26.500 questionnaires along with the 27 members of the European Union and the United Kingdom, with 1.000 respondents in each country, except Cyprus, Luxembourg, and Malta with 500 each. The sample was stratified by socio-economic characteristics based on age, gender employment status, level of education, and region of residence.

The questionnaire contains information on four categories: socio-demographics and car availability questions, information on the most frequent trip, details on medium and long-distance trips, and use of Information and Communication Technologies (ICT) related to transport, where trip substitution by teleworking and online shopping is included.

The analysis is based on a classification model, made by each of the studied variables, in which the outcome or **dependent variable** takes the value explained as follow.

On the one hand, it is defined a discrete dichotomous dummy variable **Telework (Y)** which takes the value 1 if the individual has ever replaced commuting by teleworking, once per month, 3-4 times per month, or more than 4 times per month. Likewise, the variable Y takes the value 0 if the respondent has substituted the trip to work only once or never.

On the other hand, and similarly to the previous one, the second analysis was made for the shopping trip substitution by e-commerce.

The variable **Online Shopping (Y)** takes the value 1 if the respondent has substituted the shopping trip by online commerce, rarely, sometimes, or often. Otherwise, the variable takes the value 0 if the individual has replaced the trip to the shop by buying online only once, or never.

The independent variables considered in the analysis, as explained before, include four categories (socio-economic and car availability, daily mobility, long trips and use of ICT).

3. SURVEY DESCRIPTION

In this section, we explore the impact of individual respondent characteristics on their choices, concerning telework and online shopping, by descriptive analysis, including frequency distributions and odds ratios. Later on, we use the machine learning algorithm XGBoost to obtain the relationship between the variables, highlighting the most important factors affecting individuals' choice and the overall impact on the outcome.

3.1. Trip substitution by teleworking

Males tend to telework at a higher proportion than female respondents. The odds ratio between the two genders is 1,4:1. The difference is probably due to a higher share of male respondents employed in jobs that are more suitable for teleworking. The relevance of the job type can be also induced from the correlation with education and income level. As a general trend, the ratio of teleworkers increases as the higher the education and the income level of the respondent is. Respondents with a university degree (or higher) are 2,4 times more likely to telework than respondents with just primary education. Similarly, the group of individuals with higher-middle or high-income levels are 3,8 and 6,1 times (respectively) more likely to telework than respondents with low-income level. Furthermore, looking at the income distribution by grouping teleworkers by age, we find the same pattern, so that, the higher the income, the more likelihood for teleworking. A teleworker profile that might be intuited based on the above is a male independent professional or manager with high education and high-income level.

Concerning age, the data shows an inverse association with teleworking, being the younger workers more likely to telework than advanced aged ones. This association may be related to younger's education in ICT and the lack of this type of skills in older people, but also because the group of students, normally young, might combine studies and telework.

The working day duration seems not to be an important factor for teleworking, neither seems to be for students who declare some type of telework. By contrast, people over 65 presents more probability to telework when part- or full-time work is declared, probably because they are linked to liberal and managerial professions.

Regarding the household place of residence, teleworkers present a higher likelihood of teleworking when they live in metropolitan areas or big cities rather than in small cities or rural areas. This might occur because teleworking is often linked with big companies usually placed in big cities.

Other factors affecting the probability of teleworking are car-related and mobility questions. Thus, people holding a driving license (motorcycle or car) presents a higher proportion of teleworkers. Taking this into account, owning a car presents also more teleworking probabilities despite this factor can be confounding and related to income level.

Nevertheless, individuals with a car subscription also tend to telework more than people without a car subscription, probably because this profile is associated with young professionals with low car availability and living in metropolitan areas where this kind of service is offered.

The most used mode of transport for the most frequent trip between teleworkers and not teleworkers is the car, followed by walking, private bicycle and bus services. However, using the car, the bus or going by foot are more used between non-teleworkers compared with teleworkers. Furthermore, the odds of teleworking are 5,5 times greater for bike-sharing relative to private car drivers, as do car-sharing users by 2,5 times.

In reference to the destination of the most frequent trip, the principal travel is made within the same urban area (49%) and to another urban area (34%), being this last movement more prevalent in the group of teleworkers. On the contrary, travelling outside an urban area is more prevalent in non-teleworkers. Once more, it could be due to the fact that teleworkers tend to live in metropolitan areas. Furthermore, the proportion of individuals commuting every day (or every working day) is higher in non-teleworkers compared with teleworkers.

On the contrary, people travelling two to four days per week is more prevalent in the group of teleworkers, travelling longer distances compared with non-teleworkers. This can be explained because of the size of the metropolitan city where teleworkers tend to live.

Another factor associated with teleworking is the number of long and medium distance trips, finding more trips for work business and study reason in the group of teleworkers, as well as for leisure and personal reasons. This behaviour may be associated with qualified jobs and the high-income level of the teleworker profile.

3.2. Trip substitution by online shopping

E-commerce is widely extended across Europe and is frequently used by male and female in the same proportion, being more prevalent in youngers compared with old-aged people.

Online shopping is also more used among people with high education level, for instance, graduates are 2,4 times more likely to shop online than individuals with primary education.

This could be due to higher ICT education but also because of the link with higher income level since above average income implies shopping online more frequently. For instance, people with high income are 2,3 times more likely to shop online than low-income individuals.

Similarly to the teleworking case, online shoppers tend to live in metropolitan areas and large cities, despite they have within easy reach a large product offer in the city. What is more, the bigger difference between online shoppers and traditional ones is presented in people living in the centre of a metropolitan area. At this point, this phenomenon can be explained because of gentrification of the city centre, the higher income level of the people living in central areas or the lack of car availability because of the vehicles ban in historical areas. This last assumption is reinforced with the fact that online and traditional shoppers holding a car driving license is similar. By contrast, the proportion of motorcycle license is bigger in the group of online shoppers, probably because they live in the city centre and this type of vehicles is more accessible within the downtown. Additionally, the proportion of people without a driving license is smaller in the group of online shoppers, hence not holding a driving license seems not to be a determinant for buying online.

The number of cars in the household, particularly two, presents a higher probability to buy online than households without a car. This could be explained because of the income level, nonetheless, households with more than two cars present the same proportion between online shoppers and traditional ones. This is not the case of car subscribers, where the relation is clearer, being 2,2 times more likely to buy online than non-subscribers.

The car remains to be the predominant mean of transport for the most frequent trip in both types of purchases. Concerning other means of transport, and in line with general mobility trends, walking, going by private bike and commuting by bus services are the most used means to reach the destination in the most frequent trip. This destination is usually located in the same urban area for almost half of the interviewed and more than one third are travelling to a different urban area, presenting a similar share between both types of shoppers. Given the fact that online shopping could avoid trips, we observe that people buying online tend to commute more frequently than traditional shoppers. For instance, the odds ratio of teleworkers travelling one day per week and daily commuters is 1:1,3. In addition, online shoppers spend more time and travel longer distances in the most frequent trip than traditional shoppers.

This could be due to the fact online shoppers living in metropolitan areas are more likely to commute more time and more distance to reach the frequent destination.

Lastly, online shoppers present a similar share of long-distance travels for work, business, or study purposes, but they are more likely to trip long distances for personal and leisure reasons. Furthermore, online shoppers do more medium distances trips for both purposes.

3.3. Methods

The initial data analysis suggests a strong correlation between teleworking or online shopping and certain respondent characteristics, but also suggest the existence of several confounding factors that can limit the possibility of interpreting the importance of each specific characteristic. Education level and income -for example- are to a certain degree correlated and a simple statistical analysis would not be sufficient to quantify their individual impact on the respondent's choice.

In order to solve that, we constructed a classification model that allows the generalization of the relationship between the variables taking into account the various collinearities. The model applied a tree-based approach using the well-known machine learning XGBoost algorithm. XGBoost has been tested and compared with Multinomial Logit Models in travel mode choices by Wang and Ross (2018) getting better performance. Other machine learning classifier in transport has been conducted in user choice modelling resulting in higher precision than conventional methods (Hagenauer & Helbich, 2017). Christidis and Focas (2019) analysed the uptake of electric and hybrid vehicles and car use (Focas & Christidis, 2017) within the EU using gradient boost decision trees and Random Forest respectively.

The model is set up in three parts randomly split. The first one is selected to perform the training model with 40% of the observations. The second one is the test set, with 40% of observations, which is used to evaluate the performance of the model trained before, using the previous model to predict the outcome. The third one is the validation set (20% of observations left), used to ensure the generalization of the model with unseen data.

Feature engineering is used to adapt the variables to the algorithm. We used One Hot Encoding (OHE) for the categorical variables.
XGBoost hyperparameters were selected based on the best AUC evaluation score, while the final variable election was carried out based on the outcome of the most important feature, from the predictor feature importance, and Shape Values.

The performance of the model has been evaluated with the AUC (Area Under the Curve) measure. The range of this evaluation goes from 0 to 1, being 0 when all predictions are wrong and 1 when all predictions are correct.

4. RESULTS

In this section, we describe the main results obtained from the analysis of the binary classification model regarding teleworking and online shopping.

We applied the XGBoost classification algorithm (tree-based Machine Learning model, non-linear model) to obtain the main factors affecting the uptake of teleworking and online shopping as a substitution of the trip for work and shop, respectively. For the teleworking model, the dependent variable takes the value 1 if the respondent has used this work system once per month or more, while takes the value 0 if has substituted the trip by teleworking once in his life or never.

Similarly, for the online shopping model, the outcome variable takes the value 1 if the shopping trip has been substituted rarely, sometimes, or often. If the respondent has used this service once or never, the variable takes the value 0.

In both cases, data pre-processing, feature selection, model training and evaluation has been performed. From all analysed variables, the most important features were selected in a second analysis to obtain a better performance. This selection was also based on how well these variables might explain the reasons why people perform telework and online shopping, thinking about causes and not effects.

The selected variables for the classification model were gender, age, education level, employment status, household members, income group, urbanization type, urban situation, driving license, number of vehicles per household, urban frequent destination, number of passengers in the last trip, country, population in 2018, vehicles per household member, car sharing subscription and urban-centre (combination of Urbanization type and Urban situation).

The number of observations after the data cleaning is 23.931.

4.1. Determinants of Teleworking

Once applied to the XGboost algorithm, the main factors affecting the trip substitution by teleworking are displayed in the next figure. The next graph represents the feature importance score for the most important variables ordered by how much they are helping in the prediction outcome. Thus, the more used to make the decision, the higher relative importance the variable will have.

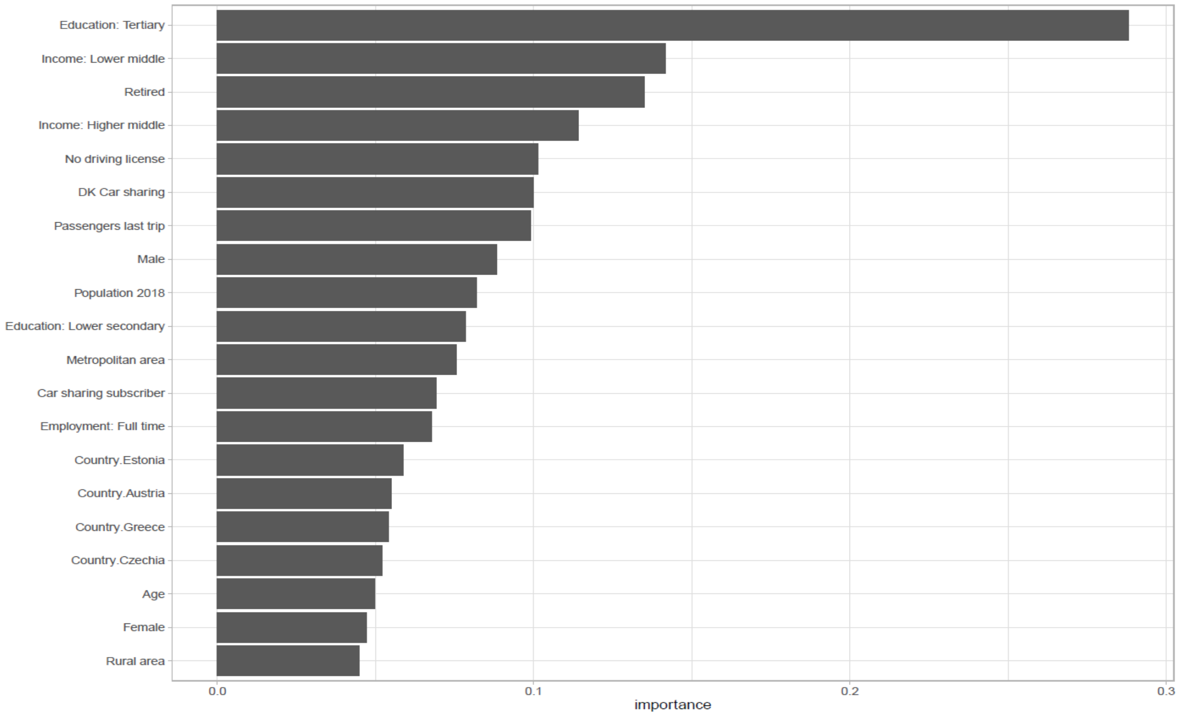

Fig. 1 – Predictor feature importance. Teleworking.

Prediction about using or not teleworking as a substitution of the working trip is influenced in the first positions by people with a high education level (tertiary or higher), with lower-middle and higher-middle income group, with employment status, with people without driving license, with gender (males), location of the household, country and age.

Figure 1 represents the main factors affecting the uptake of the trip substitution by teleworking, however, explainability is not the main feature of this kind of graphs. To resolve this, we use SHapley Additive exPlanation (SHAP), one of the most advanced methods to interpret results from tree-based models. SHAP values show the importance of each feature, the direction, and its contribution to the model outcome.

For the teleworking model, the contribution of each variable (impact on model output) is given through the shape value and the feature value as seen in figure 2. For instance, the first (and most important) variable found by the model to perform telework is having a tertiary education level, i.e., university degree or higher. The contribution to the model is given by the number on his side (0,288), which is the score. Following, we observe two dots, one yellow and one blue, meaning telework (value 1) and no telework (value 0). If the dot is on the right side, the contribution is positive, on the contrary, if the dot is on the left side will be negative. So that, having a tertiary level education will be positive for the model (feature value 1) and not having it will be negative (feature value 0)

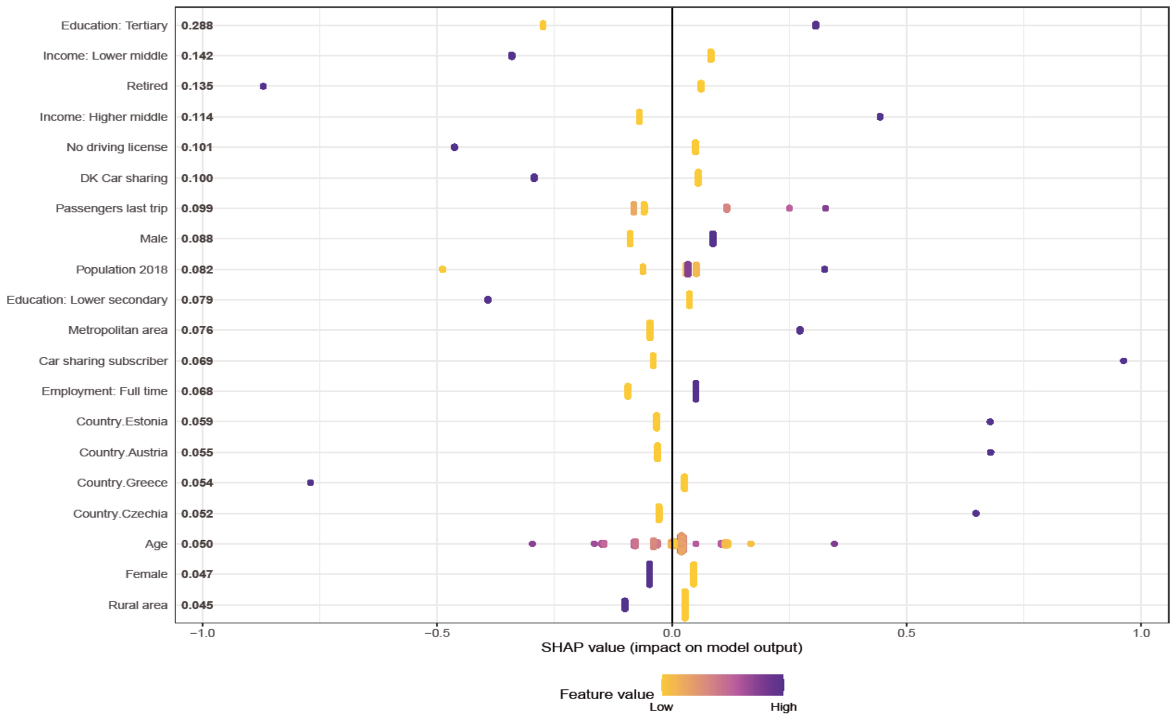

Fig. 2 – SHAP values. Teleworking.

The most important variable describing the likelihood for teleworking is to have a university degree (or higher) giving a positive value for the model, i.e., the model finds that people with high education level present more probabilities to telework. On the contrary, for individuals with a lower education level (lower secondary), the model finds a negative shape value, reducing in this case the teleworking likelihood.

Income level is normally linked with education level such as the model captures, so those individuals with lower-middle income present a negative shape value when replacing the working trip by teleworking and with higher-middle income present a positive shape value. In other words, people with higher-middle incomes tend to telework more frequently, while having a lower-middle income reduces the likelihood of telework. Gender appears to be also determinant. While male workers are more likely to telework, female professionals tend to work traditionally, probably because of the type of job developed typically by both genders.

Age presents a high variability as regards teleworking adoption, as seen in figure 2. While young people present a higher score (i.e., more prone to telework), the likelihood decreases until around 65 years old. According to the previous analysis, young professionals tend to telework more than seniors. However, when retirement age reaches, usually just liberal and managerial workers extend their professional career, precisely those with more probabilities to perform telework.

Regarding the employment status, we can identify respondents with full-time contract present a positive SHAP value (hence, full-time workers present more teleworking likelihood), in contrast to retired people, being negative, so that, retired people declaring having worked in the past are more likely to perform traditional work. This may be confounding with the previous paragraph, but it could be explained as far as retired declare to have teleworked in the past, while other people over 65 might remain working as an extension of his professional career.

Mobility patterns may also influence the teleworking choice. On the one hand, individuals without driving license are more prone to perform traditional work. On the other hand, car subscribers tend to telework more frequently, even though this profile normally is linked with high education level and living in metropolitan areas (where those services are present), which may be confounding for the model.

As for spatial factor, in accordance with the previous analysis, our model finds a positive relationship with metropolitan areas, meaning people living there present more chances to telework. By contrast, living in rural areas reduces the probability of teleworking. In addition, countries with a high population tend to telework more than countries with a low population, although work culture in every country is a determinant factor regarding remote work. For instance, individuals living in Estonia, Austria and Czechia got a positive shape value, resulting in more telework possibilities, while on the contrary, living in Greece gives a negative outcome, meaning fewer telework probabilities.

4.2. Determinants of Online Shopping

The following chart shows the main factors affecting the uptake of online shopping as a replacement of the traditional shopping trip.

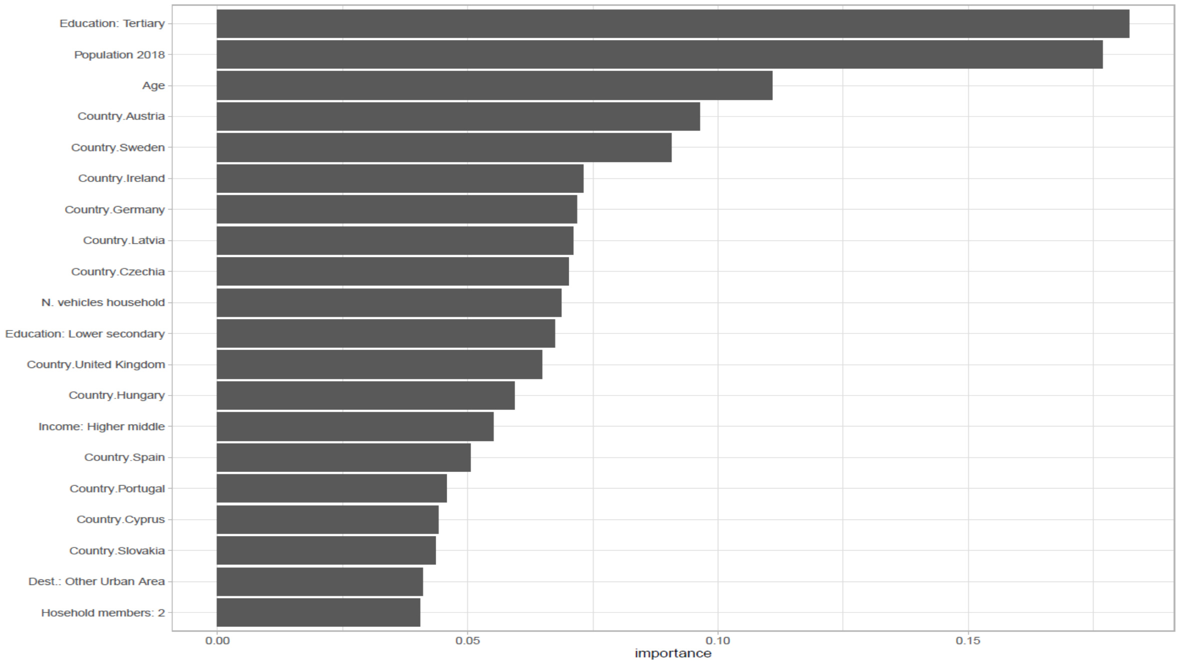

Fig. 3 – Predictor feature importance. Online shopping.

Predictions about using or not using e-commerce as a substitution of a traditional shopping trip are influenced in the first positions by people with high education level (tertiary or higher), with the level of population, age, and with people living in different countries like Austria, Sweden, Ireland, Germany, Latvia, or Czechia. It is also important the number of vehicles per household and the income level.

Next, we will explain with SHAP values the contribution of each feature affecting the prediction outcome found by the model.

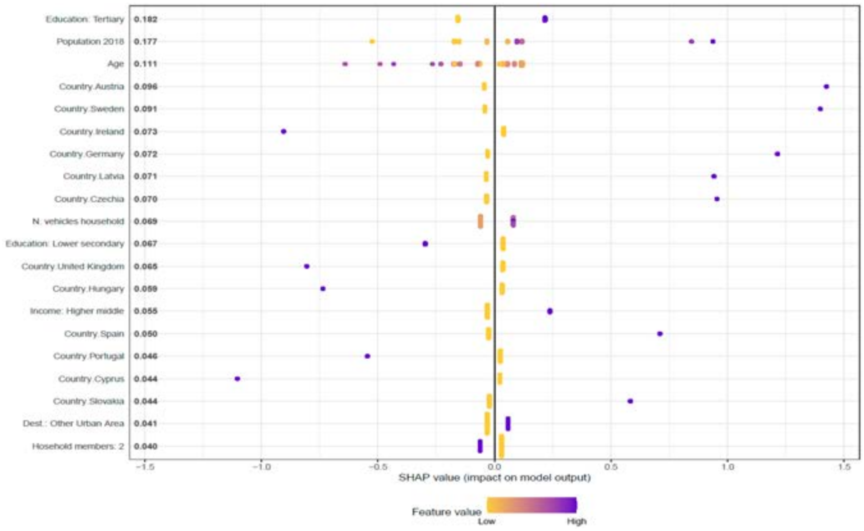

Fig. 4 – SHAP values. Online shopping.

In the same way as the teleworking case, having a high education level support the willingness to shop online as a substitution for the shopping trip, whereas people with lower secondary education tend to buy online less. Similarly, when income is higher-middle the predisposition to buy online increases. Furthermore, people between 19 and 46 years tend to shop online more frequently than younger and older individuals. In the first case probably because the acquisition power is lower, and in the second because of the lack of digital education.

Regarding individuals’ location, the model suggests high-populated countries tend to buy online more frequently than smaller countries. The country of residence appears to be a clear determinant factor affecting the online shopping choice. Countries like Austria, Sweden, Germany, Latvia, Czechia, Spain or Slovakia present a higher share of e-commerce than countries like Ireland, the United Kingdom, Hungary, Portugal or Cyprus. This result is difficult to explain given that there is not a clear pattern between both country groups, but differences in economic structure, culture and education factors, mobility schemes and accessibility or even supply chain may affect the uptake of online shopping.

4.3. Model performance

In this section, the analysis of the XGBoost classification model performance is presented. The most frequently used metric for classification problems is the Area Under the Curve (AUC) or Receiver Operating Characteristic curve (ROC). This aggregated measure of the model performance summarizes the True Positive rate (TP), versus False Positives rate (FP), by using different probability threshold.

In table 1 we present the results of the AUC-ROC test for teleworking and Online Shopping models for the test and validation datasets. The AUC range goes from 0 to 1, being 0 when all predictions are wrong and 1 when all predictions are correct.

Model	AUC Test	AUC Validation
Teleworking	0,712	0,710
Online Shopping	0,706	0,706

Table 1 – Summary of model performance.

Both models achieve a fair level of prediction, given the extensive number of variables included in the model.

5. CONCLUSIONS

This research explores the main determinant factors of teleworkers and online shoppers' profiles, replacing the trip with online procedures. The XGBoost algorithm used returns the most important factors and the impact on the model output, allowing us to determine the profile of individuals using this kind of services.

Firstly, our results confirm that the most important factors to substitute the working trip by teleworking are in general terms, having a high education level and a high-middle economic status. Gender remains determinant as far as men continue to be more likely to telework than women. As seen in the data analysis, living in low-populated countries perform fewer probabilities to telework than high-populated countries, being more likely in metropolitan areas with over one million inhabitants. However, living in certain countries favours the adoption of teleworking.

Secondly, our analysis also shows the profile of online shoppers replacing the shopping trip by e-commerce, being more likely to perform this activity by people with higher-middle education level, living in countries with high population, even though there is a high disparity between countries. The age continues to be determinant, but the range spreads from young people to the mid-age population.

The high dispersion between countries on the teleworking and online shopping adoption shows a high diversity among different regions and can be useful to bridge the gap for those who have less adoption for both ways of reducing trips through ICT.

Teleworking and online shopping can be two excellent tools to avoid trips and their negative effects (energy, congestion, pollution, transport externalities) but they must be monitored to address negative rebound effects. These rebound effects do not have to be necessarily negative. For instance, as far as more people can telework full time outside the default place of work, it can help rural or low-populated cities to attract new citizens looking for a bigger and cheaper house to live in, which eventually could change real estate market prices in big cities.

It has been mentioned high differences among European countries in the uptake of teleworking and online shopping to avoid trips. Likewise, the intensity of use shows a high variation.

On the one hand, Eastern Europe presents the lowest rate of teleworking, whereas most intensive teleworkers (declaring teleworking “often”) are placed in Finland, Austria, and the Netherlands. Besides, people declaring teleworking “sometimes” is more prevalent in Sweden, Iceland, the UK, the Netherlands, and Switzerland.

On the other hand, countries like Austria, Germany, Czech Republic, France, Sweden, and Spain present the most active (“Often” & “Sometimes”) share of online shoppers. On the contrary, countries like Cyprus, Ireland, Hungary, and Portugal present the lowest rate of e-commerce interaction (“Never” & “Once”).

As far as clean transport become more spread in the transport sector (higher share of rail mode, generalization of the electric vehicles, rising successful deliveries and optimization routes), the benefits of online shopping will be higher than now. However, congestion and most of the associated externalities will not improve with this change of technology, even though other technologies as automated cars could enhance this situation.

The scope of teleworking and online shopping remains uncertain and future work should be compared in upcoming years in order to see the evolution of these tools and the contribution to the GHG emissions mitigation. This upcoming work should answer questions about the real adoption of teleworking and online shopping habits in Europe in the post-pandemic era when both tools perform in a stable situation.

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ECONOMÍA DEL TRANSPORTE
ECONOMY ON TRANSPORT

EX-POST EVALUATION OF GOVERNMENT LOANS PROVIDED TO SHADOW TOLL MOTORWAYS IN SPAIN

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ABSTRACT

Budgetary constraints are prompting many governments to encourage private financing of transportation infrastructure through Public-Private Partnerships (PPPs). Fiscal support measures have been often used to improve the financial feasibility of these projects, but also to rebalance the economics of the contracts to compensate for changes imposed by the government. This paper analyses the awarding of subordinated public participation loans (SPPLs) to ten brownfield shadow-toll motorway PPPs in Spain after additional works were imposed by the government. SPPLs are government loans, subordinated to the senior debt, that were intended to facilitate the PPP contractors the financing of the aforementioned works. This paper evaluates the financial and social impacts of the awarding of these loans to three of these projects. To that end, the SPPL repayment capacity of the PPPs and the social benefits derived from the improvement in road safety are estimated to evaluate whether the government's decision to support these projects was justified from a social perspective. The results show that, although the government's decision was reasonable, the design of the SPPL and its awarding conditions should be improved to guarantee the public interest.

1. INTRODUCTION

Over the last few decades, budgetary constraints have led many governments to implement new mechanisms to encourage private sector participation in the financing of infrastructure (OECD, 2008). In this respect, Public-Private Partnerships (PPPs) and concession approaches have acquired a special prominence, particularly regarding the construction and operation of transport facilities. Through these schemes, the private sector finances, builds, maintains, and operates the infrastructure in exchange for a fee linked to either demand or availability for a period of time contractually agreed in advance (Yescombe, 2007). Fiscal support measures have often been used to improve the financial feasibility of these projects (Vassallo and Sánchez-Soliño, 2007), but also to rebalance the economics of contracts to compensate for changes imposed by the government.

However, this form of government intervention may impose greater risk on the government and even threaten the financial sustainability of the public sector.

This paper evaluates the awarding of subordinated public participation loans (SPPLs) to ten brownfield motorway PPPs in Spain (known as first-generation motorways) as a means to rebalance their economics after the government imposed additional works not included in the original contracts. These government loans, subordinated to the senior debt, were intended to facilitate the PPP contractors the financing of the aforementioned works. On the one hand, the upgrading of these motorways, built in the 1980s, was deemed necessary by the government given the large increase in traffic volumes and accident rates. On the other hand, the conditions of these loans were very advantageous for the PPP contractors, to the point that could be considered insufficient to guarantee the interest of the State against that of the shareholders. The objective of this research is to evaluate whether the government's decision to support these projects was justified from a sustainability standpoint, taking into account the social benefits, the financial feasibility of the loan and the public interest. To that end, an *ex-post* evaluation of the financial and social impacts of the awarding of the SPPLs to three of the ten PPP contracts of the first-generation motorways is carried out.

The paper is organised as follows. After the Introduction, Section 2 focuses on the Spanish PPP context and describes how SPPLs are implemented to support infrastructure PPPs. Section 3 describes the case study, particularly regarding the context and conditions under which the SPPLs were awarded. Section 4 outlines the methodology adopted to evaluate the SPPLs performance from the sustainability point of view and the suitability of the government's decision to support the projects. Section 5 presents the results of our analysis. Section 6 discusses the results and sets out the most relevant implications arising from the case study analysed. Finally, Section 7 presents the main conclusions and highlights further research questions.

2. SPANISH SUPPORT TO PPP PROJECTS

Spain has extensive experience in promoting toll motorways through concession contracts. Since the late 1960s, 54 concessions totalling 3,307 km have been awarded, of which 2,759 km are State motorways (Ministerio de Fomento, 2018). Since the late 1990s, the country has gained significant experience in shadow toll road projects. At the regional level, 26 shadow toll projects totalling around 1,200 km (Acerete et al., 2018) have been awarded so far. For its part, the Central government has tendered and awarded 10 projects based on a combination of shadow toll and availability payment approaches, and one project that relies entirely on availability payments, totalling 1,042 km altogether.

Although these schemes have allowed the construction and update of an extensive network of high-quality privately financing motorways, they have prevented neither overcapacity nor frequent recourse to contract renegotiation, with consequent changes in initial terms, prices, and recourse to public aid (Engel et al., 2015). In this respect, Spanish law obliges the government to restore the economic balance of the contract, to the benefit of the relevant party as it corresponds, in the following cases: (i) when the government modifies, for reasons of public interest, the contractual terms originally agreed; (ii) when circumstances of force majeure or actions undertaken by the government lead directly to the substantial disruption of the economics of the contract; and (iii) when the assumptions established in the contract itself for its revision occur. However, the Spanish Government has gone beyond these causes to avoid the bankruptcy of road concessions. This way of acting has been highly motivated by the effects of a legal provision (known as the State's Financial Liability) included in the public contracts law that regulates the compensation to the PPP contractor in case of early termination of the contract. This clause commits the government to compensate the private sponsors for the works that have been built and not yet depreciated in case that the early termination of the contract has not been caused by their negligence. It is worth noting that, until the amendment of the public contracts law in 2015 (Law 40/2015), bankruptcy caused by low traffic levels was not considered negligence by the private sector so it prompted this compensation. This situation encouraged the government not to let concessionaires go bankrupt and, consequently, to assist them when they experienced financial difficulties (Baeza and Vassallo, 2011).

As a result, a large number of concessions have had their economic balance restored so far (Acerete et al., 2018; Baeza and Vassallo, 2011) at the expense of the user, the taxpayer or both. Mechanisms often used to adjust the economic balance of contracts include contract term extensions, fare increases, *ex-post* introduction of revenue mitigation mechanisms, and the awarding of cash subsidies or SPPLs. These government loans are presently the most important public instrument for supporting PPP contracts in Spain since they allow to improve the financial feasibility of projects without increasing the national public deficit, but also establish a fairer means of sharing profits between the private sector and the government (Vassallo and Sánchez-Soliño, 2007).

2.1 SPPL's Regulation

SPPLs are currently regulated by Royal Decree-Law 7/1996, which defines them as a subordinated financial instrument whose main characteristic is that the lender would receive a variable interest depending on the evolution of the outcomes of the borrowing company's activity. The criteria to determine such evolution may be either profit, revenues, sales or any other variable demanded by the government or freely agreed by the contracting parties. The characteristics of these loans can be freely designed by the government as long as they comply with three rules (Vassallo and Sánchez-Soliño, 2007):

- SPPLs must always be subordinated to other senior debt. Therefore, SPPL holders (the government in this case), will be repaid only after the PPP contractor has met its obligations to the senior lenders.
- The expected return of SPPLs must be related to the economic performance of the PPP contract. The idea behind this approach is that the government partially shares the project's profits and losses with private sponsors.
- The expected yield of SPPLs should be market–based, otherwise the government could use SPPLs to provide hidden subsidies that should be accounted for in the public deficit.

Likewise, the PPP contractor may not amortise the borrowed capital in advance, unless the early amortization implies payment of the net present value of the expected future benefits according to the economic-financial plan approved by the competent government body at the time of the return of the capital.

Although this mechanism has important advantages compared to other means of fiscal support, it also has some issues (Vassallo and Sánchez-Soliño, 2007). One of the problems is that the government could misuse this mechanism as an implicit subsidy by providing loans that the PPP contractor will ultimately not be able to repay. Also, this mechanism turns the government into a borrower of the project. Therefore, if the project does not perform as expected, the annual interests incurred will significantly decrease while the risk that the loan is not repaid will increase. Finally, if the supported project cannot turn its financial position around and goes bankrupt, the contract must be liquidated with the consequent activation of the State's Financial Liability. In that case, the government —and ultimately the taxpayer— will bear both the costs associated with assuming responsibility for the infrastructure and the non-repayment of the SPPL and its interests until the end of the contract.

2.2 Practical implementation of SPPLs in motorway concessions and PPPs in Spain

SPPLs have been implemented by the Spanish government either as an *ex-ante* support mechanism or as an *ex-post* means to rebalance the economics of concession and PPP contracts. Regarding the first case, bidders have been offered the possibility of requesting SPPLs at an early stage of the procurement process to strengthen the economic feasibility of the project and, consequently, encourage private participation in the tender. This approach was used, for example, in 2004 in the procurement of the *Cartagena-Vera*, the *Madrid-Toledo*, and the *Ocaña-La Roda* motorways and the Alicante's ring road; and, two years later, in the procurement of the *Málaga-Alto de las Pedrizas* motorway (Vassallo and Sánchez-Soliño, 2007).

However, SPPLs have also been granted to already awarded PPPs to compensate the contractor for amendments to contracts or changes made by the government on the grounds of promoting the public interest; or to improve the viability of PPPs in the event of poor economic performance or even on the brink of bankruptcy. The suburban toll motorway concessions around Madrid (R-2, R-3, R-4 and R-5) represent a good example of the use of this instrument by the government in a failed attempt to avoid those concessions going bankrupt. The economic performance of these concessions was pretty damaged by traffic shortfalls caused by the economic recession (and an overly optimistic estimate of traffic demand), and large cost overruns in the expropriation process. In this context, the government granted SPPLs to help them pay the additional costs incurred when acquiring the right-of-way and to provide liquidity because of the revenue shortfall (Baeza and Vassallo, 2011; Vassallo et al., 2012). However, despite the regulatory and financial aid, estimated at around €600 million, all concessionaires eventually went bankrupted (Bel et al., 2017).

Another example of the use of SPPLs to rebalance the economics of the contract to compensate PPP contracts for a discretionary change in the initial contractual conditions by the government is the present case study. As will be later explained, PPP contractors of the first-generation motorways received SPPLs as compensation for the government's imposition of additional works not foreseen in the original projects.

3. CONTRACT ANALYSIS OF THE FIRST-GENERATION MOTORWAY PPPS

3.1 Main characteristics

In 2006, the Spanish Ministry of Transportation (MT) launched the First-Generation Motorways Plan (hereinafter the Plan). Its purpose was to improve the alignment standards, quality and safety levels of a set of important motorways in Spain that were built in the early 1980s with quality standards far below those of motorways designed and built years later, making these roads much less safe than the rest of the network. Given the government's budgetary constraints and the need to improve the roads as soon as possible, the government decided to procure them as PPPs. Thus, the MT tendered the upgrading, maintenance and operation of eleven brownfield sections, totalling 993 km, which were finally awarded during 2007.

The contracts included three types of works: (i) initial works to adjust the motorway design to the current technical and functional standards required; (ii) major repairs to guarantee a proper level of service; and (iii) routine maintenance activities throughout the life of the contract. The private sector was entrusted with the design, financing, construction and operation of the infrastructure for a period of 19 years.

The government decided to keep the motorways free of charge by using a combination of shadow toll and availability payment approaches, committing itself to pay a fee to the PPP contractor based on both traffic demand and a set of performance indicators during the life of the contract. The “demand fee” is calculated monthly according to (i) the type of vehicle (light or heavy); (ii) the number of vehicles-kilometres of each type circulating on the motorway; (iii) the fare applicable to each type of vehicle per kilometre travelled; (iv) until the completion of the initial works, the percentage of motorway section in service at the end of the previous year; and (v) the correction factor, upwards or downwards, depending on a set of performance indicators stated in the contract that measure the condition of the road and the quality of service provided.

3.2 Amendments to the contracts

The financial crisis, which began shortly after the contracts were awarded, had a great impact on the actual traffic volumes on the motorways. This situation was exacerbated by the government’s reluctance to approve the definitive designs provided by the PPP contractors, which caused important delays in the beginning of works. In these circumstances, the feasibility of the contracts was at risk, and with it the possibility of improving the motorways and, henceforth, their safety rates. For this reason, in 2010 the government prompted an overall change in the contract terms aimed at both including additional works and imposing stricter requirements considered indispensable to provide the right service.

According to Spanish law, the government has the right to change the terms of the contract to bring it closely into line with the public interest. If this change affects the economic balance of the contract, the initial conditions can be modified in favour of the private contractor or the government to compensate for this change (Vassallo et al., 2012). The main measures established for restoring the economic balance of the PPP contracts included: (i) the increase in the fares originally approved to compensate for additional works; and (ii) the possibility of granting SPPLs to PPP contractors to finance these additional works. The criterion established to calculate the new fare was to preserve the Internal Rate of Return (IRR) before taxes of the projects. The PPP contractors submitted new Economic-Financial Plans (EFPs) that included the additional investment and the new fares and, once approved by the government, became part of the contract documents. This rebalancing meant an increase in fares ranging from 21% to 67% over those initially approved, and an average increase in the price of the contracts for the government of around 37%. In addition, the value of the SPPLs granted to PPP contractors reached almost €400 million.

3.3 Granting of SPPLs

The PPP contractors were also granted SPPLs as compensation for the government's requirement of additional works not foreseen in the original contracts. The selection of this mechanism was motivated by two main reasons: (i) to facilitate the PPP contractors the financing of additional works at a time when the country was going through a deep financial crisis, and (ii) to avoid incurring a greater public deficit, since the Euro Pact required Spain to adopt strict control over national public accounts.

The conditions of the SPPLs were very advantageous for PPP contractors. First, the debt to the State was classified as subordinated debt, which allowed contractors to reduce pressure on equity, improve the risk profile of the senior debt and mitigate the liquidity risks of the project. Secondly, the repayment of the principal was set to take place six months before the end of the contract through a single payment. These repayment conditions allowed them to benefit from the entire loan during the whole contract period. Thirdly, a three-year grace period was established for the payment of the loan interests. The interests accrued in this period are to be capitalised together with the loan principal. This allowed the private sponsors not to pay interests during the most sensitive stage of the project, the construction phase. Finally, interest rates were, at least initially, below those of the market since the government would receive as remuneration from the loan the higher of the following amounts: (i) the amount resulting from applying a fixed interest rate of 175 basis points on the outstanding SPPL, or (ii) the amount resulting from applying equation (1).

$$R = 0.5 \times I \times \frac{RaDf}{MaDf} \times PL \qquad (1)$$

where R is the annual remuneration; I, the project IRR before taxes; RaDf, the actual annual demand fee; MaDf, the maximum annual demand fee; and PL, the outstanding amount of the participation loan.

4. METHODOLOGY USED IN THE CASE STUDY

This section undertakes an *ex-post* evaluation of the impacts of the SPPLs awarded by the government to the PPP contractors of the first-generation motorways. These projects have exceeded half of their contract period, which is a reasonable time to conduct the analysis proposed. Specifically, three of the ten sections are analysed: (i) *Autovía del Arlanzón* (A1-T2), the project with the best economic performance among the first-generation PPPs so far; (ii) *Autovía Medinaceli-Calatayud (Aumecsa)* (A2-T3), the worst economic-performing project within the sample; and (iii) *Autovía de los Llanos (Aullasa)* (A31-T1), which has shown an average economic performance compared to the rest of the first-generation motorways. The analysis is aimed at evaluating the positive and negative impacts of the government's decision to support these projects from the financial and social perspectives. The methodology used comprised 3 main steps that are summarised below.

4.1. Selection of a set of performance indicators

The first step consists of the selection of a set of indicators to assess the actual performance of the selected PPP projects from 2010 to 2015. Two different types of indicators are selected: financial and social. On the one hand, the evolution of the financial indicators will later be compared with that foreseen in the EFPs approved after the economic rebalancing of the contracts. This comparison will allow us to evaluate whether the projects are performing as expected from the financial standpoint and, consequently, if they will be able to face the payback of the SPPLs principal. On the other hand, the social indicators are intended to evaluate the benefits arising from the projects themselves to evaluate their social feasibility. The financial indicators selected are investment, income, and dividends; and the social indicators: accident rates and anticipation in the commissioning of the works.

4.2 Analysis of the financial sustainability for the government

The second step consists of analysing the financial impact of awarding the SPPLs for the government. To that end, the capacity of the PPP contractors to repay the principal of the loan together with the capitalization of the interests accrued during the three-year grace period is assessed. Since the reimbursement of the SPPL will take place six months before the end of the PPP contract, the last year's free cash flow (FCF) (2026) for each PPP is estimated. It is considered that, as there is no mandatory imposition of creating a reserve account, the SPPL repayment will be borne with last year FCF. This is a crucial variable to evaluate the capacity of the PPP sponsors to repay the SPPLs, given that other senior loans should have been previously repaid, as is usual in project finance.

For its calculation, the evolution of the main variables affecting the PPP cash flow in the period 2017-2026 is estimated by assuming the elasticities to socioeconomic variables calculated by previous research studies for the case of Spain (Gomez et al., 2015; Gomez and Vassallo, 2016). According to the aforementioned authors, there is a marked and stable correlation between the variation in GDP per capita and the evolution of light vehicle traffic; and between the variation of industrial GDP and the evolution of heavy vehicle traffic. In order to allow for uncertainty in the evolution of the economy, we have defined three potential scenarios based on the forecasts of Spanish GDP growth from different agencies: a base scenario, an optimistic scenario, and a pessimistic scenario. Then, the simplified FCF estimate is made for each project and scenario by calculating the difference between income and expenditure. Finally, we estimate whether the government is running a risk of not being repaid by contractors by comparing the expected FCF in 2026 with the SPPL commitments to be reimbursed by contractors that year.

4.3 *Ex-post* evaluation of the social impacts of the SPPLs

The last step of the methodology consists of assessing whether the government's decision to support these projects was justified from a social perspective. To that end, an estimate of the social gains of the projects in terms of improved road safety is used as a proxy of the social impact derived from the awarding of the loans. The estimation has been carried out following the methodology developed by Pérez de Villar (2015), whereby the annual social benefit derived from improving road safety on a certain motorway is calculated according to equation (2):

$$SB_{annual} = PIA\ x\ V_{PIA} = (PIA_{ex} - PIA_{\mathrm{r}})x\ V_{PIA} \tag{2}$$

Where: PIA is the number of accidents with victims avoided as a result of the execution of a certain measure, which is calculated as the number of accidents expected on the motorway according to the general trend (PIA_{ex}) minus the real number of accidents that occurred in the motorway (PIA_{r}). Since PIA_{ex} is a highly uncertain value, Pérez de Villar (2015) recommends using as an approximation of the average value corresponding to roads with similar characteristics. V_{PIA} is the average statistical value of avoiding a victim in a traffic accident on roads with characteristics similar to that analysed, which is calculated according to equation (3).

$$V_{PIA} = \frac{\sum_{sr} FAT x\ V_{FAT} + \sum_{sr} SEI x\ V_{SEI} + \sum_{sr} SLI x\ V_{SLI}}{\sum_{sr} PIA} \tag{3}$$

Where: $\sum_{sr} FAT$, $\sum_{sr} SEI$, $\sum_{sr} SLI$ are the total number of fatalities, seriously and slightly injured on roads with similar characteristics. V_{FAT}, V_{SEI} and V_{SLI} are the value of avoiding a fatality, a seriously injured and a slightly injured. $\sum_{sr} PIA$ is the total number of victims on roads with similar characteristics.

Finally, we compare the estimated social benefit produced by road safety improvements until the end of the PPP contracts (2026) with (i) the additional investment made with respect to a scenario 0 in which the government has not supported the projects and, therefore, the existing roads have not been upgraded, and (ii) the potential financial loss estimated for the government in the pessimistic scenario. These comparisons allow us to evaluate the social feasibility of the projects and the extent to which the risk borne by the government in providing SPPLs to the projects was offset by the social benefits. It is worth noting that the evaluation of social benefits is very conservative for two reasons. On the one hand, society will keep on benefiting from accident rates reduction beyond 2026. On the other hand, other social gains (such as travel time savings, comfort improvement, fuel savings or reduced air pollution emissions) are not taken into account in this estimate.

5. RESULTS

This section summarises the main findings of the three selected PPP projects of the Plan. First, it shows the actual performance of the projects compared to the new EFPs approved. Then, the SPPL repayment capacity of PPP contractors is calculated for different scenarios in order to estimate its potential impact on the public budget. Finally, social gains derived from the improvement in road safety are estimated to assess whether the government did it right when deciding to grant SPPLs to support the projects.

5.1 Financial performance and social benefits

5.1.1 Capital and O&M costs

Regarding the capital cost of the initial works, all PPPs managed to adjust very well to the estimates conducted in their EFPs. As can be seen in Table 1, two of the three projects analysed incurred lower costs than expected. In contrast, there has been significant under-investment in major repairs and rehabilitation actions compared to the original estimates.

In this regard, only A2-T3 and A31-T1 carried out rehabilitation works worth, in both cases, far less than expected. Finally, PPP contractors incurred higher O&M costs than originally planned. This was likely caused by the incentives provided by the contracts to achieve better maintenance and operational performance through service indicators.

Section	Construction costs	Rehabilitation costs*	O&M costs*
A1-T2	-2.69%	-100%	17.36%
A2-T3	-7.94%	-74.13%	4.27%
A31-T1	1.18%	-88.30%	54.52%

* In the period 2009-2015

Table 1 - Deviation of the main costs from EFP's estimation

5.1.2 Income

Table 2 shows the evolution of the deviation of current revenues —both from traffic and availability— from those foreseen by the EFPs, which considered no income from availability payments. It can be observed that all PPPs, especially A2-T3, obtained less income than originally expected, especially during the first years of operation. In the last years analysed, due to the improvement of the Spanish economy and the availability bonuses, the total revenue obtained almost coincides with the original estimates.

Section	2009	2010	2011	2012	2013	2014	2015	2016
A1-T2	-	-	-29,7%	-17,3%	-1,5%	7,2%	1,4%	-6,3%
A2-T3	-	-15,6%	-67,0%	-48,9%	-31,9%	-2,7%	-12,2%	-3,5%
A31-T1	-1,7%	-33,6%	-2,8%	-17,5%	-5,0%	-6,5%	10,4%	-4,1%

Table 2 - Income deviation from EFP's estimation in the period 2009-2016

The actual dividend distribution to project shareholders for two of the PPPs analysed has substantially differed from that envisaged in the EFPs. In the case of A1-T2, dividends began to be distributed in 2013, one year later than planned. However, the accumulated amount distributed till 2016 was 37% higher than initially envisaged, with an over-distribution of €3.03 million. In the case of A31-T1, dividends began to be paid in 2014, four years ahead of schedule, with €4.24 million being over-distributed. Finally, as of 2016, A2-T3 had not yet distributed dividends, following the schedule established in the EFP, with dividends to be distributed from 2018 on. This PPP has obtained lower economic results than expected so far and has been incurring losses despite the additional income from indicators, obtaining the worst economic performance of the PPPs under study.

5.1.3 Accident rates

Table 3 shows the evolution of the hazard (HI) and mortality (MI) indexes. An important decrease in their values can be observed comparing the situation before the projects were awarded (2006 and 2007) and after works were completed (2014 and 2015).

Quantitatively, the HI on the motorways analysed with respect to the starting situation has improved between 78 and 90%, while the MI has fallen by 29% on average. As can be observed in the same table, two of the three motorways are significantly safer than the rest of the State roads with similar characteristics in terms of traffic levels (AADT) and road type (urban or interurban).

Section	Before works				*Works in progress*	After works				Equivalent roads
	2006		2007		*2008-2013*	2014		2015		2015
	HI	MI	HI	MI		HI	MI	HI	MI	Average HI
A1 - T2	18.64	0.46	15.48	0.17		3.63	0.27	3.37	0.27	6.06
A2 -T3	19.25	0.94	27.89	1.75		6.26	0.45	4.22	0.21	3.97
A31 - T1	14.7	0.22	17.82	0.84		2.07	0.13	1.86	0.37	6.06

Table 3 - Evolution of hazard and mortality indexes of the PPPs analyzed before and after the completion of works and average hazard index of equivalent roads for 2015

5.1.4 Anticipation in the commissioning of the works

One of the main reasons why these projects were undertaken under the PPP approach was the urgency of the Plan and the insufficient resources to undertake these actions through conventional budgetary approaches within a reasonable period of time. In that respect, the Strategic Plan of Infrastructure and Transport (PEIT) estimated that it would take about eight years to meet all investment needs if they were to be built with budgetary resources (Ministerio de Fomento, 2005). This estimation was, however, based on an economic growth scenario that did not occur given the economic downturn that soon after affected the country and resulted in continued budget reductions for the road infrastructure program since 2009. The PPPs analysed were completed within 1.5 (A31-T1) to 3.5 years (A2-T3).

Therefore, the implementation of the actions was anticipated in a range between 6.5 and 4.5 years with respect to the option of undertaking the actions through the conventional procedure estimated by the MT. As a result, society has been reaping the benefits of the positive savings and externalities derived from the works in advance.

5.2 Estimates of the debt repayment capacity of the PPP contracts

In order to estimate the repayment capacity of the SPPL, according to the methodology previously defined, we have estimated the FCF in the last year of the contract (2026). To that end, we estimated: (i) traffic revenues; (ii) availability payments; (iii) O&M costs; (iv) capital costs in major repairs and rehabilitation projects, and (v) corporate taxes. The hypotheses and the procedure adopted for their calculation are summarised below.

- Annual traffic revenues are calculated as the product of the volume of traffic on the road section (in vehicles x km) each year and the fare (excluding VAT) applied in the same period, differentiating between traffic and fares for light and heavy vehicles. The evolution of light and heavy traffic over time has been obtained, for each scenario, by applying the elasticities estimated by Gomez et al. (2015) and Gomez and Vassallo (2016) to the socioeconomic variables of each scenario (GDP per capita and industrial GDP). For its part, the fare is updated yearly according to the variation of the national Consumer Price Index (CPI) by using the Spanish CPI forecasts for the period 2017-2026 from the International Monetary Fund (IMF).
- Annual availability revenues in the period 2017-2026 are assumed to be a constant percentage of total revenues consistent with previous years.
- Annual O&M costs in the period 2017-2026 have been calculated based on those of the previous years, assuming that the only increase they will experience in the future will be caused by inflation.
- Given the difficulty of estimating future investments in road rehabilitation, the values foreseen for this purpose in the EFPs delivered by the PPP contractors have been adopted in the analysis.

- The corporate tax is calculated as the legal rate (25%) times the Profit Before Taxes (PBT). The PBT has been annually calculated for each of the proposed scenarios as annual revenues minus O&M costs, depreciation of the assets, and financial expenses.

After obtaining the expected FCF in 2026, the last step of the analysis consisted of estimating whether they are enough to cover the repayment of the principal of the SPPL including the capitalization of interests accrued during the three-year grace period. Table 4 shows that the amount that PPP contractors have to return to the government the last year of the contract is, for all scenarios, higher than the expected FCF generated. Thus, according to the principles of project finance, whereby lenders should only rely on project cash flows for debt repayment, PPP contractors will not be able to repay the full amount of the loan in the last year of the contract.

Section	SPPL principal + 3-year interests	Scenarios	Last year FCF (M€)	Difference with respect to the scenario (M€)
A1-T2	49.56	Optimistic scenario	43.37	-6.19
		Base scenario	*40.98*	*-8.58*
		Pessimistic scenario	38.33	-11.23
A2-T3	51.30	Optimistic scenario	28.16	-23.14
		Base scenario	*26.66*	*-24.64*
		Pessimistic scenario	26.15	-25.15
A31-T1	20.58	Optimistic scenario	18.77	-1.81
		Base scenario	*17.51*	*-3.07*
		Pessimistic scenario	16.24	-4.34

Table 4. Amount to be returned by each PPP contractor to the government in the last year of the contract, estimated free cash flow (FCF) available that year for that purpose and estimated amount that would not be returned in each scenario

5.3 Estimate of the social benefits of the PPP projects

In order to obtain an approximation of the social gains derived from the projects, a conservative estimate of the social benefit derived from the improvement in road safety since the commissioning of the first section (A31-T1) until the end of the PPP contracts (2026) is made according to the methodology previously explained (Pérez de Villar, 2015).

To that end, it has been assumed that if these motorways had not been upgraded, the evolution of the accident rates —measured through the HI— of the first-generation motorways under study would have followed the same trend of the rest of the Spanish roads with similar characteristics.

The annual social benefit (SB_{annual}) is calculated following equation (2) as the product of the number of victims avoided on the motorway sections analysed with respect to the hypothetical scenario where no upgrading actions are undertaken, and the value of preventing a victim calculated according to equation (3) with the monetary values provided by the Handbook on External Costs of Transport (DG MOVE, 2014).

From the analysis conducted, we estimated that the social benefit derived from the reduction of accident and mortality rates on the three motorways in the 2011-2026 period totalled €363.82 million actualised to 2007 prices. On the other hand, the total investment related to the establishment and upgrading of the motorways, including additional works approved in 2010, updated to 2007 amounted to €360.91 million. This estimate shows that the social benefit derived from the reduction of the accident rate exceeds the total investment made for the establishment and upgrading of the three sections, which endorses the social feasibility of the projects. Finally, the potential financial loss estimated for the government in the pessimistic scenario, actualised to 2007 prices with the same discount rate used for the social benefit, amounts to €16.8 million, which is negligible compared to the social benefits of the motorways.

6. DISCUSSION OF THE RESULTS AND POLICY IMPLICATIONS

The *ex-post* evaluation enabled us to evaluate whether the government's decision to support the PPPs analysed was socially justified. The SPPLs, together with the rest of measures agreed when restoring the economic balance of the contracts, allowed the government to push ahead with the projects and undertake the works it deemed necessary to improve road safety on the motorways. The analysis shows that these projects have proven to be extremely successful in decreasing accidents rates, thereby producing high social benefits that greatly exceed the potential financial loss estimated for the government in the pessimistic scenario analysed. Moreover, both users and society have been enjoying these benefits well in advance thanks to the government's decision to support the PPP contracts. Finally, if the government had chosen not to do so, the contracts would have likely been early terminated, thereby entailing important costs for society (termination payments to contractors, additional cost to re-tender the contracts, etc.) and the benefits arising from the projects would have been delayed.

The case study analysed also provides future lessons for governments that need to make prompt decisions responding to sudden PPP problems. The first lesson is that a right *ex-ante* design of the contract substantially contributes to reducing problems once the contract is awarded. In the case shown in this paper, the government's reluctance to approve the final designs provided by PPP contractors, even though they met the minimum requirements, delayed the financial close of the projects and, subsequently, the beginning of the works.

This fact, along with traffic shortfalls caused by the economic recession, were the main causes that threatened the projects' viability.

Thus, if the government had included in the projects' tendering specifications the technical requirements and all the works deemed necessary, the problems would have been much limited.

The second lesson is that support mechanisms must be properly designed so that the government does not take a higher risk than the shareholders. In the present case study, the conditions under which the SPPLs were awarded did not set sufficient measures to guarantee the public interest against that of the shareholders. The results show that, if no action is taken in this regard, there is a significant risk that PPP contractors will not be able to repay the principal of the loans even though the PPP projects are performing well and, in two of the cases, distributing more dividends than expected. In this respect, some of the issues identified might have been avoided if the government had set some provisions to safeguard the SPPL seniority to the shareholders. For example, the government could allow for a more flexible amortization approach of the SPPL, or require PPP contractors to set up a SPPL service reserve account at the end of the grace period for its provision.

The third lesson is that the level of risk actually borne when providing support mechanisms to PPPs should be assessed and if possible quantified. SPPLs may involve contingent liabilities with a significant impact on the future public budget, but they were not assessed before being awarded. The fourth lesson from this paper is that an independent entity, rather than the MT, should be in charge of measuring the contingent liabilities arising from these loans. These contingent liabilities, once estimated for all the projects, should be accounted for within the national budget at the time the loan is granted. This way, governments will have the correct incentive to provide SPPLs at the right price, and only when they add value.

7. CONCLUSIONS

This paper is a good example of the complexity of managing PPPs due to the incompleteness inherent to these contracts. The case study sheds some light on key aspects to respond to government decisions about providing support to PPPs in trouble with potential high benefits for the society. It also shows how taking drastic decisions in that respect, such as forcing the termination of the contracts, may not be the best solution from the social point of view. This case study proves how governments often try to solve problems as quickly as possible without conducting the right analysis to measure the impact, both social and fiscal, in the medium and long term.

The main conclusions from the paper are two. The first one is that a good governance approach along with the right *ex-ante* design of the contract will mitigate the impact of future unexpected problems.

The second conclusion is that the best way to deal with problems over the life of the contract is to define the right procedure to address them. In this respect, a proper design of the support measure and assessing the consequent government exposure to risk is necessary to ensure the financial sustainability of the public sector when adjusting the contracts to unexpected events.

Future research should focus on using more quantitative approaches to find an optimal equilibrium between commitment and flexibility in PPPs to ensure that decisions are taken to maximise sustainability. This analysis should value the impact on different stakeholders.

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METODOLOGÍA DE PRIORIZACIÓN DE INVERSIONES EN LOS PROCESOS DE PLANIFICACIÓN DE TRANSPORTE

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RESUMEN

Tras la publicación del Libro Blanco del Transporte (2011) surgen múltiples directivas europeas proponiendo reformas estructurales en el sector para fomentar su eficiencia. En materia de inversiones, buscan optimizar la labor de los administradores de infraestructura, tanto a nivel técnico como presupuestario y financiero. Estas directivas se han ido incorporando progresivamente al ordenamiento jurídico español, donde el Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA) es el organismo que establece las directrices generales de planificación del transporte mediante la elaboración planes estratégicos. La planificación pormenorizada se detalla en planes directores, sectoriales o programas de actividad, en los que generalmente intervienen los gestores de infraestructura.

Actualmente, el desarrollo de estos instrumentos incide en la importancia de identificar las inversiones más urgentes y priorizar las actuaciones a desarrollar. En este sentido, el presente artículo describe una metodología para priorizar actuaciones en transporte con el fin de optimizar las inversiones en dicho sector.

La metodología consta de dos fases: una priorización inicial basada en un análisis multicriterio a tres niveles: a nivel estratégico (nivel 1), donde se planifican actuaciones globales, de carácter de red, y se tiende a priorizar corredores, nodos o ámbitos territoriales sin llegar a priorizar actuaciones concretas; y en planes directores o sectoriales, priorizando actuaciones que pueden ser muy dispares (nivel 2) o de la misma naturaleza (nivel 3). Por tanto, se trata de una metodología aplicable a diferentes instrumentos de planificación combinando niveles según las características propias de cada uno de ellos.

La segunda fase consiste en un contraste de los resultados obtenidos en el análisis multicriterio por un grupo de expertos que, con una visión crítica e integradora, apliquen criterios de priorización no contemplados en la fase previa y consideren posibles solapes en la planificación a distintos niveles y con otras planificaciones previas en el ámbito de estudio, permitiendo perfeccionar la priorización y facilitando la posterior estimación de recursos y plazos de implementación.

1. INTRODUCCIÓN

1.1 Origen y antecedentes

Con la publicación en 2011 del “Libro Blanco de Transporte, hoja de ruta hacia un espacio único europeo de transporte”, la Comisión Europea comienza a establecer las bases para la creación de un entorno común de transporte a nivel europeo. En el caso del transporte ferroviario, estas bases se han ido concretando en los denominados “Paquetes Ferroviarios" y, finalmente, en la Directiva 2012/34 RECAST que señala la necesidad de mejorar las condiciones de inversión en el sector como uno de sus objetivos fundamentales.

En España, la Ley 38/2015 del Sector Ferroviario, que resulta de la transposición de la Directiva RECAST, establece la necesidad de que los Estados miembros redacten una Estrategia Indicativa para el desarrollo de la red ferroviaria y que los administradores de infraestructuras aprueben un Programa de Actividad para un periodo no inferior a cinco años. En este sentido, actualmente se está trabajando en la elaboración del Programa de Actividad de Adif y Adif AV. Para el desarrollo de éste y de otros instrumentos de planificación ferroviaria, cada vez adquiere mayor importancia el poder identificar las inversiones más necesarias y priorizar el conjunto de actuaciones previstas en la red ferroviaria. Por este motivo, Adif solicitó a Ineco su colaboración para la elaboración de una metodología que permitiera priorizar, de forma práctica y objetiva, las inversiones correspondientes a las actuaciones ferroviarias contempladas en diferentes programas de necesidades de inversión. La metodología desarrollada y los criterios de priorización fueron definidos de manera conjunta y consensuada entre Ineco y Adif, aplicando dicha metodología con éxito a distintos planes directores y al conjunto de la red ferroviaria convencional.

A raíz de este trabajo, surge la necesidad de ampliar el alcance y el ámbito de aplicación de la metodología propuesta a otros territorios y a otros niveles de planificación, incluso para la priorización de actuaciones previstas en otros modos de transporte, no sólo en transporte ferroviario.

1.2 Marco general y objetivos

El objetivo del presente trabajo es desarrollar una propuesta metodológica que, de forma práctica y basada en una serie de criterios objetivos y medibles, permita la priorización de inversiones no sólo de carácter ferroviario, sino que sea igualmente aplicable para priorizar actuaciones que afectan a otros modos de transporte. La metodología desarrollada será especialmente útil en la elaboración de planes directores, planes sectoriales u otros instrumentos de planificación, siempre y cuando contemplen actuaciones específicas que lleven aparejadas partidas de inversión.

En España, el organismo que establece las directrices en materia de planificación de transporte es el Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA) a través de la elaboración de los planes estratégicos de infraestructuras a nivel nacional. En este sentido, en julio de 2005 se aprobó el Plan Estratégico de Infraestructuras y Transporte (PEIT) para el periodo 2005-2020, donde se indicaban las prioridades para el desarrollo de las políticas sectoriales en materia de infraestructuras. Sin embargo, debido a la coyuntura socioeconómica de los años siguientes a la aprobación del PEIT, fue necesaria la reconfiguración de dicha planificación con la inclusión de nuevos objetivos, aprobando en 2015 el Plan de Infraestructuras, Transporte y Vivienda (PITVI), cuyo plazo de vigencia finaliza en 2024.

El PITVI contempla un conjunto de actuaciones concretas en los distintos modos de transporte, definidas como resultado de materializar las nuevas directrices de eficiencia y sostenibilidad y de mejora de la seguridad del sistema de transporte en su conjunto. La valoración económica de dichas actuaciones según la distribución de recursos prevista hasta 2024 entre los distintos programas de actuación definidos (Programa de Regulación, Supervisión y Control, Programa de Gestión y Prestación de Servicios, y Programa de Actuación Inversora) y por modo de transporte se muestra de forma resumida en la siguiente imagen.

Valoración económica de las actuaciones del PITVI [Millones de € constante de 2012]		
Carreteras	36.439	26%
Ferrocarriles	61.302	44%
Aeropuertos y navegación aérea	7.222	5%
Puertos	6.788	5%
Ayudas al transporte	15.899	11%
Inversión ajena puertos	6.575	5%
Inversión privada carreteras	4.030	3%
Total transportes	**138.255**	**100%**

Tabla 1 – Estimación económica de las actuaciones del PITVI en infraestructuras y transportes, 2012-2024, por modos y conceptos

Sin embargo, en el PITVI no se detalla la valoración económica ni el plazo de ejecución previsto para cada una de ellas, ni de forma individualizada ni por bloques o subprogramas de actuaciones. Por tanto, el Plan no muestra expresamente una priorización de las actuaciones que contempla, aunque sí establece entre sus directrices la necesidad de "*adoptar una evaluación sistemática de las actuaciones para una eficaz priorización y racionalización de las inversiones, incorporando mecanismos de análisis coste-beneficio y previsiones de rentabilidad económica, financiera y social*".

En España también se elaboran planes estratégicos sectoriales que desarrollan la planificación estratégica de infraestructuras y/o servicios de transporte, pero de un elemento concreto del sistema. Generalmente, los planes estratégicos sectoriales son documentos que establecen los objetivos y las directrices a seguir, pero que no recogen actuaciones de carácter muy concreto. A nivel nacional destacan, por ejemplo, la Estrategia Logística de España o la Estrategia Indicativa del desarrollo, mantenimiento y renovación de la infraestructura ferroviaria del MITMA, esta última en cumplimiento a lo establecido en la Ley 38/2015 del Sector Ferroviario y que actualmente se encuentra en proceso de redacción. De forma análoga, la nueva Ley de Carreteras 37/2015, que también persigue adaptar la ordenación del transporte por carretera a la normativa comunitaria siguiendo criterios de seguridad y eficiencia en la asignación de recursos, establece la necesidad de elaborar un Plan estratégico de las carreteras del Estado que, como instrumento técnico-jurídico de política sectorial de carreteras, recoja las previsiones y los objetivos a cumplir, así como las prioridades de actuación.

Un escalón por debajo en la planificación del transporte se encuentran los planes directores o sectoriales para un modo de transporte y/o un territorio concreto. En estos documentos ya intervienen los propios gestores de la infraestructura y contemplan actuaciones más concretas que generalmente llevan asociadas partidas de inversión. Los Planes Directores de los puertos de titularidad estatal, por ejemplo, son elaborados por las propias Autoridades Portuarias, quienes definen las necesidades de desarrollo del puerto durante un horizonte temporal determinado y su valoración económica, entre otros aspectos. En el sector ferroviario, Adif establece en sus Planes Directores las actuaciones e inversiones previstas en la red ferroviaria de un determinado territorio por anualidades o periodos concretos.

Finalmente, la planificación más pormenorizada, tanto a nivel nacional como regional, se desarrolla en programas de actuación o programas de actividad, en los que se detallan actuaciones, generalmente a corto plazo y muy concretas, que llevan aparejadas partidas de inversión. En estos casos, además del MITMA y los propios gestores de la infraestructura de transporte, pueden intervenir otras Administraciones Públicas autonómicas o locales y organismos asociados.

En cualquier caso, en todas las etapas e instrumentos de planificación comentados se incide cada vez más en la importancia de racionalizar la asignación de recursos y priorizar las acciones a desarrollar. Pero tanta variedad de planes, ámbitos y agentes que intervienen en estos procesos, sumado a la diversidad de modos y servicios de transporte, suponen en muchos casos un conjunto de actuaciones tan heterogéneo que dificulta en gran medida su priorización, haciendo que la toma de decisiones sea verdaderamente compleja.

Por todo lo anterior, el presente trabajo define una metodología para priorizar inversiones en el sector transporte que sea capaz de adaptarse a las diferentes casuísticas, de modo que pueda aplicarse en múltiples instrumentos de planificación y a diferentes sectores del sistema tan sólo realizando algunos ajustes.

2. METODOLOGÍA PARA LA PRIORIZACIÓN DE INVERSIONES

Tras analizar algunos antecedentes sobre procesos de priorización de actuaciones desarrollados en diferentes instrumentos de planificación con el objetivo de analizar las metodologías empleadas en dichos documentos e identificar todos los criterios utilizados, se ha propuesto una metodología para la priorización de las inversiones en transporte que consta de dos fases:

I. Priorización de actuaciones mediante un análisis multicriterio a tres niveles:
   - Nivel 1: Priorización entre corredores, nodos o ámbitos territoriales
   - Nivel 2: Priorización de actuaciones de distinta índole
   - Nivel 3: Priorización de actuaciones de la misma naturaleza

II. Contraste de los resultados del análisis multicriterio por un grupo de expertos

A continuación se describen cada una de las fases metodológicas.

2.1 Fase I - Priorización mediante análisis multicriterio a partir de indicadores

En una primera fase se realiza una priorización de las actuaciones contempladas en el Plan en base a un análisis multicriterio. La categorización de las actuaciones que se puede llevar a cabo a tres niveles distintos:

Nivel 1. Priorización de corredores, nodos o ámbitos territoriales.

Se trata de una priorización especialmente útil para infraestructuras lineales. Permite valorar la ejecución de un conjunto de actuaciones previstas sobre una determinada vía o línea ferroviaria, o bien la ejecución de una nueva infraestructura, priorizando unos corredores frente a otros. En este caso no se evalúan actuaciones específicas, como podría ser la electrificación de un determinado tramo ferroviario o el desdoblamiento de un tramo de carretera, sino que se estudia la conveniencia de actuar sobre una carretera o línea ferroviaria concreta con respecto a actuar en otras, categorizándola con mayor o menor prioridad. El resultado es un listado de corredores, carreteras o líneas ferroviarias, catalogados según el orden de prioridad para actuar sobre ellos atendiendo a una serie de criterios generales que evalúan la relevancia del corredor, tramo o trayecto en el conjunto de la red, independientemente del cúmulo y tipo de actuaciones que deban desarrollarse en cada caso (criterios de priorización de categoría 1).

El nivel 1 de priorización es aplicable tanto a corredores íntegros como a trayectos más concretos. A modo de ejemplo, en el “Programa de Necesidades de Inversión en las Líneas de Galicia y Asturias y sus conexiones” de Adif se realiza una priorización de grandes itinerarios ferroviarios conformados por subtrayectos. Más adelante se detallan las diferentes categorías de criterios de priorización empleados y los que aplican en cada caso. Este nivel de priorización también es válido en caso de querer valorar en qué nodos logísticos o de transporte (puertos, terminales intermodales, etc.) es prioritario actuar, o incluso entre distintos ámbitos territoriales, si bien conviene señalar que en estos casos no todos los criterios de priorización establecidos en el análisis multicriterio aplican, por lo que el resultado no es tan riguroso como en el caso de las infraestructuras lineales.

Nivel 2. Priorización de actuaciones de distinta índole.
Como se ha comentado anteriormente, existe una gran diversidad no sólo de instrumentos y agentes que intervienen en los procesos de planificación, sino también de tipologías de actuaciones a programar. No obstante, en el marco de un plan director o un plan sectorial se contempla generalmente todo tipo de actuaciones y en ocasiones resulta interesante poder catalogarlas según su orden de prioridad, independientemente de su tipología.

A modo de ejemplo, el PITVI cataloga las actuaciones previstas en el horizonte del Plan (año 2024) en 22 categorías, tal y como se muestra en la figura adjunta.

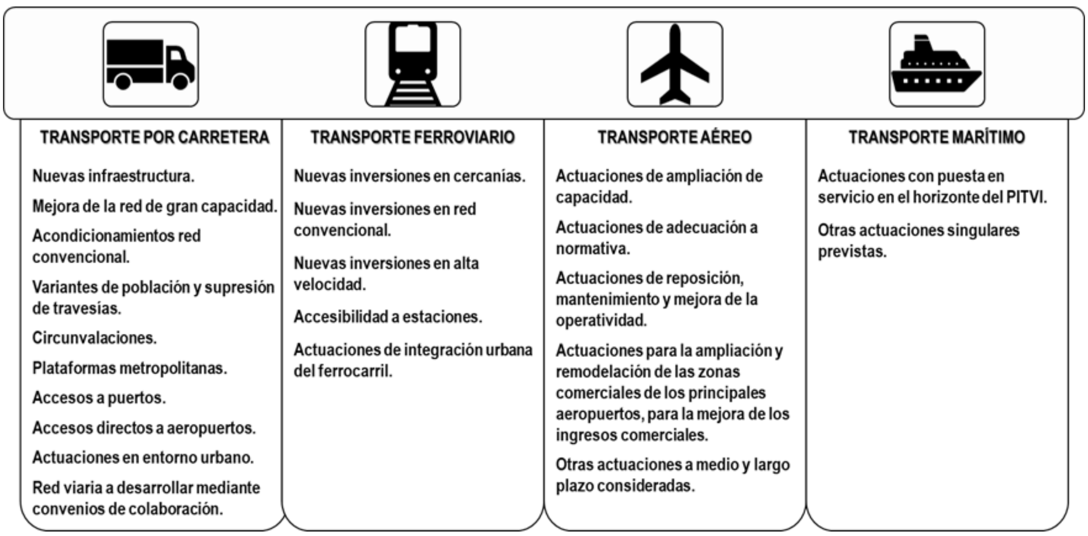

Fig. 1 – Clasificación de las actuaciones que contempla el PITVI (2012-2024)

Cada una de estas categorías es, a su vez, divisible en múltiples tipologías de actuaciones. Tan sólo en el modo ferroviario, las necesidades de inversión en la red pueden deberse a actuaciones de tipo infraestructural, duplicaciones de vía, renovaciones de catenaria, mejoras en los sistemas de señalización, etc.

Por tanto, en ocasiones se precisa estudiar si resulta más prioritario realizar, por ejemplo, la electrificación de una línea en un trayecto ferroviario determinado o la duplicación de vía en otro trayecto ferroviario. Incluso en un mismo trayecto, puede ser necesario analizar si resulta más conveniente la electrificación de la línea o la actualización del sistema de control y gestión del tráfico.

Para estos supuestos se diseñó un segundo nivel de priorización en la propuesta metodológica, en el que intervienen tres categorías de criterios de priorización. Por un lado, un conjunto de criterios generales (criterios de priorización de categoría 2) que catalogan los corredores, tramos o trayectos atendiendo a la complejidad y relevancia del conjunto de actuaciones que en ellos deben llevarse a cabo. Por otro lado, un conjunto de criterios específicos para llevar a cabo la priorización de actuaciones encaminadas a la mejora de prestaciones (criterios de priorización de categoría 3) o a la reposición y gestión de activos (criterios de priorización de categoría 4). Las diferentes categorías de criterios de priorización empleados se detallan en el apartado 3.2.

Nivel 3. Priorización de actuaciones de la misma naturaleza.
Con este tipo de priorización se evalúan y clasifican actuaciones de la misma tipología, resultando especialmente útil en el desarrollo de programas de actuaciones específicos, como programas para la reparación/conservación de carreteras.

En estos supuestos, el proceso de priorización funciona de manera muy similar al nivel 2. Por un lado, se clasifican los corredores por orden de prioridad atendiendo a un conjunto de criterios generales (criterios de priorización de categoría 2) que evalúan la complejidad y relevancia de las actuaciones a desarrollar. Por otro lado, dentro del conjunto de criterios para la mejora de prestaciones (criterios de priorización de categoría 3) o para la reposición y gestión de activos (criterios de priorización de categoría 4) se aplican aquéllos específicos para la tipología de actuaciones que se están evaluando.

Conviene señalar que no todos los documentos e instrumentos de planificación que priorizan actuaciones lo hacen siguiendo estrictamente uno de estos tres niveles. Por ejemplo, el "Programa de Necesidades de Inversión en las Líneas de Galicia y Asturias y sus conexiones" de Adif determina en una primera fase cuáles son los trayectos ferroviarios prioritarios, para después clasificar las actuaciones a realizar en cada trayecto según su tipología y priorizar sus inversiones en diferentes horizontes temporales.

En cambio, el documento "Seguridad en carreteras convencionales: un reto prioritario de cara al 2020" de la Asociación Española de la Carretera, también analizado en el estudio de antecedentes, prioriza aquellos tramos que soportan mayores niveles de tráfico y que tienen un índice de peligrosidad superior a la media con relación a determinados tipos de accidentes. Sin embargo, las actuaciones propuestas, cuya tipología responde a las causas que producen esos tipos de accidentes mayoritarios, no se priorizan unas sobre otras.

En la figura 2 se muestra una clasificación tipo de los instrumentos de planificación del transporte generalmente utilizados.

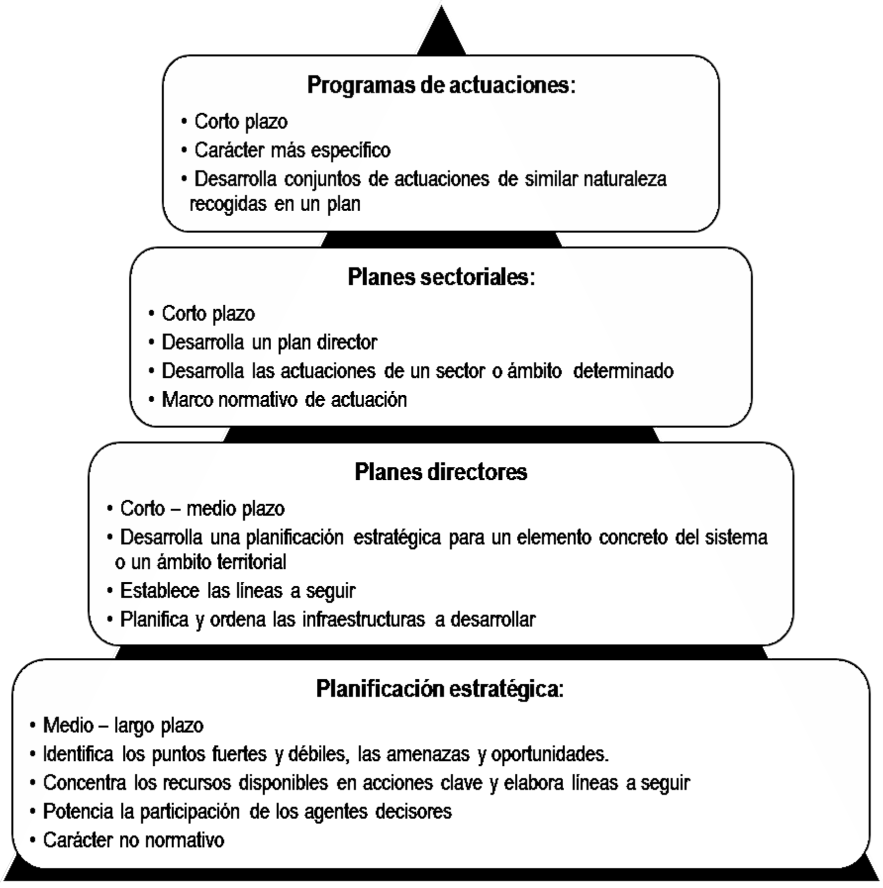

Fig. 2 – Instrumentos de planificación del transporte. Fuente: Planificación y explotación del transporte. Universidad Europea de Madrid.

Tal y como se ha comentado en la introducción, a nivel estratégico, donde se planifica actuaciones de carácter global de red, se tiende a priorizar tramos de carreteras o trayectos/líneas ferroviarias (nivel 1), sin llegar a priorizar actuaciones concretas.

En los planes directores o sectoriales, lo habitual es priorizar unas acciones sobre otras, dentro de un conjunto de actuaciones que pueden ser muy dispares (nivel 2) o todas de la misma naturaleza (nivel 3) porque previamente han sido debidamente clasificadas.

Mientras que en el caso de planes específicos o programas de actuaciones, se prioriza actuaciones que son todas ellas de la misma tipología y responden, por tanto, a criterios de priorización muy específicos (nivel 3). No obstante, tanto en los planes directores o sectoriales como en los planes específicos o programas de actuaciones, se considera de especial interés introducir una primera fase en el proceso en la que se realice una priorización también de trayectos o líneas ferroviarias.

Por tanto, en base a las características propias de cada instrumento de planificación, se propone seguir el siguiente esquema para la priorización de inversiones en transporte mediante análisis multicriterio por niveles:

	ANÁLISIS MULTICRITERIO POR NIVELES	
	Priorización por multicriterio (paso 1)	**Priorización por multicriterio (paso 2)**
Planificación estratégica	Nivel 1: Priorización de corredores, tramos o líneas	
Planes directores y/o sectoriales	Nivel 1: Priorización de corredores, tramos o líneas	Aplicar uno de los siguientes niveles de priorización: • Nivel 2: Priorización de actuaciones de distinta índole • Nivel 3: Priorización de actuaciones según su tipología
Programas de actuaciones	Nivel 1: Priorización de corredores, tramos o líneas	Nivel 3: Priorización de actuaciones de la misma tipología

Tabla 2 – Priorización de inversiones mediante análisis multicriterio por niveles

La fase I de la propuesta metodológica descrita ha sido trasladada a una hoja de cálculo para simplificar su aplicación práctica. La herramienta tiene múltiples funcionalidades que se irá detallando en posteriores apartados. No obstante, conviene señalar que para una mejor visualización de la priorización resultante y su posterior tratamiento resulta conveniente la representación gráfica del análisis multicriterio por niveles en mapas o esquemas mediante códigos de colores.

2.2 Fase II - Contraste de los resultados por un grupo de expertos

Tras la priorización mediante análisis multicriterio de la Fase I, se debe realizar un contraste de los resultados obtenidos por un grupo de expertos con amplia experiencia en planificación de transporte. Dicho contraste deberá llevarse a cabo cubriendo al menos los siguientes aspectos:

- Análisis crítico e integración de las priorizaciones anteriores (niveles 1, 2 y 3).
- Identificación de solapes con otras planificaciones existentes, descartando aquellas actuaciones incluidas en otros planes.
- Análisis de la urgencia de las actuaciones priorizadas.
- Análisis de resistencias y propuestas de soluciones.
- Categorización final de actuaciones por orden de prioridad:
    - Actuaciones estratégicas (prioridad alta)
    - Actuaciones relevantes (prioridad media-alta)
    - Actuaciones ordinarias (prioridad media-baja)
- Estimación de recursos y propuesta de plazos de implantación.

3. PRIORIZACIÓN MEDIANTE ANÁLISIS MULTICRITERIO

3.1 Lógica y etapas de la priorización mediante análisis multicriterio

En el ámbito del transporte, el análisis multicriterio se emplea generalmente para emitir un juicio comparativo entre distintos proyectos o medidas heterogéneas. Por tanto, puede contribuir a la evaluación de un programa o de una política concreta valorando los efectos que sus acciones ya ejecutadas han generado con relación a diferentes criterios. Sin embargo, en los procesos de planificación, las alternativas o actuaciones a evaluar todavía no se han ejecutado. En estos casos el análisis multicriterio permite evaluar otros aspectos, tales como la necesidad de actuación en determinados territorios/elementos del sistema, o la capacidad que las distintas acciones contempladas tienen para alcanzar unos determinados objetivos. En definitiva, facilita la toma de decisiones y contribuye a definir el contenido de los programas y las asignaciones de los recursos entre las distintas acciones contempladas durante el proceso de planificación.

En el caso que nos ocupa, en la primera fase del estudio se ha planteado una priorización de actuaciones basada en un análisis multicriterio de múltiples etapas:

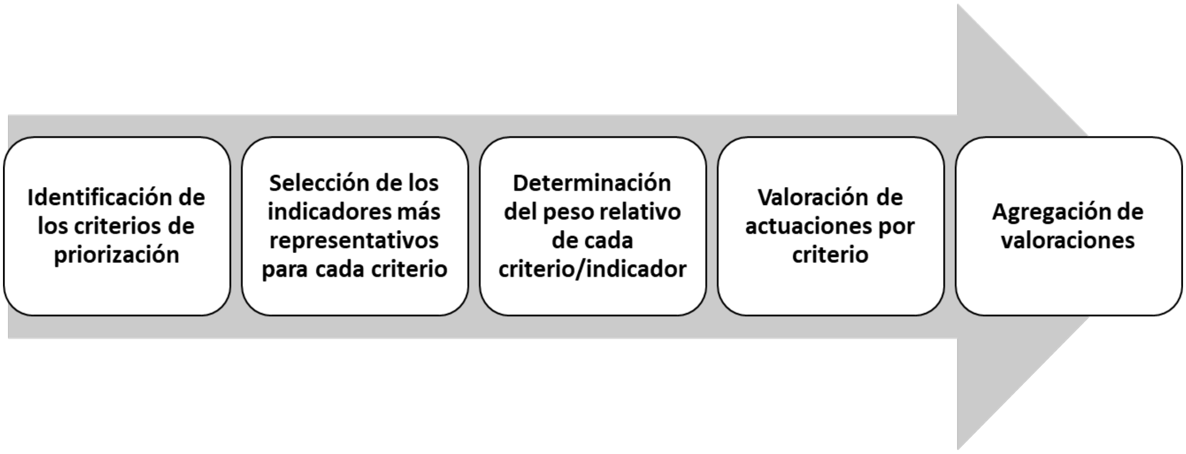

Fig. 3 – Etapas del análisis multicriterio para la priorización de actuaciones, fase I.

El análisis parte de la identificación de los criterios de priorización a considerar, los cuales deben definirse antes de realizar el análisis a partir de unas reglas consensuadas entre todos los agentes que intervienen en el proceso de planificación para contemplar todos los puntos de vista. Los criterios no deben resultar redundantes aunque es inevitable que exista cierta relación entre muchos de ellos. En cualquier caso, deben conformar uno o varios conjuntos coherentes que por sí solos conduzcan a resultados objetivos y admisibles. En el siguiente apartado se detallan las categorías en las que se clasifican los criterios empleados atendiendo al nivel de priorización donde se emplean y los objetivos que persiguen, así como los bloques en los que a su vez se desagregan.

La segunda etapa consiste en seleccionar, para cada uno de los criterios identificados en el punto anterior, uno o varios indicadores asociados que permitirán poder medir su progresión y realizar una valoración numérica del mismo. Estos indicadores han de ser evaluables y se consideran de tres tipos distintos: cuantitativos, cualitativos o dicotómicos.

Los indicadores cuantitativos se miden de acuerdo con sus parámetros de cálculo y se clasifican en base al rango en el que se encuentren. Algunos ejemplos son la intensidad media diaria (IMD) de una carretera, el número de circulaciones programadas en un tramo ferroviario o la demanda esperada con el desarrollo de una determinada actuación. Los indicadores cualitativos se miden según el grado de incidencia en cada actuación, como por ejemplo la definición de la facilidad de ejecución de una actuación (que podría ser baja, media o alta). Por su parte, los indicadores dicotómicos se miden de acuerdo con la existencia o no de un atributo en las distintas actuaciones y, por tanto, se clasifican en "sí" o "no".

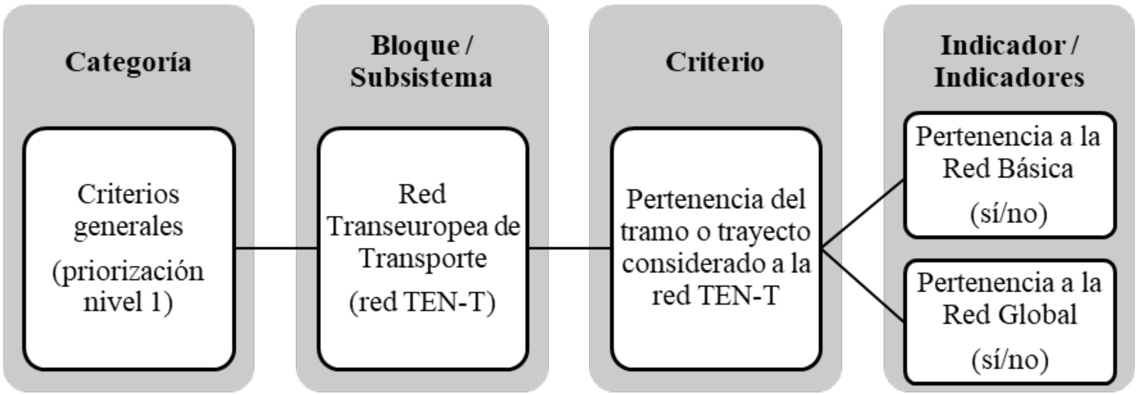

Fig. 4 – Ejemplo de categorización de criterios de priorización e indicadores asociados

La siguiente etapa consiste en determinar el peso relativo de cada indicador. Como la metodología desarrollada contempla cerca de una centena de indicadores, se ha optado por asignar un peso a cada una de las categorías de criterios y, dentro de cada categoría, se ha asignado un peso a cada bloques o subsistemas, para finalmente asignar un peso a cada uno de los indicadores que lo componen, de modo que el peso relativo de cada indicador se obtiene como resultado de todos los anteriores. En este punto conviene señalar que, al tratarse de una metodología adaptable a diferentes instrumentos de planificación, modos de transporte, etc., el número de criterios que aplica en cada caso puede variar sustancialmente.

No obstante, la herramienta está diseñada de modo que el cálculo del peso relativo de cada indicador se ajusta al número de criterios finalmente contemplados en el análisis.

En la cuarta etapa del análisis, para cada elemento analizado (corredor, tramo de carretera o trayecto, actuación, etc.) se da respuesta a cada uno de los indicadores que aplican, asignándoles valores numéricos independientemente del tipo de indicador de que se trate (cuantitativo, cualitativo o dicotómico), homogeneizando la puntuación en un intervalo de 1 a 10. De esta forma se consigue que todos los indicadores tengan una puntuación equivalente.

Para poder llevar a cabo este proceso ha sido necesario recurrir a distintas modalidades de calificación atendiendo a la naturaleza de cada parámetro. Concretamente, se han empleado 4 modalidades distintas, que son:

- **Calificación gradual positiva**: se aplica a indicadores cuantitativos en los que se priorizan aquellos trayectos que adquieren valores más altos, como por ejemplo en el caso del número de circulaciones existentes o de la demanda esperada.
  En estos casos se otorga la calificación más alta (10 puntos) al valor máximo de todos los obtenidos para el conjunto de elementos analizados y una calificación de 0 puntos al valor más bajo, distribuyendo la calificación del resto en función del valor de datos que se le haya otorgado. Para ello se ha empleado la siguiente expresión:

$$\text{Calificación} = \frac{(\text{Vi} - \text{Vmin}) \text{ x } 10}{(\text{Vmax} - \text{Vmin})} \qquad (1)$$

  Siendo Vi el valor otorgado a cada uno de los trayectos.
- **Calificación gradual negativa**: se aplica a parámetros cuantitativos en los que se priorizan aquellos trayectos en los que se adquieren valores más bajos, como por ejemplo los parámetros relacionados con la inversión requerida.
  En estos casos se otorga la calificación más alta (10 puntos) al valor mínimo, y una calificación de 0 puntos al valor más alto, distribuyendo la calificación del resto de tramos/trayectos en función de su valor asignado, en base a la siguiente expresión:

$$\text{Calificación} = \frac{(\text{Vmax} - \text{Vi}) \text{ x } 10}{(\text{Vmax} - \text{Vmin})} \qquad (2)$$

Siendo Vi el valor otorgado a cada uno de los trayectos.

- **Calificación dicotómica**, que se emplea en el caso de indicadores de tipo dicotómico formulados de tal manera que la respuesta es única y se corresponde con un "sí" o un "no". En estos casos se otorga la máxima calificación (10 puntos) a los trayectos cuya respuesta es "sí" y 0 puntos a aquellos cuya respuesta es "no". Para que esta modalidad de calificación sea efectiva hay que ser muy cuidadoso a la hora de definir los criterios dicotómicos, de modo que para todos ellos la respuesta "sí" corresponda a un mayor grado de prioridad.

- **Calificación específica:** se aplica a criterios cualitativos y también a aquellos criterios cuantitativos o dicotómicos cuyos valores posibles responden a distintas categorías o bien no se adaptan a las modalidades de calificación anteriormente comentadas. Por ejemplo, el nivel de saturación de un tramo ferroviario responde a cuatro categorías concretas (rojo, naranja, amarillo o verde) y cada una de ellas llevará asociada una calificación distinta. Lo mismo sucede con el nivel de servicio de las carreteras, escala cualitativa sobre las condiciones de circulación en relación a su capacidad, que abarca desde el nivel A (flujo libre) hasta el nivel F (congestión).

El objetivo de esta fase es llegar a otorgar a cada elemento analizado una puntuación por criterio. Gracias a estas calificaciones se pueden priorizar territorios, corredores, tramos de carreteras o líneas ferroviarias, además de poder comparar actuaciones entre sí.

En la última etapa del análisis debe comprobarse que las valoraciones se expresan de forma homogénea y sobre todo si diversas maneras de dirigir la operación conducen a resultados similares o, por el contrario, exageradamente dispares. Por ejemplo, que una acción ocupe el primer lugar en la priorización y el último en otra tan sólo modificando la escala de algunos parámetros. Finalmente, se procede a la agregación de las valoraciones. Existen distintos métodos (la suma ponderada, el producto ponderado, las relaciones de superación, etc.), aunque en la metodología propuesta se ha optado por el más sencillo, la suma ponderada, pero adaptando el cálculo al número de criterios finalmente contemplados en el análisis, como se ha comentado con anterioridad.

La herramienta desarrollada muestra los resultados en una o varias tablas de valoración (dependiendo de si la priorización se ha abordado a uno o varios niveles) que permiten sintetizar los resultados obtenidos por acción respecto de cada criterio y en su conjunto.

		Trayecto1	Trayecto2	Trayecto3	Trayecto4	Trayecto5
PRIORIZACIÓN NIVEL 1 (criterios Categoría 1)		3,9	2,2	3,0	6,6	5,5
PRIORIZACIÓN NIVEL 2		4,0	3,7	2,7	4,4	3,4
Valoración según criterios generales (criterios Categoría 2)		6,2	6,3	1,7	3,4	5,6
Valoración según criterios Upgrade (criterios Categoría 3)	Mejoras globales	0,7	0,7	1,0	0,8	0,5
	Infraestructura	0,5	0,6	0,8	0,6	0,4
	Vía	0,5	0,6	0,8	0,6	0,4
	Electrificación	0,5	0,6	0,8	0,6	0,4
	Control, gestión del tráfico y teleco.	0,5	0,6	0,8	0,6	0,4
	Estaciones viajeros	0,3	0,4	0,5	0,4	0,3
	Terminales mercancías	0,3	0,4	0,5	0,4	0,3
	Valoración según criterios Upgrade	3,4	3,7	5,1	3,9	2,7
Valoración según criterios de reposición y gestión de activos (criterios Categoría 4)	Infraestructura	0,6	0,3	0,3	1,4	0,5
	Vía	0,6	0,3	0,3	1,4	0,5
	Electrificación	0,6	0,3	0,3	1,4	0,5
	Control, gestión del tráfico y teleco.	0,6	0,3	0,3	1,4	0,5
	Valoración según criterios Reposición y gestión de activos	2,3	1,2	1,3	5,7	1,9

Tabla 1 – Ejemplo de tabla de resultados de priorización (niveles 1 y 2) para un plan director ferroviario que contempla múltiples trayectos.

3.2 Criterios de priorización

Tal y como se ha comentado con anterioridad, se han definido distintas categorías de criterios atendiendo al nivel de priorización planteado y a los objetivos que pretenden evaluar:

- Categoría 1 de criterios generales para la jerarquización por corredores, tramos de carretera o trayectos ferroviarios atendiendo a su relevancia. Son empleados exclusivamente para llevar a cabo la priorización de nivel 1.
- Categoría 2 de criterios generales para la jerarquización por corredores, tramos de carretera o trayectos ferroviarios, pero en este caso atendiendo al conjunto de actuaciones contempladas en cada caso. Se trata de la primera valoración que se obtiene en los niveles de priorización 2 y 3 cuando se comparan actuaciones a desarrollar en distintos corredores, tramos o trayectos.
- Categoría 3 de criterios específicos para llevar a cabo la priorización de actuaciones encaminadas a la mejora de prestaciones, bien de distinta índole (nivel de priorización 2) o de la misma naturaleza (nivel de priorización 3).
- Categoría 4 de criterios específicos para llevar a cabo la priorización de actuaciones encaminadas a la reposición y gestión de activos, bien de distinta índole (nivel de priorización 2) o de la misma naturaleza (nivel de priorización 3).

Estas categorías se componen de una serie de criterios que, a su vez, se agrupan en bloques o subsistemas que garantizan que todos los conceptos necesarios para evaluar correctamente las actuaciones han sido tenidos en cuenta.

Así, la **Categoría 1** (criterios generales para jerarquización por corredores atendiendo a la relevancia del corredor) se subdivide en cuatro bloques:

- ✓ Red europea: engloba criterios que valoran la pertenencia o no del nodo, tramo o trayecto a la Red Transeuropea (red TEN-T), distinguiendo entre red Básica perteneciente a algún corredor (Mediterráneo o Atlántico) o a sus propuestas de ampliación, Red básica, Red Global y otras y, en el caso de infraestructuras lineales, la existencia o no de tráficos transfronterizos en dicho tramo o trayecto.
- ✓ Conectividad: en infraestructuras lineales, conjunto de criterios que consideran si el tramo o trayecto conecta o no con la red TEN-T, con alguna carretera de alta capacidad, con algún eje ferroviario de Alta Velocidad o con nodos logísticos importantes.
- ✓ Demanda: se trata de un conjunto de criterios que valoran aspectos relacionados con la demanda. Comprende la demanda actual y potencial, distinguiendo entre viajeros y mercancías, el tráfico actual y el grado de saturación de la infraestructura.
- ✓ Seguridad: criterios principalmente relacionados con el número de accidentes e incidencias registrados en el tramo o trayecto considerado.

La **Categoría 2** (criterios generales para jerarquización por corredores atendiendo a la complejidad y relevancia de las actuaciones que en ellos deben desarrollarse) se divide en:

- ✓ Complejidad de ejecución: contempla criterios relacionados con la complejidad técnica de las actuaciones a desarrollar y con las afecciones que éstas podrían ocasionar al servicio prestado.
- ✓ Madurez: engloba criterios que miden la compleción de las actuaciones previstas en términos de inversión y de financiación comprometida con respecto a la inversión total prevista, bien por fondos europeos, por el Fondo Financiero de Accesibilidad Terrestre Portuaria o por convenios con CCAA y Ayuntamientos, entre otros.
- ✓ Funcionalidad: conjunto de criterios de distinta índole que buscan medir la funcionalidad de las actuaciones a desarrollar. Engloba la demanda esperada, tanto de viajeros como de mercancías, el ahorro en los tiempos de viaje que supondría actuar sobre ese tramo o trayecto y la mejora de conectividad, entendida como la mejora de la conexión con la red TEN-T, con carreteras de alta capacidad, con ejes ferroviarios de Alta Velocidad o con nodos logísticos importantes. Asimismo, incluye el criterio "efecto red", que trata de evaluar la repercusión que las actuaciones previstas podrían tener sobre el resto de la red. Por ejemplo, en el caso de la puesta en servicio de un nuevo tramo ferroviario, los efectos que tendría sobre la explotación

de la red ferroviaria asociada, como podrían ser la introducción de nuevos servicios o la descongestión de líneas ferroviarias paralelas.

- ✓ Sostenibilidad: engloba criterios de rentabilidad económica-financiera (inversión total, TIR, VAN y relación entre el VAN y la inversión realizada) y de sostenibilidad ambiental (emisiones y ruido).
- ✓ Territorio: valora aspectos relacionados con la cohesión y el reequilibrio territorial, como el incremento de población atendida o la conexión entre ciudades importantes.
- ✓

La **Categoría 3** se divide en:

- ✓ Mejoras globales: incluye criterios relacionados con mejoras de capacidad o mejoras de la velocidad de circulación.
- ✓ Infraestructura: engloba criterios para valorar la necesidad de desarrollar actuaciones de tipo infraestructural.
- ✓ Otros criterios específicos sectoriales: incluye criterios para medir la necesidad de desarrollar actuaciones relacionadas con aspectos más concretos del modo de transporte analizado: en transporte ferroviario, por ejemplo, criterios específicos de actuaciones de vía (duplicaciones o variantes de vía, adaptaciones de carga por eje para el transporte de mercancías, implantación de ancho UIC...), de electrificación, de instalaciones, etc.

Por último, la **Categoría 4** contempla criterios que miden el nivel de riesgo derivado del estado de los elementos que componen el sistema de transporte, así como otros criterios relacionados con la gestión de sus activos. Se divide en bloques atendiendo a cada uno de los subsistemas que lo conforman. Por ejemplo, en el modo ferroviario hay un bloque para infraestructura, otro para vía, otro para electrificación y otro para instalaciones de control de mando y señalización (CMS).

Como se ha comentado anteriormente, cada uno de estos bloques que forman las categorías engloba una serie de criterios que se desarrollan a través de uno o más indicadores. Éstos permiten priorizar la importancia de las diversas actuaciones a realizar, teniendo en cuenta tanto el marco general de implantación de las mismas como las afecciones que las nuevas acciones pueden generar.

4. CONCLUSIONES

En los actuales procesos de planificación, en línea con las directrices europeas que buscan el fomento de la eficiencia en materia de inversiones, está cobrando cada vez mayor importancia la labor de identificar las inversiones más urgentes y priorizar las actuaciones a desarrollar, en especial cuando se trata de inversiones en transporte.

En este sentido, el presente artículo describe una metodología para priorizar actuaciones en transporte en base a los resultados de un análisis multicriterio que puede llevarse a tres niveles: a nivel estratégico, priorizando, por ejemplo, unos corredores sobre otros, a nivel sectorial priorizando todo tipo de actuaciones, independientemente de su tipología, o a nivel específico, priorizando unas actuaciones sobre otras en el marco de un programa de actuaciones común.

La propuesta metodológica presentada es por tanto adaptable a diferentes instrumentos de planificación, e incluso a distintos modos de transporte. No obstante, del estudio realizado se concluye que en todos los casos es recomendable involucrar a todos los agentes implicados en el proceso de definición y selección de los criterios de priorización que serán utilizados en el análisis, de modo que puedan conformarse uno o varios conjuntos coherentes que por sí solos conduzcan a resultados objetivos y admisibles. Dichos criterios no deben resultar redundantes, aunque es inevitable que exista cierta relación entre muchos de ellos, en algunos casos incluso contradictorias, y deben ser mediable y evaluables mediante un conjunto asociado de indicadores que permitan estudiar su progresión.

El planteamiento inicial del presente trabajo, correspondiente a la Fase I de la metodología propuesta, buscaba tratar de objetivar la aplicación de estos criterios, desarrollando una metodología para priorizar inversiones en base a un análisis multicriterio que, como también sucede en otros procedimientos usados con el mismo fin, suele contar con cierto grado de subjetividad.

No obstante, los resultados de esta primera etapa deben considerarse con cierta prudencia, si va a servir de apoyo a la toma de decisiones en materia de planificación del transporte.

En un análisis multicriterio como el planteado no se pueden eliminar totalmente los factores subjetivos. Por ello, en la segunda fase se plantea la realización de un contraste de los resultados obtenidos por un grupo de expertos con amplia experiencia en planificación de transporte que realicen un análisis crítico de la priorización resultante, con el objetivo de identificar sinergias y solapes con otras planificaciones existentes, y considerar otros factores no incluidos en la fase de análisis multicriterio por ser difíciles de valorar, como la aceptación social de las actuaciones propuestas, los compromisos políticos preexistentes, o la elaboración de un análisis de urgencia.

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THE EMERGENT LONG TAIL BUSINESS MODEL IN THE AIRLINE INDUSTRY. THE CASE OF VOLOTEA

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ABSTRACT

We analysed to what extent the business model of the Spanish airline Volotea can be understood as a distinct business model. We characterized this emergent business model, comparing it to other models applied in the short haul market. We conclude that this business model can be described as a long tail business model in the airline industry. We also point out that this emergent model can support a blue ocean strategy in some mature markets, although this strategy would require opening the business' black box to analyse it at the activity level.

1. INTRODUCTION

Business models are nowadays recognised as useful frameworks to understand how businesses work, and what their underlying economic logic is (Magretta, 2002). They are also used to describe how an interrelated set of decision variables are addressed to create sustainable competitive advantage in specific markets (Morris et al., 2005).

Business models have also been used in the airline industry to describe how airlines compete (Corbo, 2017; Klophaus et al., 2012; Lohmann & Koo, 2013), or to understand how their strategies evolve (Corbo, 2017; Daft & Albers, 2013; Jean & Lohmann, 2016; Mason & Morrison, 2008).

On the other hand, business model innovation, understood as "a process that deliberately changes the core elements of a firm and its business logic" (Bucherer et al., 2012, pg. 184), has the power to create new markets (Dew et al., 2011), reshape entire industries (Johnson et al., 2008) and create new ones (Teece, 2010). In the airline industry, the success of Southwest Airlines and what was its innovative business model at the time has been used as an example of a disruptive change capable of creating a huge blue ocean of new customers (Casadesus-Masanell & Enric Ricart, 2010; Kim & Mauborgne, 2005; Teece, 2010).

Academia has mainly used the concept as a descriptive tool. Going further and using it as a prescriptive tool could generate higher returns. We understand prescriptive to mean an earlier use of the tool, in order to generate new business models (Osterwalder & Pigneur, 2010), or at least to describe and understand the logic of new business models as soon as they emerge. This line of reasoning was used, for example, by Bachwich and Wittman (2017) in order to decide whether the business model introduced by Ultra Low-Cost Carriers (ULCC) can be understood as a distinct business model.

In this study, we shift our attention to what could currently be another emergent business model, i.e. the model implemented by the Spanish airline Volotea. The firm has implemented a differential business model, focusing on thin routes, with a unique definition of its target. This approach realigns the remaining components in its strategy, making it stand out from the other well-known business models.

Through a search of multifaceted literature, and using Volotea as a case study, we identify the features that differentiate this model from other similar ones in the airline industry, describing the logic behind it and cataloguing it as a long tail model (Anderson, 2006).

The article continues as follows. Section 2 reviews the literature that focuses on business models in the airline industry. Section 3 presents our case study. Section 4 presents our methodology. Section 5 presents and discuss the results, placing Volotea's business model in a wider context. Finally, Section 6 offers conclusions and opens up further opportunities for this line of research.

2. THE BUSINESS MODEL FRAMEWORK IN THE AIRLINE INDUSTRY

Most of the research carried out to date on applying the business model framework in air transport has focused on airlines, with few exceptions. One of these exceptions is the application of the framework to maintenance, repair and overhaul companies in the aviation industry conducted by Schneider et al. (2013).

In the airline industry, the business model framework has been applied almost from the emergence of the concept in management literature at the beginning of the century to explain the success of low-cost carriers, firstly in the USA and later in Europe (Casadesus-Masanell & Enric Ricart, 2010; Francis et al., 2006).

Most of the contributions have applied the framework at business level, although some authors have also transferred the framework to corporate level (Whyte & Lohmann, 2015). It could also be useful to apply the framework at a lower level (activity level) for some specific requirements (Schneider et al., 2013), as we will point out later, in Section 5.

An industry-specific parameterisation of business model components is required in order to use the framework. It is also important to distinguish the parameter values of the components that are subject to conscious managerial decisions from those that are outcomes or performance indicators of distinct business model practices such as load factor and profitability, which are not a constituent part of the business model itself (Daft & Albers, 2013).

The parameter values of business model components, which are managerial choices, also act as shift parameters, thus differentiating between and identifying alternative business models. This is the main use attributed to the framework in the literature. We now present a more detailed list of applications of the framework in the airline industry, organised by their main goal and adding some useful examples:

- Identifying and characterising different business models through their components (Pereira & Caetano, 2015).
- Capturing the emergence of a new business model: ultra low-cost carriers' business model in the case of Bachwich and Wittman (2017).
- Showing differences in the application of the same business model (hybrid model) between different carriers (Corbo, 2017).
- Comparing different options for the same business model: Mason and Morrison (2008) built a robust methodology for comparing the low-cost business model used by different airlines.
- Analysing the convergence of different business models: legacy or full-service carriers and low-cost carriers in the case of Jarach et al. (2009) and Daft and Albers (2013).
- Analysing the evolution of business models (Lohmann & Koo, 2013).

3. THE CASE OF VOLOTEA

Volotea began to operate in 2012. The firm was set up in Barcelona, Spain, by the same experienced team that created Vueling in 2004. Eight years later, in 2020, Volotea has carried over 25 million passengers, offering 346 short-haul routes that connect over 90 cities in 14 countries, with a fleet of 39 aircraft. In 2018, its revenue reached €396.1 million and its EBITDAR grew to €55.6 million. It carried 6.57 million passengers, up 36% over the previous year.

Volotea defines its strategy very simply: "…we connect small and medium-sized European cities with non-stop direct flights at very competitive prices" (taken from https://www.volotea.com/en/about-volotea/ in March 2020). Setting this risky managerial decision as the first element of its business model, Volotea then redefined the remaining components of the model, thus assuring their required coherence and accomplishing the most important conditions of a good business model. In order to describe this redefinition and to show the implications of this commitment, we tested Volotea's business model against the eight-indicator ex-ante assessment scale drown up by Mateu and March-Chorda (2016):

- *The value creation condition* is guaranteed by "a good service, sensible times, friendly airports and complicity with the local area and simple hospitality" (also taken from Volotea's website).
- *The complete value proposition condition* is accomplished because all the required resources and capabilities are available, including the knowledge gained by the team in past experiences, such as Vueling.
- *The sufficient size of the market condition* is achieved by expanding its operations to a huge part of the European geography (14 countries, at present). Here it is useful to remember that there are 38 cities in Europe with more than one million inhabitants, and 629 cities with between 100,000 and one million inhabitants. The number of possible routes between cities in the second group is ten times greater than the number of routes between cities in the first group and between the first and the second groups.
- Complying with *the access to the potential customer condition* is trivial because it is affordable to publicise the routes on offer in small and medium cities.
- *The predisposition to make efforts by potential customers' condition* is also obvious, given the competitive prices and the short travel times offered by direct flights.
- *The affordable cost condition* is accomplished by prompting mechanisms that can reduce unit costs when income increases. Given that it is difficult to achieve economies of scale in thin routes, density and scope economies must be mobilised by adding several routes and destinations (Caves et al., 1984).
- *The entry barriers existence condition* is granted by the small amount of traffic on these routes, which makes them natural monopolies (Fageda, 2006).
- Finally, *the superiority over competitors' condition* must be built, though this is easy in routes where there is no competition. This is also facilitated by the smaller size of the aircraft, as competitors may not be able to fill their larger planes.

The information presented here also frames Volotea's business model can be framed in a more general paradigm, *the long tail business model* (Anderson, 2006). We will come back to this in Section 6.

4. METHODOLOGY

Once ex-ante evidence of the robustness of Volotea’s business model had been demonstrated, we turned our focus towards analysing its main features, and examining how it differs from other short-haul business models. As our perspective was an exploratory one, we used an inductive and qualitative approach using case studies is useful (Yin, 1993).

We identified four different short-haul business models which were used for comparison. They dovetailed with the models implemented by low cost carriers, hybrid carriers, regional carriers and regional feeder carriers. This last case corresponded to carriers that feed the hubs of network carriers (also known as legacy or full-service carriers), usually through an agreement or operating for the network carrier as a subsidiary. On the other hand, although the ultra low-cost carrier business model has been suggested as a distinct business model (Bachwich & Wittman, 2017) we have not included it in this study because there are no airlines applying this business model in Europe.

Our methodology was based on the methods proposed in the literature in Section 2. We looked for specific indicators that showed significant variations between different business model components. When this specific literature did not provide these indicators, we looked for additional indicators in other fields (this is the case of the Degree Centrality indicator, for example). The final list is shown in the first column of **Table 1**. Although most of the indicators are related to several business model components, we included them under one component, in order to simplify the presentation of results in **Table 1**.

We include here the origin of the data, and the definition of some specific indicators. Most of the data for this work was obtained from the airlines’ websites, and was cross-checked with data provided by other specialised services. Specifically, routes and destinations were cross-checked using flightconnections.com, and fleets were crosschecked using airfleets.es and planespotters.net. We accessed these websites during January and February 2020. Flight frequencies were related to the middle week of February 2020, in order to avoid seasonal flights. The distance between airports was taken from dices.net.

Data related to the size of airports, in terms of number of passengers, was limited to Spanish airports, which were taken as a sample. This data referred to the whole of 2019, and was taken from aena.es. Routes departing from or arriving at Spanish airports represented a huge part of the total number of routes offered by Vueling (86.6%), Air Nostrum (100.0%) and Binter (100.0%). On the other hand, they only represented 26.3% of the total number of Volotea routes and 15.2% of Ryanair’s.

All in all, we considered this percentage a representative sample for our qualitative analysis.

Degree Centrality aims to define the extent to which a network is centralised around a certain node. To do so, we applied Freeman's work (1978) to the network of an airline. The *Degree of connectivity of a node* explains to what extent that node is connected to other nodes (see **Equation 1**).

$$\mathbf{c(k) = \sum_{i=1}^{n} f(i,k)} \qquad (1)$$

Where:

c(k) is the Degree of connectivity of node k

f(i,k) is a function that is equal to 1 if and only if the nodes i and k are connected by an edge (route) and 0 in any other case

n is the total number of nodes in the network

The *Degree Centrality* of the network is calculated using **Equation 2**.

$$\mathbf{DC = \frac{\sum_{i=1}^{n}(Max.c(k) - c(i))}{(n-1)(n-2)}} \qquad (2)$$

Where:

DC is the Degree Centrality of the network

Max.c(k) is the degree of connectivity of the node with the highest degree of connectivity of the n nodes in the network

c(i) is the degree of connectivity of node i

(n-1)(n-2) equals the maximum value that the numerator can reach and, once divided, normalises the result, making DC a number between 0 and 1

In order to complete the comparison, we chose a paradigmatic airline for each of the business models. The choice of these examples was based on two conditions. The first was that their affiliation to the business model was not controversial, at least to a reasonable extent. As Lohmann and Koo (2013) established, the passenger airline industry is a continuum of different business models. Nevertheless, Klophaus et al. (2012) developed a robust framework to measure the degree of hybridisation of low-cost carriers, with a scale that included 13 indicators. Ryanair was qualified by these authors in 2012 as a ‘pure low-cost carrier’. Although Ryanair has evolved since then to a certain degree of hybridisation, we found that it remains close to this original model.

The case of Vueling is quite different, dovetailing with only 8 of the 13 low-cost indicators established by Klophaus et al.' assessment. Today it is even farther from the pure low-cost model, and using the Klophaus et al. categorisation, it could be classed as a 'hybrid carrier with dominating full service airline characteristics'.

The choice of Air Nostrum as a regional feeder carrier (Fageda & Flores-Fillol, 2012) is similar, though much clearer in this case, because Air Nostrum does not sell tickets for its own flights. Air Nostrum's tickets are all marketed by Iberia, demonstrating the subsidiary role of Air Nostrum in Iberia's network. Binter's strategy is clearly regional, focused on the Canary Islands.

The second condition in the choice of airlines in this comparison was related to the availability of data. The specific situation of airport management in Spain, which is controlled by a semi-public organisation (AENA), facilitated access to data. We used data from Spanish airports as a sample for some indicators, in line with other authors (Fageda, 2013). This led us to choose airlines with a strong presence in the Spanish market.

5. RESULTS

Table 1 shows the results of our research. Further information about key indicators is shown in **Fig. 1** and **Fig. 2**.

As expected, the most distinctive features of the Volotea business model are related to frequencies, but also to its network structure and the aircraft models chosen for its fleet. Volotea's average weekly frequency is just over half of the next airline in this indicator (Ryanair), 2.69 vs. 4.16. Its frequency distribution is also distinctive, as shown in Fig. 2. Volotea's curve decreases sharply from a high figure in the first category (1 to 2 weekly flights). None of the other airlines have this type of pattern. In addition, the Degree Centrality of the Volotea network is also radically different from that of other airlines. Volotea's score in this indicator is 0.32, thus showing that its network is close to a theoretical point-to-point network. The closest Degree Centrality to that of Volotea was obtained by Ryanair, with 0.63. Finally, Volotea's fleet consists of small-size narrow-body aircraft. They are smaller than the planes used by Ryanair and Vueling, though larger than those of Air Nostrum and Binter.

In terms of airports served, **Fig. 1** shows Volotea's preference for medium-sized airports. 86% of Volotea's passengers fly to or from airports hosting between two and 30 million passengers. Its curve is similar to that of Binter, thus showing that Volotea avoids the largest airports, which only accounted for 7.1% of its flights in this indicator.

Conversely, Volotea serves an extensive geographical area, similar to that of Ryanair and closer to that of Vueling, as the distance between the furthest nodes reveals. Additionally, Volotea serves 14 countries, more than double regional airlines like Air Nostrum and Binter. Volotea does not come close to Ryanair and Vueling in this category, but this is probably due to it being a young airline.

Business model components • Indicator	VOLOTEA	RYANAIR	VUELING	AIR NOSTRUM	BINTER
Customer segments • Main target segments • Number of destinations • Airport size • Area served (furthest nodes) • Countries	All 83 (See Fig. 1) 4291 km. 14	Leisure & VFR, less attention to business 267 (See Fig. 1) 4932 km. 33	Leisure & VFR, more attention to business 151 (See Fig. 1) 6099 km. 25	All, mainly business 54 (See Fig. 1) 3237 km. 6	All 27 (See Fig. 1) 3563 km. 6
Value proposition • Number of routes • Average weekly frequency	319 2.69 (See Fig. 2)	1365 4.16 (See Fig. 2)	327 7.91 (See Fig. 2)	119 14.5 (See Fig. 2)	31 21.96 (See Fig. 2)
Key resources and activities • Fleet: o models o ranges (km.) o capacities (pax) • Network structure o Degree Centrality o Connecting flights	36 small-size narrow-body aircraft B717 / A319 3815-6950 125-156 0.32 No	273 medium-size narrow-body aircraft B737 5765 189 0.63 Sporadically	122 medium-size narrow-body aircraft A319 / A320 /A321 5600-6950 144-220 0.85 Yes	43 regional jets & turboprops ATR72 / CRJ200-1000 1665-3100 50-100 0.68 Yes	28 regional jets & turboprops ATR72/E195/CRJ1000 1665-4537 72-132 0.87 Yes
Cost structure • Routes/aircraft • Routes/airport • Airports/aircraft • Flights/aircraft	8.86 3.74 0.42 23.84	5.00 5.11 1.02 20.80	2.68 2.17 0.81 21.20	2.77 2.20 0.79 40.13	1.11 1.14 1.03 24.31

Table 1 - Business model components and indicators for the analysed airlines

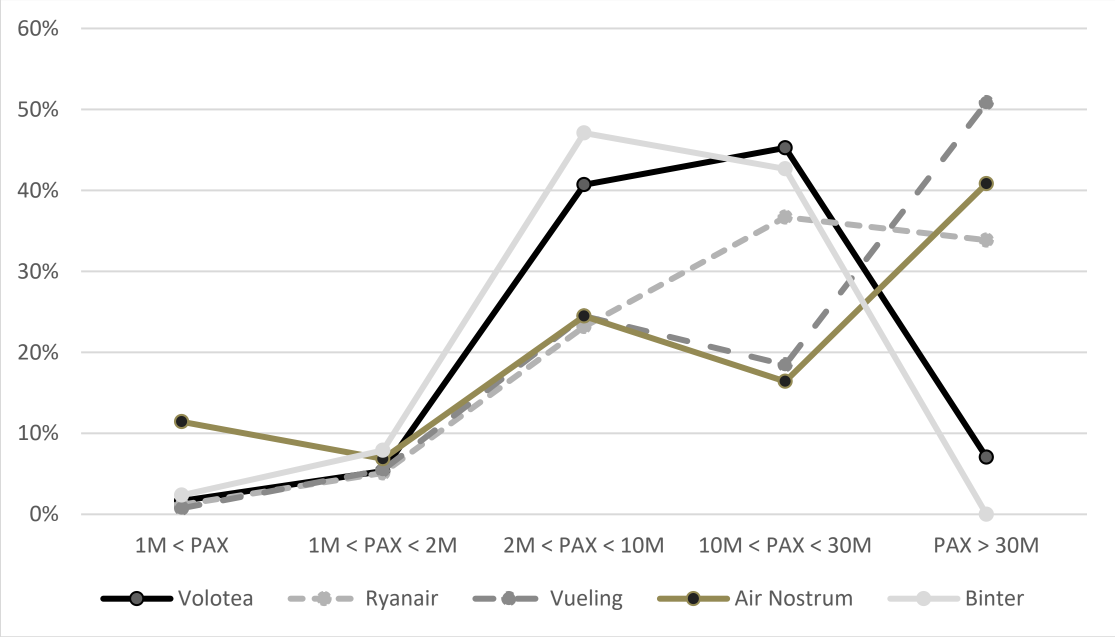

Fig. 1 - Distribution of passengers by airport size

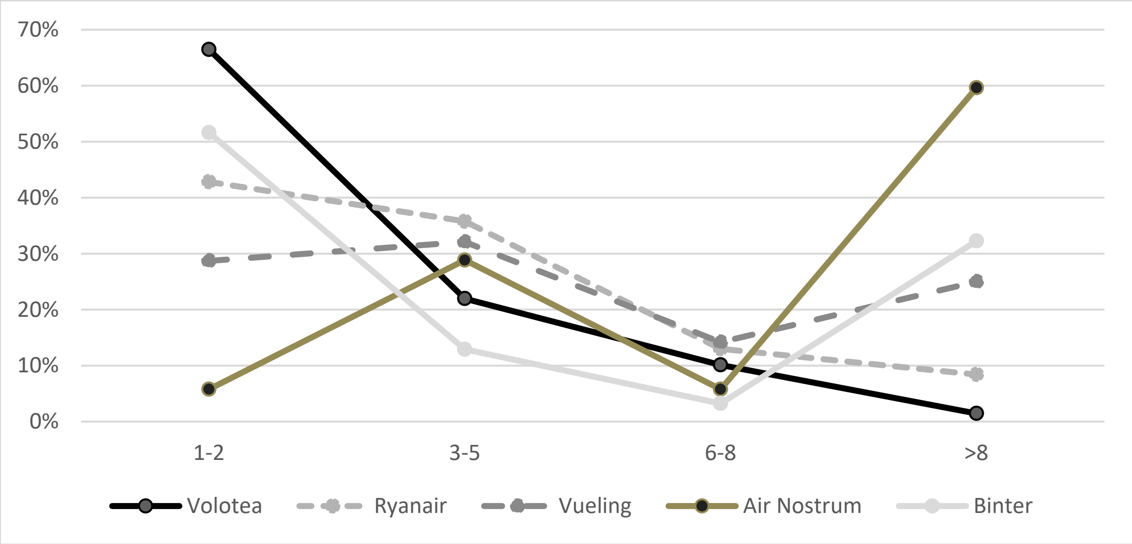

Fig. 2 - Weekly frequencies

We conducted a broader exploration of business model literature to search for a more generic business model that could dovetail with Volotea's model (Gassmann et al., 2014), and found that it could be framed as a *long tail business model* in the airline industry. The initial interest and subsequent definition and characterisation of the long tail business model was related to digital business. This is the kind of business which initially takes advantage of targeting a manifold of niche markets (Anderson, 2006). Well-known examples include the distribution of music, books and software.

The idea behind the long tail business model is that there are very few bestsellers, but a long list of items that only sell a few copies. Nevertheless, the store can sell a high number of units by joining all these less sold titles together. This a good business in this case for the distribution channel, probably not for the producers. This means that a business level analysis is not sufficient in this scenario and a useful analysis needs to be carried out at the activity level (Jarillo, 2003). In any case, the idea of serving a large number of low traffic routes conceptually matches the logic behind the long tail business model.

Economies of scale have been proposed as one of the key mechanisms of the low-cost business model. They bring significant cost reductions in key activities like buying aircraft, aircraft maintenance, handling, distribution and selling. Long-tail effects can bring this kind of cost reductions in a large part of the same activities (Sansonetti, 2010) although, in this case, we are talking about scope or density economies (Caves et al., 1984). Although these economies are less powerful, they can achieve sufficient savings to set attractive prices.

6. CONCLUSION

Volotea's business model brings together enough differential characteristics to be catalogued as a distinctive business model. It has distinguishing features from regional business carriers, and others that make it stand out from low-cost carriers and hybridised carriers. In addition, it has other characteristics that make it different from all other carriers.

The identification and characterisation of this business model reveals a large number of future developments that could be explored. An in-depth analysis could show the minimum threshold for thin routes to add value to the airline business, as well as other required conditions to make the effort rewarding. Our research also suggests the need to open the business' black box to analyse it at the activity level. Breaking down airline costs by activities would probably show how to increase the profitability of this business model, pointing to the activities that could act as leverage. Finally, a third line of research that we find promising and useful for practitioners would be to define and quantify the size of the market for this business model in Europe and other parts of the world.

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TOLL HIGHWAYS IN FINANCIAL DISTRESS: THE WINDING ROAD TO TERMINATE THE CONTRACTS

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ABSTRACT

Spain has extensive experience in the promotion of toll highways through contractual public private partnerships (PPPs) in the form of concession contracts. The Central Government has awarded thirty-two contracts since 1967, fourteen of them in the last two decades. Over time, Spain has been developing a broader legal framework to regulate these contracts. However, in 2013, nine out of the fourteen toll highways awarded between 1999 and 2006 filed for bankruptcy after years of financial distress. Most of these projects had been in operation for less than eight years and were severely affected by optimistic estimates of traffic demand and the economic crisis of 2007.

Given the imminent termination of the contracts, the government, the concessionaires and the financial institutions began to position themselves strategically, and adopted different measures to safeguard their own interests. Their decision-making has been highly motivated by a legal provision —known as State's Financial Liability— that guaranteed a termination payment to the PPP contractor in case bankruptcy was not attributable to the private sector.

This research shows the causes that motivated the bankruptcy of the contracts, and studies the strategical behavior of the different stakeholders involved according to their specific interests. From this case study, some lessons are provided on the correct way to design termination clauses in PPP contracts with the aim of safeguarding good service to the user while, at the same time, avoiding opportunistic behavior.

1. INTRODUCTION

Since the 1960s different Spanish governments have resorted to public-private partnerships (PPPs) as a means to construct and upgrade roads (Baeza, 2008). During 2018, the toll highway network in Spain consists of 2,957 km, of which 2,457 km are owned by the central government. Toll highways represent approximately 17% of the high-capacity road network, that is most of the high capacity network in Spain is free of charge (Ministerio de Fomento, 2019).

Toll highways in Spain have maintained most of their distinctive features over time. These are usually greenfield projects that were awarded through competitive tendering based on the open-procedure. They have been characterized by the allocation of most risks to the private sector, but also by the provision of an important termination guarantee by the government, the State´s Financial Liability (*Responsabilidad Patrimonial de la Administración o RPA)* (Ortega, Baeza and Vassallo, 2016).

This guarantee has been one of the most controversial issues of the concession regulation in Spain, since, in case of early termination of the contract, it commits the government to pay to the concessionaire the amount of capital costs (expropriation and construction costs) not yet depreciated at the time the contract expires. A new legislation passed in 2016 changed the concept by setting that, if the contract termination was not prompted by the government, the amount of the RPA will be the market value of the project. However, this new regulation does not apply retroactively.

The RPA and the government´s propensity to renegotiate contracts encouraged aggressive bidding behavior. Previous research has shown that Spanish bidders overestimated traffic forecasts and underestimated the capital investments in their bids as a strategic decision to win the tender at all costs (Baeza and Vassallo, 2010).

2. THE FINANCIAL PROBLEMS OF THE SPANISH TOLL HIGHWAYS

After twenty years, the central government recovered the toll concession approach to build new highways in 1996. The need to contain the country’s public deficit to comply with the European Union requirements to control government expenditure was one of the main reasons for returning to the concession approach.

Most of the toll highways included in this new program intended to supply greenfield alternatives to alleviate increasing congestion on sections of the existing toll-free highway network, especially those giving access to the city of Madrid.

However, in 2012 and 2013, nine of the fourteen toll highways awarded between 1999 and 2006 filed for bankruptcy after years of financial distress and negotiations between the government, concessionaires and lenders (see Table 1).

Currently, it can be claimed that the results of the latest toll-highway package have not been as expected. There are three main reasons for this situation: traffic underestimation, costs overruns during the expropriation and construction phases, and the economic crisis.

Highway	**Length (km)**	**Concessionaire**	**Year of award/ commissioning**	**Year of bankruptcy**
R-3 Madrid-Arganda	33.1	ACCESOS DE MADRID	1999 / 2004	2013
R-5 Madrid-Navalcarnero	29	ACCESOS DE MADRID	1999 / 2004	2013
Santiago-Alto de Santo Domingo	56.6	ACEGA	1999 / 2003	-
Ávila-Villacastín	23.1	CASTELLANA	1999 / 2002	-
Segovia-El Espinar	27.7	CASTELLANA	1999 / 2003	-
León-Astorga	38	AULESA	2000 / 2003	-
R-2 Madrid-Guadalajara	64.1	HENARSA	2000 / 2003	2013
R-4 Madrid-Ocaña	53	MADRID SUR	2000 / 2004	2013
M-12 EjeAeropuerto	8.8	EJE AEROPUERTO	2002 / 2005	2013
AP-36 Ocaña-La Roda	148	MADRID LEVANTE	2004 / 2006	2013
AP-41 Madrid-Toledo	60	MADRID TOLEDO	2004 / 2006	2012
AP-7 Cartagena-Vera	114	AUCOSTA	2004 / 2007	2013
AP-7 Circunvalación de Alicante	28.5	CIRALSA	2004 / 2007	2013
Málaga-Alto de las Pedrizas	24.5	GUADALCESA	2006 / 2011	-

Table 1 – Toll highway concessions awarded by the Central government from 1999 onwards

Firstly, the forecasts included in the economic-financial plans of the toll highway concessions were, in all cases, very optimistic. As a result, ever since the highways came into operation, actual traffic flows have been much lower than originally forecasted (Baeza & Vassallo, 2012).

Figure 1 summarizes the traffic deviations in the highways analyzed since their commissioning to the present. These deviations are measured as the percentage of actual traffic over that foreseen by concessionaires. Therefore, values below 100% show traffic overestimations.

The figure also differentiates those highways that ultimately went bankrupt (represented by dots) from those that stayed afloat (represented by triangles). The green line shows the average trend of traffic deviations for all the highways included in the sample.

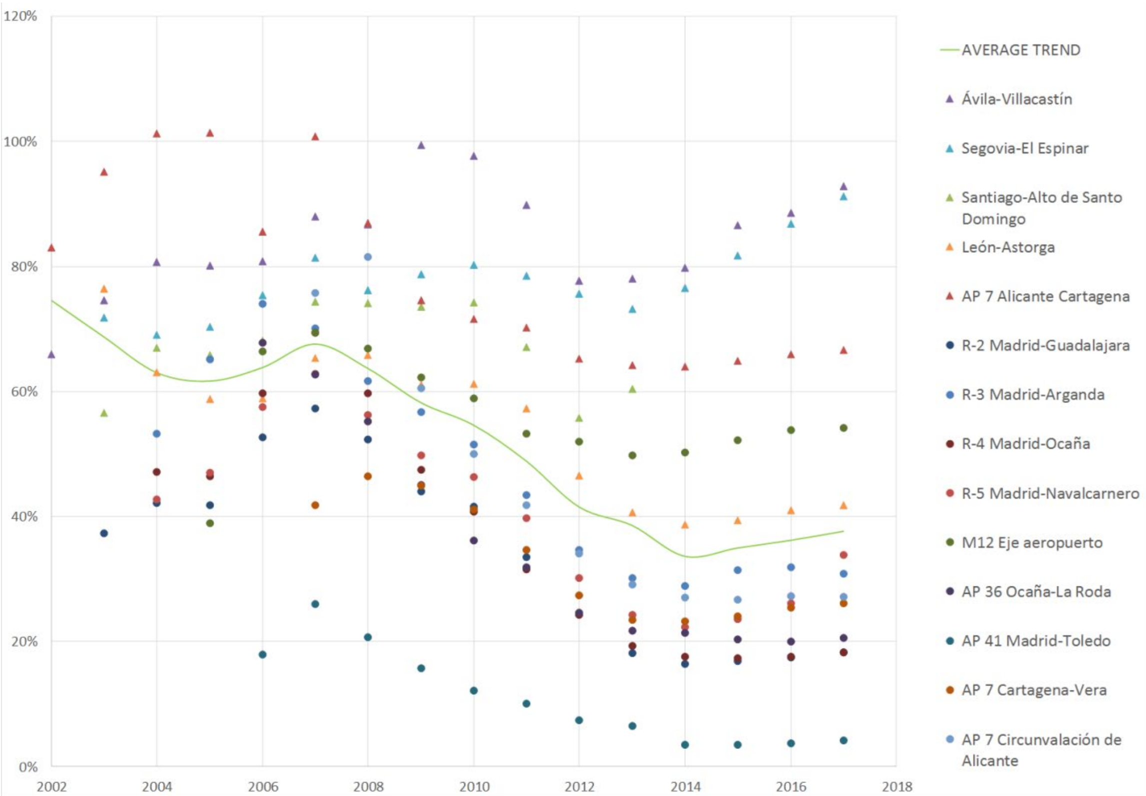

Figure 1 – Traffic deviations in the Spanish toll highway concessions since their commissioning

Secondly, the underestimation of construction costs conducted by the concessionaires in their bids was far from negligible (Vassallo et al., 2013). For example, the year in which the R-3 and R-5 highways came into operation, the cost overruns were 33.70%, and those of the Eje Aeropuerto exceeded 25%.

Moreover, the higher additional costs experienced by the highways were mainly due to expropriations. The cost of acquiring the right-of-way ultimately became much higher than expected as a result of a Supreme Court ruling stated in 2008 on how to quantify the price of land. The Supreme Court understood that highways are general road systems intended to create a city due to the existence of evident urban expectations (Baeza & Vassallo, 2011).

Finally, the impact of the economic crisis in Spain has been one of the greatest among the European countries. The country was in recession for seven quarters, which was reflected in negative GDP growths in both 2009 and 2010, and then it stabilized for a short period of time to fall back into recession for eleven quarters between 2011 and 2013.

Road demand on toll highways, which is very correlated with the evolution of the country's macroeconomic variables such as GDP per capita or industrial GDP (Gomez et al., 2015), was severely affected.

3. THE STRATEGIC BEHAVIOR OF THE STAKEHOLDERS

The strategic behavior followed by the main stakeholders involved in the process is studied in this section. The stakeholders considered are sorted into three different groups: the government, concessionaires and lenders.

3.1. Government

The general optimism in the country when the concessions were awarded led the government to conduct very optimistic feasibility studies assuming very high traffic growths and urban development expansions.

Between 2010 and 2012, the government approved a set of measures aimed at rebalancing the economics of the contracts to keep the concessions afloat. It began by granting subordinated public participation loans (SPPL) and compensation accounts.

On the one hand, SPPLs covered the expropriation costs exceeding 175% of the costs initially estimated by the PPP sponsors. The interest rates payable by the concessionaires over the life of the contracts would depend on the future revenues of the toll highways, with a minimum cap rate of 1.75%. On the other hand, the purpose of the compensation account was to provide liquidity to the concessionaire whose traffic and income were too low. Through the compensation accounts, the concessionaires would receive from the government the difference between 80% of the toll revenues originally expected and the actual revenue during a period of three years.

In 2012, a new conservative government took office in Spain. One of its priorities was to reduce the national public deficit and since highway traffic was not recovering, he opted to cancel the granting of additional SPPLs to the concessionaires, as well as the compensation accounts.

The subsequent declaration of bankruptcy of the nine aforementioned toll highways put the government in a complex situation. At that point, the maximum RPA related to the concessions bankrupted amounted to over €3.56 billion (Baeza & Vassallo, 2014), in a context where Spain was in the midst of a severe economic recession.

In addition, the Supreme Court ruled that the government was responsible for paying the additional costs of expropriation to landowners. To avoid paying twice, the government approved Royal Decree-Law 1/2014 that modifies the public procurement law on the valuation of state aid for land expropriation.
Under this provision, the government was allowed to reduce the RPA compensation to each concessionaire in the amount of money corresponding to the expropriation costs paid directly by the government when the SPV failed to meet its obligations to the owners.

3.2. Concessionaires

The optimism previous to the recession, the high competitiveness of the Spanish market, and the existence of the RPA guarantee encourage bidders to adopt aggressive strategies.

Between 2010 and 2011, the granted SPPLs represented a total of €532 million. With respect to compensation accounts, a total of €71.52 million were granted in these years. These measures eased the financial problems of the concessionaires for a few years. However, as traffic levels did not recover substantially, they ended up being useless in the long term for both the government and concessionaires.

After the government withdrew the state aid previously mentioned, private companies sued the government in court for withdrawing what had already been pledged, but the initiative was not successful.

Some sponsors negotiated with the lenders the restructuring of the debt to avoid insolvency. However, this option was finally not viable and triggered the start of a series of bankruptcies. Between 2012 and 2013, nine toll highway concessions were declared bankrupt. The reasons for synchronized bankruptcies are not clear. Sponsors might have thought that this situation could help them reach a better agreement in the negotiation phase given the fact that the government should avoid reimbursement of the RPA at all costs.

3.3. Lenders

The estimates conducted by the shareholders based on the feasibility studies produced by the government, along with the RPA and the seniority of their debt were sufficient for the lenders to join the project by providing large loans. The most common financial structure was a mini-perm (short-term loan) that had to be refinanced after few years of operation. However, the shortage of traffic and the excess of costs meant that the concessionaires could not refinance their mini permits (short-term loans), so long-term financing remain dependent of future government aid.

After the withdrawal of state aid, banks were no longer willing to accept a negotiated solution so sponsors ended up declaring bankruptcy. In this situation, financial institutions in Spain were required by law to create provisions for the total amount of credit granted to the bankrupt company. This measure had a great impact on the balance sheets and profit and loss accounts of the banks.

4. MEASURES TAKEN AFTER DECLARING BANKRUPTCY

The government proposed that an existing State-owned company called SEITTSA absorb bankruptcy toll roads without paying any compensation to the concessionaires. In return, creditors would have to waive around half of the senior debt outstanding at the time, which was around €2 billion. The remaining liabilities —around another €2 billion— would be entirely acquired by the main national banks in exchange for a 30-year treasury-backed bond. This bond would be issued by SEITTSA with a nominal value equal to the remaining liabilities, and a 4% guaranteed interest rate equivalent to the Treasury 30-year bond rate at that time. The most important banks of Spain (Santander, BBVA, Caixa, Bankia, Sabadell, Popular) would buy the liabilities of other banks with minor participation, most of them foreign ones. The main advantage of this solution for the government was that it avoided the payment of the RPA and its immediate consequences on the public deficit. However, some foreign banks, which financed few specific projects performing above the average, felt disadvantaged by a solution based on the average behavior of the portfolio.

In 2015, the Madrid Commercial Court initiated the liquidation process for the companies Autopista Madrid Levante, and Eje Aeropuerto, after no agreement was reached. The opening of the liquidation phase was an important date for the government because, once this phase was effective, the depreciation count for the final RPA calculation was stopped.

Some concessionaires managed to appeal to the courts to return to the negotiation phase, thus activating again the depreciation of the assets and reducing the value of the RPA. For this reason, between 2016 and 2017, lenders began selling their senior debt to hedge funds with the aim to recover at least part of their losses as soon as possible.

Cuts in these transactions ranged from 60% to 70% of the outstanding value of the loans. This clearly shows the little hope of lenders to achieve a good outcome in the liquidation process.

Hedge funds bought a large share of the senior debt from bankrupt concessions. Their strategy was to liquidate the firms as soon as possible to obtain the maximum value of the RPA.

Since the hedge funds had eliminated any possibility of restructuring the outstanding debt, the government decided that the nationalization of the toll highways with the subsequent payment of the RPA was the only solution to end the conflict.

In July 2017, the government decided that SEITTSA (a state-owned company) would take over both the toll roads that were already in the liquidation phase and those that would be liquidated in the future. In 2018, the liquidation plans of eight concessionaires were approved and SEITTSA gradually absorbed the toll roads.

At the date of this document, the government was carrying out the due diligence to estimate the final amount of the RPA liabilities to be paid, as well as the value of the new assets managed by SEITTSA.

5. CONCLUSIONS

The bankruptcy of highway concessions in Spain has had very negative reputational consequences since the credibility of the PPP model has been seriously damaged.

From the analysis performed, some lessons are pointed out. The first lesson is that the concession model requires risk allocation approaches resilient to economic cycles. If traffic flows are very sensitive to the evolution of the economy, it is advisable to apply other models, such as payment for availability, regardless of whether the government decides to charge users or not.

The second lesson is that guaranteeing a government termination payment in case of bankruptcy does not provide the right incentive for interested parties. On the one hand, this approach encourages the government to do everything possible to avoid termination of the contract, which can extend the litigation process without finding a good solution for the society. On the other hand, concessionaires take advantage of this guarantee to obtain cheap financing from lenders who do not pay much attention to assess the real viability of the project.

The third lesson is that legislation and contracts should be much better prepared to properly regulate the possible early termination of a concession. The lack of regulation seems to be the main cause that explains the long litigation processes and the difficulty in reaching a final solution to the problem.

Finally, one of the worst consequences of the process was the impact on the reputation that the negative experience has had on the concession model, the government and the legal system. This reputational aspect has been particularly sensitive for the general public and foreign institutions.

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ANÁLISIS DE LA PREDISPOSICIÓN A COMPARTIR VEHÍCULO POR LOS ESTUDIANTES UNIVERSITARIOS

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RESUMEN

La reducción de las emisiones derivadas del transporte es un asunto prioritario para la consecución de los Objetivos de Desarrollo Sostenible de la Agenda 2030. Por ello, incentivar el uso de medios de transporte sostenibles resulta fundamental y requiere de un análisis pormenorizado de las preferencias de los usuarios.

De ahí que en este trabajo se haya planteado el objetivo de analizar la predisposición que declaran los usuarios a realizar sus desplazamientos viajando como acompañante de un vehículo, como una de las medidas que puede reducir el uso individual del vehículo privado que es, además, uno de los principales problemas que caracteriza los patrones de movilidad en la isla de Tenerife. Específicamente, se analizará el caso de los estudiantes universitarios de la Universidad de La Laguna (ULL), en Tenerife. Para ello, se ha confeccionado una encuesta de preferencias reveladas, realizada en 2016, que permitió caracterizar la elección actual del modo de transporte y la predisposición que declaran los estudiantes a viajar como acompañantes en sus desplazamientos a los centros de estudio universitarios.

Entre los resultados obtenidos se encuentra que el número de vehículos disponibles en el hogar y el coste del viaje suponen un desincentivo para que los estudiantes conductores modifiquen sus patrones de movilidad actuales. Además, la estabilización de la jornada de estudio y la duración del viaje contribuyen positivamente a la probabilidad de que un estudiante opte por viajar como acompañante; mientras que los aspectos relacionados con la seguridad son los que hacen que los estudiantes estén menos predispuestos a compartir un vehículo. A la luz de los resultados obtenidos, se propone homogeneizar los horarios de clase del alumnado, reservar estacionamientos para vehículos de alta ocupación e impulsar la inversión en carriles BUS-VAO que permitan potenciar las ventajas más efectivas: las de índole personal.

1. INTRODUCCIÓN

La reducción de las emisiones derivadas del transporte es un asunto prioritario para la consecución de los Objetivos de Desarrollo Sostenible de la Agenda 2030, ya que influye en la consecución de los objetivos número 11 “Ciudades y comunidades sostenibles” y número 13 “Acción por el clima”. La Unión Europea se ha comprometido por ello a disminuir las que provienen del transporte un 60% por debajo de los niveles de 1990 para 2050. Siendo el vehículo privado el mayor contribuyente a las emisiones del transporte por carretera, incentivar el uso de medios de transporte sostenibles resulta fundamental y requiere de un análisis pormenorizado de las preferencias de los usuarios.

En este trabajo nos centraremos en la movilidad de los estudiantes universitarios de la ULL, en Tenerife. La isla de Tenerife (España), cuenta con una población de 928.604 habitantes, en la que el transporte terrestre se realiza fundamentalmente a través de la red de carreteras. Como única excepción cuenta en el área metropolitana de La Laguna-Santa Cruz con 16 km de metro ligero repartidos en 2 líneas. Éste, junto con el servicio de autobuses, forma la totalidad de la oferta de transporte público de la isla. La situación que ha caracterizado el transporte interno de la isla pone de manifiesto la necesidad de implementar medidas de gestión de movilidad que desincentiven el uso individual del coche, promueva el transporte público e introduzcan una intermodalidad en la que se impliquen modos de transporte sostenibles en las etapas iniciales y/o finales del viaje, como puede ser los desplazamientos a pie, viaje en bicicleta, etc.

Entre las diferentes medidas que se pueden aplicar, en este trabajo nos centraremos en la del uso compartido del coche. Así, tal y como señala el Parlamento Europeo (2019), los automóviles modernos pueden considerarse medios de transporte limpios si se comparten en lugar de utilizarse individualmente. Para fomentar esta modalidad de transporte, en muchas ciudades se han construido carriles exclusivos BUS-VAO. En España comienza con esta experiencia en 1994 con la construcción de dos carriles BUS-VAO en la CN-VI de Madrid. Basado en el uso de estos carriles, Pozueta et al. (1997) ponían de manifiesto, entre otros aspectos, la gran diferencia entre el número de personas que se declaran dispuestas a compartir, frente al número real de usuarios del sistema -que es mucho menor-.

Se puede encontrar en la literatura científica diversos estudios que tratan de averiguar cuáles son las principales razones que llevan a los usuarios a compartir el coche y, además, tratan de caracterizar el perfil de los usuarios de coche compartido. (Olsson, Maier, y Friman, 2019). Neoh, Chipulu y Marshall (2017) categorizaban en su metaanálisis las variables que influyen en la decisión de compartir en 3 subgrupos: Factores demográficos, situacionales (como la existencia de un carril Bus-VAO) y subjetivos.

Son los factores incluidos en esta última categoría, los que han adquirido un mayor foco de atención en los últimos años; ya que como señalan Homem de Almeida, de Abreu y Viegas (2013) la actitud juega un papel importante en la decisión de participar en un grupo de coche compartido.

Los factores psicológicos relevantes en la decisión varían entre los estudios, lo que puede ser debido a que la motivación de los usuarios cambia con el tiempo y las experiencias que hayan tenido. (Julagasigorn, Banomyong y Varadejsatitwong, 2018).

Dado que las universidades son tanto generadores como atractores de una porción importante de viajes en una región (Moreno, Sarmiento y González-Calderón, 2011) tienen un papel significativo como vectores para promover políticas sostenibles de transporte.

Además, la gestión del espacio de aparcamiento aparece como un problema habitual en entornos universitarios (Azzali y Sabour, 2018; Rotaris y Danielis, 2014; Ibeas, dell´Olio, dell'Olio y Barreda, 2010; entre otros). Ya sea con el objetivo de resolver los problemas de movilidad de la comunidad universitaria, o de fomentar en ellas sistemas de transporte sostenible; se ha estudiado en distintas universidades, cuál es el reparto modal de estudiantes y personal, así como el potencial y/o restricciones existentes al cambio de modo, con el objetivo de proponer o evaluar distintas medidas. (Balsas, 2003; Gurrutxaga, Iturrate, Oses y García, 2017; Papantoniou, Yannis, Vlahogianni, Attard, Regattieri, Piana y Pilati, 2020; Riggs, 2014) Así, por ejemplo, en la universidad de Western Australia (UWA) (Shannon, Giles-Corti, Pikora, Bulsara, Shilton y Bull, 2006) concluyeron que un 20-30% de los usuarios podría cambiar su comportamiento en el corto plazo. En la universidad de Barcelona (Miralles-Guasch y Domene, 2010) los usuarios que desean cambiar de modo suben hasta el 54%, si bien esta cifra se ve influenciada por efectos de demanda cautiva.

Aunque la opción del coche compartido no aparece en todos los casos de estudio, encontramos algunos donde se evalúa el uso de coche compartido en entornos universitarios (véase, entre otros, Tezcan 2016; Galatoulas, Koutra, Rycerski, Candanedo y Ioakeimidis, 2017; Gallo y Buonocore 2017). En general, se encuentre un resultado común que apunta a una actitud en favor del coche compartido.

Los antecedentes al actual estudio se encuentran en los trabajos previos realizados en la Universidad de La Laguna para captar los patrones de movilidad de los estudiantes en sus desplazamientos al centro de estudios, para evaluar diferentes políticas de transporte y derivar los valores del tiempo. Así, en el 2005 se obtuvieron las disposiciones a pagar de los estudiantes, por los ahorros de tiempo de viaje, teniendo en cuenta que las preferencias son heterogéneas (Amador, González, 2005). En el año 2007 se desarrolla una encuesta de preferencias reveladas y declaradas para captar el reparto modal y la predisposición a usar un tranvía que uniría los campus universitarios.

En el 2009 se realiza nuevamente una encuesta a los estudiantes de la ULL, en este caso solo de preferencias reveladas, para evaluar las declaraciones hechas por los alumnos dos años antes acerca de su predisposición a cambiar al tranvía.

Esta última encuesta permitió comprobar la fiabilidad de los modelos a la hora de predecir que el reparto modal una vez que el tranvía se implantara en la isla de Tenerife (González, Martínez y Esquivel, 2012; González, Lorente y Martínez, 2017), permitió evaluar el efectos sobre los valores del tiempo y las elasticidades de demanda cuando se utilizan datos de panel entorno a la implantación de un nuevo modo (González, Marrero y Marrero, 2016) y permitió captar la importancia del efecto inercia cuando se implantan políticas de ampliación de la oferta de transporte público (González, Marrero y Cherchi, 2017).

La Universidad de La Laguna forma parte del proyecto U-MOB (red de universidades por la movilidad sostenible) y ha implantado medidas como el circuito universitario de autobús, iniciativas para promover el uso de la bicicleta y puntos de recarga de vehículos eléctricos. Habiendo recibido el reconocimiento por su compromiso con la movilidad sostenible y segura, de la Dirección General de Tráfico y el proyecto europeo STARS. Sin embargo, cuando se analizan los patrones de movilidad se detecta como sigue teniendo un papel predominante el uso del coche sin acompañante y el transporte público tiene un elevado porcentaje de usuarios que son cautivos (lo eligen porque no tienen disponible otra alternativa). Todo ello pone de manifiesto la necesidad de seguir investigando de cara a aportar nuevas medidas que hagan que se dé un comportamiento más sostenible.

En este trabajo se plantea el objetivo de analizar la predisposición de los estudiantes de la Universidad de La Laguna a compartir el vehículo en sus desplazamientos, como una de las medidas que se podría proponer para mejorar los patrones de movilidad actuales de los universitarios de La Laguna. Concretamente se estudia la predisposición a cambiar del modo de transporte habitual y viajar como acompañante en un vehículo con otras personas. Se estiman diferentes especificaciones econométricas con el objeto de evaluar cuál produce un mejor resultado y se ajusta mejor a los datos utilizados. Específicamente, se ha trabajado con una encuesta realizada en 2016 a los estudiantes de la Universidad de La Laguna, con la intención de valorar la potencial demanda existente para un carril bus-VAO diseñado por el Cabildo de Tenerife en la TF-5. Dicha encuesta se estructuró en dos partes. La primera es una encuesta de preferencias reveladas que permitió caracterizar la elección actual del modo de transporte y la predisposición que declaran los alumnos a viajar como acompañante. La segunda parte es una encuesta de preferencias declaradas en la que se estudia cómo se podría modificar su comportamiento debido a la existencia del nuevo carril bus-VAO, donde se simula como serían las características de su viaje en cada uno de los modos que podría utilizar.

En la realización de este trabajo se han utilizado los resultados de la primera parte, es decir, de la encuesta de preferencias reveladas.

Los modelos que se utilizan este trabajo son modelos de elección discreta; específicamente se han utilizado las especificaciones de un logit binomial, un logit multinomial y dos logit ordinales; tal y como se comentó, el objetivo que se persigue es seleccionar el modelo que mejor se ajuste a la base de datos utilizada.

Una vez seleccionado el modelo, se pueden analizar los resultados y proponer opciones de políticas que permitan impulsar entre los alumnos el uso del coche compartido.

El resto del trabajo se organiza de la siguiente forma. En el apartado 2 se describen las principales características de la universidad, y se presenta un análisis descriptivo de los datos obtenidos en la encuesta de preferencias reveladas. En el apartado 3 se expone la metodología utilizada. A continuación, en el apartado 4 se comentan los resultados más destacados. Por último, se recogen algunas de las principales conclusiones que pueden extraerse del análisis realizado.

2. DATOS

2.1 Contexto del estudio: Universidad de La Laguna

La Universidad de La Laguna, situada en la isla de Tenerife (Islas Canarias, España) desde su fundación en 1792, es el centro de educación superior más antiguo de Canarias. La universidad se reparte entre 6 campus: Adeje, Anchieta, Central, Ofra, Santa Cruz y Adeje; estando la mayoría localizados en el área metropolitana de la isla, entre las ciudades de San Cristóbal de La Laguna y Santa Cruz de Tenerife. Con más de 25.000 personas entre personal y alumnado, es una entidad que genera una intensa actividad en la isla y atrae un importante número de viajes cada día.

2.2 Encuesta de preferencias reveladas y análisis de los datos

La información utilizada para estimar los modelos de elección discreta se obtiene de la encuesta de preferencias reveladas que se realizó a los alumnos de la Universidad de La Laguna en la primavera de 2016 en formato de cuestionario on-line. Esta encuesta obtuvo en el plazo de 2 meses una muestra de 3003 encuestados de entre los 18.343 alumnos matriculados en el curso 2015/2016.

Una vez filtrados los datos (se eliminan aquellos que no responden a preguntas clave en el análisis y a aquellos que entregan respuestas incompletas o incorrectas), se obtiene una muestra de 2695 respuestas, lo que supone un 14.7% del total de alumnos y es superior a los 2124 necesarios para un tamaño muestral para un margen de error del 2% y nivel de confianza del 95%.

En el cuestionario se pregunta a los alumnos acerca de:

- Las características socioeconómicas del encuestado y su unidad familiar (sexo, edad, tamaño de la unidad familiar, número de coches en la familia, ingresos…).
- El modo transporte habitual para desplazarse y las características del viaje (coste, tiempo).
- Los motivos principales por el que eligen este modo.
- La disponibilidad que tienen de utilizar otros modos de transporte.
- La predisposición a utilizar el coche compartido, y en el caso de los conductores de compartir su coche y las ventajas e inconvenientes de esta alternativa.

La Tabla 1 refleja las principales características socioeconómicas de la muestra, su modo de transporte habitual y su predisposición a compartir.

La mayoría de los alumnos acude a su centro de estudios 5 días por semana, sin embargo, menos de la mitad lo hace siguiendo un horario regular en el que acuden siempre a la misma hora. Esto puede ser relevante a la hora de valorar opciones de regularización de horarios del alumnado.

También se observa la predominancia del uso del vehículo privado e individual como modo de transporte, representando este un 39% de los encuestados, este ha sido un resultado habitual en los patrones de movilidad de los estudiantes estudiados previamente (González et al, 2016, 2017). De los 1165 alumnos que declaran que viajan en coche como conductor, el 72% lo hacen solos. Suponiendo vehículos de 5 plazas, esto supone que a diario se desplazan 3356 asientos vacíos. Por otro lado, vemos que un 39% de los alumnos, que viajan en transporte público, declara que elige su medio de transporte habitual debido a que no dispone de coche. Nos encontramos, por tanto, entre los usuarios del transporte público, con una demanda cautiva que aparentemente utilizaría el vehículo privado si dispusiera de esa opción.

El transporte público, en su conjunto, abarca otro 39% de la muestra, siendo el tranvía la opción de esta modalidad más utilizada, a pesar de que sólo está disponible en el área metropolitana de la isla. Esto se debe a que esta es también el área en la que residen de forma habitual la mayoría de los estudiantes y a la cercanía de la mayoría de los campus universitarios a las paradas del tranvía.

A pesar de que sólo el 27% de los conductores viajan acompañados y un 10% de los estudiantes declaran viajar en coche como acompañante, los estudiantes muestran una actitud a priori positiva ante la opción del uso del coche compartido, ya que un 68% afirman estar en gran medida o totalmente dispuestos a viajar en coche como acompañantes. Una vez que veamos qué factores son los que influyen en esta predisposición a compartir y que estimemos la importancia de cada uno de esos factores, a través del cálculo de los efectos marginales, podremos buscar opciones para fomentar que los alumnos den el paso y se decidan a utilizar este modo.

Cabe señalar, que a pesar de que el cuestionario original incluía información sobre el ingreso de la unidad familiar de los encuestados, no se ha podido utilizar durante el desarrollo de los modelos, debido a que la mitad de los encuestados escogieron no responder a esa pregunta.

Esto es una situación habitual en este tipo de encuestas, en los que la gente se muestra reacia a declarar su renta. Se opta, por tanto, aproximar esta variable económica de forma indirecta, atendiendo a la tasa de motorización en la unidad familiar de los alumnos, de la cual sí se tienen datos.

Género		
Mujer	1096	59%
Hombre	1599	41%
Edad		
Menos de 21 años	1546	57%
De 22 a 25 años	740	27%
De 26 a 30 años	244	9%
Más de 30 años	165	6%
Ingreso familiar mensual		
Menos de 450	206	8%
$450 \leq x < 900$	360	13%
$900 \leq x <1500$	461	17%
$1500 \leq x \leq 2400$	230	9%
Más de 2400	100	4%
No sabe / No contesta	1338	50%
Días que acude al centro		
Entre 1 y 3 días	249	9%
4 días	684	25%
5 días	1765	65%
Acude al centro siempre a la misma hora		
Sí	1265	47%
No	1430	53%
Tasa de motorización		
Coches/Miembros de la familia		53%
Dispone de coche para acudir al centro		
Nunca	1205	48%
Ocasionalmente	354	13%
Habitualmente	1136	38%

Modo de transporte habitual		
A pie	282	10%
En coche como acompañante	262	10%
En coche como conductor	1165	43%
En autobús	314	12%
En tranvía	515	19%
Transporte público combinado (2+)	157	6%
Otro	6	0.2%
Motivo principal de elección del modo		
Tiempo	1257	47%
Coste	329	12%
No dispone de coche	866	32%
Otros	243	9%
Está dispuesto a viajar compartiendo vehículo		
En absoluto	185	7%
En poca medida	690	26%
En gran medida	1072	40%
Totalmente dispuesto	748	28%

Tabla 1 – Características socioeconómicas de la muestra

En la Tabla 2 se recoge la información ofrecida por el Ministerio de Universidades acerca de los alumnos matriculados en la universidad de La Laguna en el curso 2015-2016. Comparando con la tabla 1 podemos ver que el reparto de nuestra muestra por género resulta muy similar al del total de la comunidad universitaria durante este curso, por lo que sabemos que la población está adecuadamente reflejada en la muestra. Lo mismo ocurre con el reparto por edades, en el que vemos que estamos ante una población joven, con un 93% menor de 30 años.

Total por género		
Mujer	10593	58%
Hombre	7750	42%
Total por edad		
De 18 a 21 años	10000	55%
De 22 a 25 años	5191	28%
De 26 a 30 años	1846	10%
Más de 30 años	1306	7%

Tabla 2 – Alumnado matriculado en la ULL durante el curso 2015-2016

Fuente: Sistema Integrado de Información Universitaria (SIIU). Secretaría General de Universidades.

Para poder obtener información acerca de la percepción subjetiva que tienen los alumnos sobre la opción de utilizar el coche compartido, se les preguntó acerca de las ventajas e inconvenientes que consideraban que tiene como alternativa. Los alumnos pudieron escoger uno o varios de los factores propuestos o señalar “Otro” y escribir los suyos propios.

Los factores recogidos pueden categorizarse como factores que les suponen ventajas o inconvenientes a diferentes niveles:

- Ventajas a nivel personal: Son factores que afectan al alumno de forma directa, como el ahorro económico, ganancias de tiempo o existencia de plazas de aparcamiento reservadas para vehículos con 2 o más ocupantes.
- Ventajas a nivel social: Factores que afectan al entorno social del alumno, como conocer gente.
- Ventajas a nivel externo: Son factores que resultan ventajosos para el conjunto de la sociedad como la reducción de la contaminación, la reducción de la congestión o el ahorro energético.
- Problemas de pérdida de libertad: Problemas relacionados con la pérdida de independencia a la hora de viajar con otras personas como someterse a un horario fijo, tener problemas a la hora de regresar a casa.
- Problemas de horarios: Retrasos, impuntualidad, dificultad para conciliar horarios.
- Problemas de seguridad: El miedo o inseguridad que les genera viajar en el mismo vehículo con desconocidos.

En la Tabla 3 vemos los resultados relativos a las ventajas e inconvenientes que declaran los estudiantes para viajar como acompañante.

Ventajas	
A nivel personal	83%
A nivel social	4%
A nivel externo	9%
No veo ninguna ventaja	4%
Inconvenientes	
Pérdida de libertad	35%
Problemas de horarios	55%
Problemas de seguridad	2%
No veo ningún problema	8%

Tabla 3 – Ventajas e inconvenientes de viajar en coche como acompañante

3. METODOLOGÍA

Dada la naturaleza de carácter discreto de las respuestas que entregan los estudiantes acerca de la predisposición a viajar como acompañante (véase Tabla 1), parece conveniente plantear el uso de modelos de elección discreta. Estos modelos permiten ejecutar regresiones para situaciones en las que la variable dependiente no es continua sino discreta, es decir, que solo toma valores concretos que se corresponden con las distintas categorías sobre las que el individuo realiza su elección.

Estos modelos se clasifican en distintos grupos, dependiendo de la naturaleza concreta de la variable discreta a modelizar, dependiendo de si esta es binaria o multinomial, ordenada o no, etc. La polivalencia y utilidad de estos modelos es tal que han sido aplicado a múltiples campos de investigación, como la demanda de transporte (González, Román y Marrero, 2018; Arbeláez, Sarmiento y Córdoba, 2020; Cherchi y Ortúzar, 2002, 2010) o la articulación de políticas públicas (Barroso, Abásolo y Cáceres, 2016; Pinilla, González, Barber y Santana, 2002), en otros campos (Rodríguez, Romero, Cano y Guirao, 2019).

En concreto, dada la naturaleza de carácter ordinal de las respuestas que entregan los estudiantes acerca de la predisposición a compartir el vehículo, los modelos más adecuados son los ordinales. Ello debido a que esta predisposición puede ser ordenada de menor a mayor predisposición. En particular, la especificación más usual en este escenario es la de un modelo logit ordinal que sigue la siguiente regresión de variable dependiente que, a su vez, es una variable latente o no observada (Y_i^*) que depende de un conjunto de variables explicativas que determinan la decisión del individuo.

$$Y_i^* = x_i'\beta + \varepsilon_i \tag{1}$$

De esta forma, la elección del individuo queda explicada por el componente sistemático de la regresión ($x_i'\beta$), el cual es observado directamente por el investigador, y por el componente aleatorio (ε_i), el cual representa los posibles errores de observación cometidos por el investigador, así como aquellos aspectos que no pueden ser observados como los gustos o las preferencias de los individuos investigados.

Así, la elección de cada individuo (i) entre las distintas alternativas ($0, \dots, J$) dependerá del valor de la variable latente (Y_i^*) y de los umbrales (μ_j) que separan los valores correspondientes a cada una de las categorías, de tal forma que

$$Y_i = \begin{cases} 0, \ si \ Y_i^* \leq \mu_0 \\ 1, \ si \ \mu_0 \leq Y_i^* \leq \mu_1 \\ 2, \ si \ \mu_1 \leq Y_i^* \leq \mu_2 \\ \vdots \\ J, \ si \ \mu_{J-1} \leq Y_i^* \end{cases} \tag{2}$$

A partir de este enfoque y considerando, como ya se adelantó, que la función de distribución del término aleatorio (ε_i) es logística (Λ), el modelo probabilístico que permite calcular la probabilidad de elección de cada alternativa queda definido como sigue:

$$P(Y_i = j) = P\left(\mu_{j-1} \leq Y_i^* \leq \mu_j\right) = P\left(\mu_{j-1} - x_i'\beta \leq \varepsilon_i \leq \mu_j - x_i'\beta\right) = \Lambda\left(\mu_j - x_i'\beta\right) - \Lambda\left(\mu_{j-1} - x_i'\beta\right),\ j = 0, \cdots, J \quad (3)$$

Tanto los umbrales ya mencionados como el vector de parámetros del modelo, que en especificaciones ordenadas es común a todas las alternativas, pueden ser estimados mediante el método de máxima verosimilitud.

A partir de la estimación, los resultados pueden ser interpretados mediante el uso de distintas herramientas como, por ejemplo, los efectos marginales que permiten conocer el efecto que, sobre la probabilidad de elección, tiene un cambio en las variables explicativas. Los efectos marginales se pueden obtener de la siguiente forma:

$$\frac{\partial P(Y_i=j)}{\partial x_{im}} = [f\left(\mu_{j-1} - \beta' x_i\right) - f\left(\mu_j - \beta' x_i\right)]\beta_m,\ j = 0, \cdots, J \quad (4)$$

Por la propia naturaleza de los efectos marginales en este tipo de modelos, se puede obtener una primera conclusión sobre las categorías extremo, y es que estas presentan signo opuesto. En este sentido, dado que es una relación que necesariamente se va a verificar, resulta conveniente examinar si la satisfacción de este supuesto resulta conveniente en el análisis de cada caso objeto de estudio (Rodríguez y Cáceres, 2007).

Por otra parte, los resultados también pueden ser interpretados a partir del cálculo de odds-ratios que, para un modelo logit ordinal, se definen como:

$$\Omega_j(x_i) = \frac{P(Y_i \leq j)}{P(Y_i > j)} = \frac{F(\mu_j - \beta' x_i)}{1 - F(\mu_j - \beta' x_i)} = e^{(\mu_j - \beta' x_i)},\ j = 0, \cdots, J-1 \quad (5)$$

Este cálculo permite comparar la probabilidad de estar en una categoría (menor o igual a j) frente a otra superior. Si se estiman a nivel individual, pueden ser interpretados como el patrón de sustitución entre dos categorías para un individuo con un vector de características concreto. De esta forma, el cociente de odds-ratios permite conocer el patrón de sustitución entre categorías cuando, además, se produce una variación unitaria en una de las variables explicativas.

Dado que uno de los objetivos de este trabajo es evaluar la adecuación de diferentes especificaciones econométricas para analizar la predisposición a compartir vehículo que declaran los estudiantes, se plantean además del logit ordinal otros modelos de elección discreta. Específicamente, las especificaciones de los logit multinomiales y binomiales.

Estas permiten suavizar algunos supuestos de la especificación ordenada y, sobre todo, permiten ver si las variables explicativas relevantes varían de acuerdo con la especificación planteada. A continuación, se presentan brevemente algunas de las características de los modelos mencionados.

El modelo logit multinomial no considera la existencia de un orden implícito en las alternativas entre las que elige el individuo, siendo esta la principal diferencia con la especificación ordinal además elimina ciertas restricciones como la exigencia de contar con signos distintos en los efectos marginales de las alternativas extremo. Estos modelos cuentan con el respaldo teórico de la Teoría de la Utilidad Aleatoria propuesta por Domencich y McFadden (1975).

Este enfoque se basa, principalmente, en cuatro pilares fundamentales: el individuo cuenta con toda la información y actúa racionalmente maximizando su utilidad, toma su elección de acuerdo con sus propias características y los atributos de las alternativas, cada alternativa reporta un nivel de utilidad determinado que depende de un componente sistemático u observable u de un componente aleatorio, y, una vez maximiza, elegirá aquella alternativa que le reporta mayor nivel de utilidad. A partir de estos fundamentos, la probabilidad de elección de cada alternativa viene definida así

$$P(Y_i = j) = \frac{e^{x_i'\beta_j}}{1+\sum_{k=1}^{J} e^{x_i'\beta_k}}, j = 0, \dots, J \tag{6}$$

Ahora bien, como ocurre con el modelo ordinal, para interpretar los resultados se deben emplear instrumentos como los efectos marginales

$$\frac{\partial P(Y_i=j)}{\partial x_{im}} = P(Y_i = j)\left[\beta_{jm} - \sum_{k=1}^{J} \beta_{km} P(Y_i = k)\right], j = 0, \dots, J \tag{7}$$

O los odds-ratios y cocientes de estos, los cuales permiten conocer el patrón de sustitución entre distintas alternativas, permitiendo así describir las preferencias de los individuos.

$$\Omega_{j/k} = \frac{P(Y_i=j)}{P(Y_i=k)} = \frac{e^{x_i'\beta_j}}{e^{x_i'\beta_k}} = e^{x_i'(\beta_j-\beta_k)}, j = 0, \dots, J, j \neq k \tag{8}$$

Por último, el modelo logit binomial parte del supuesto de que cada individuo debe elegir entre dos alternativas distintas, identificadas por los valores 0 y 1. Este modelo sigue, por tanto, la distribución logística y la probabilidad de elección de cada alternativa puede obtenerse a partir de la siguiente expresión:

$$P(Y = j) = \frac{e^{X\beta}}{1+e^{X\beta}} = \Lambda(X\beta) \tag{9}$$

En el caso del modelo binomial, el signo de sus parámetros sí que puede ser interpretado directamente, aunque, al igual que en el resto de los modelos, sus resultados pueden interpretarse a través del cálculo de efectos marginales u odds-ratios.

4. RESULTADOS

Tal y como se ha venido argumentando en el aparatado metodológico, la naturaleza de la variable dependiente de los modelos propuestos (predisposición del individuo a viajar como acompañante) y el objetivo de este trabajo justifican el uso de los modelos de elección discreta. Uno de los objetivos que se persiguen en este trabajo es evaluar cuál es la especificación econométrica que mejor se ajusta a los datos (ordenada, no ordenada, etc.) y ver si las variables explicativas cambian o no en función de la especificación utilizada.

El primer planteamiento que se hizo consistió en usar diferentes agrupaciones de las categorías de las respuestas a la predisposición a viajar como acompañante, ya que los individuos cuando responden no necesariamente considerar el agrupamiento que se les da y pueden estar considerando que varias categorías significan lo mismo. Así, inicialmente se consideraron las cuatro categorías entregadas, esto es: en absoluto, en poca medida, en gran medida y totalmente predispuesto. Posteriormente esas cuatro categorías se agrupan en tres y después en dos, dando lugar a diferentes modelos. Por esa razón, se presentan los resultados de tres especificaciones distintas, dependiendo del número de categorías que se consideren de la variable dependiente y de la propia naturaleza del modelo. En concreto, se plantean especificaciones de un modelo logit multinomial, un modelo logit ordinal y un modelo logit binomial.

Inicialmente se presentan, en la Tabla 4, las definiciones de las variables que han resultado significativas en uno o varios de los modelos, así como la agrupación que se ha hecho de las distintas categorías de la variable endógena (*Disposición a compartir vehículo)* y cuál de ellas actúa como referencia. Además, se recoge la variable dependiente que se utiliza en cada especificación y sus agrupaciones sucesivas.

Variable	***Valores***
Norte	1 = Reside en el norte 0= Reside en otro lugar
Tasa de motorización	Variable continua
Asistencia todos los días de la semana	1= Asiste 5 días a clase 0= Asiste 4 o menos días
Todas las asignaturas en horario de mañana	1 = Asignaturas concentradas en el turno de mañana 0 = Asignaturas concentradas en el turno de tarde o repartidas en ambos turnos

Variable	***Valores***
Disponibilidad de vehículo	1 = Dispone habitual u ocasionalmente de vehículo 0= Nunca dispone de vehículo
Tiempo de viaje	Variable continua
Coste del viaje	Variable continua
Elección del modo: no coche	1 = Elige el modo actual por no tener vehículo 0 = Otro motivo de elección del modo actual (p. ej.: tiempo)
Elección del modo: economía	1 = Elige el modo actual por razones económicas (p. ej.: más barato) 0 = Otro motivo de elección del modo actual (p. ej.: tiempo)
Ventaja: Fact. Personales	1 = Ventajas personales 0 = Resto de opciones
Ventaja: Fact. Sociales	1 = Ventajas sociales 0 = Resto de opciones
Ventaja: Fact. Externos	1 = Ventajas externas 0 = Resto de opciones
No encuentra ventaja	1 = No ve ventaja a compartir 0 = Resto de opciones
Problema: Libertad	1 = Problema asociado a la libertad 0 = Resto de opciones
Problema: Horarios	1 = Problema asociado al tiempo 0 = Resto de opciones
Problema: Seguridad	1 = Problema asociado a la seguridad 0 = Resto de opciones
No encuentra problema	1 = No ve problema a compartir 0 = Resto de opciones
Disposición a compartir vehículo modelo logit multinomial con cuatro categorías	0 = en absoluto 1 = en poca medida 2 = en gran medida 3 = totalmente predispuesto
Disposición a compartir vehículo modelo logit ordinal con tres y cuatro categorías	0 = en absoluto 1 = en poca medida 2 = en gran medida o totalmente pred.
Disposición a compartir vehículo modelo logit binomial	0 = en absoluto o en poca medida 2 = en gran medida o totalmente pred.

Tabla 4 – Descripción de las variables empleadas en los modelos

En primer lugar, se presenta el análisis del modelo logit multinomial en el que las alternativas son las cuatro opciones que se dan en el cuestionario a la pregunta relativa a la disposición a compartir vehículo en su viaje. Esta especificación, de acuerdo con el diseño inicial de la encuesta, modela la probabilidad de elección entre las siguientes cuatro alternativas: en absoluto, en poca medida, en gran medida y totalmente dispuesto. Los resultados de la estimación de este modelo, así como los efectos marginales para cada categoría, se presentan en la Tabla 5.

A pesar de que parece que el modelo se ajusta bien a los datos, si se toma como referencia aspectos como la significación individual y conjunta del modelo, sí que se observa que el porcentaje de observaciones que es capaz de predecir adecuadamente es inferior al 50%. Por esta razón, se optó por hacer distintas agrupaciones de las categorías de elección de la variable endógena que permitieran conocer qué aspectos podrían contribuir a la mejora predictiva del mismo. Finalmente, resultó que, tras unir las dos últimas categorías (predispuesto en gran medida y totalmente predispuesto) en una única, el modelo ganaba capacidad de predicción, por lo que se opta por realizar esta y las siguientes dos estimaciones con tres categorías de elección: en absoluta, en poca medida y en gran medida, esta última considerando la agrupación planteada.

	Estimación de parámetros			***Efecto marginal sobre la prob.***			
	P (Y=1)	***P (Y=2)***	***P (Y=3)***	***P (Y=0)***	***P (Y=1)***	***P (Y=2)***	***P (Y=3)***
Norte	0.25	0.41**	0.46**	-0.0209	-0.0218	0.0181	0.0245
Tasa de motorización	-0.21	-0.66**	-0.93***	0.0315	0.0825	-0.0296	-0.0844
Elección del modo: no coche	1.03***	1.00***	0.97***	-0.0587	0.0304	0.0239	0.0044
Elec. del modo: economía	0.62**	0.44	0.83***	-0.0350	0.0196	-0.0509	0.0664
Ventaja: Fact. Personales	0.19	0.91***	1.21***	-0.0403	-0.1276	0.0576	0.1103
No encuentra ventaja	-1.39***	-23.6	-23.8	0.8644	3.4685	-2.6615	-1.6714
No encuentra problema	0.31	1.03	2.37***	-0.0605	-0.1871	-0.0573	0.3049
Constante	1.22***	1.64***	1.11***	-	-	-	-

$N = 2695 \quad R^2_{MCF} = 0.0712 \quad \chi^2(21) = 481.89\ (0.0000) \quad LnL = -3141.7279$

Niveles de significación: *** p < 0.01; * p < 0.05; * p < 0.10

Predicciones correctamente predichas: 44.2%

Tabla 5 – Estimación del modelo logit multinomial con cuatro categorías

A la luz de los resultados obtenidos cuando se hacen diferentes agrupamientos de la variable endógena, se observa que las estimaciones mejoran en su capacidad predictiva. Ello permite concluir que, para los individuos encuestados, la elección entre las dos categorías superiores

-aquellas que indican un mayor nivel de predisposición a compartir vehículo- no está del todo clara. Es decir, consideran ambas categorías como similares y por ello los modelos que las agrupan representan mejor el comportamiento revelado por los estudiantes acerca de la predisposición a compartir coche.

En relación con la especificación multinomial de tres categorías, esto es, sin considerar el orden que inicialmente se daba a las alternativas, se obtienen los resultados que se presentan en la Tabla 6. En cuanto a la adecuación del modelo, se observa que todas las variables resultan significativas individualmente, aunque a niveles distintos de significación del 1% y el 10%. A nivel conjunto, se rechaza la hipótesis planteada en el contraste, resultando así también adecuadas. Además, otros indicadores como el pseudo R-cuadrado (McFadden, 1974) y el porcentaje de predicciones correctas mejoran sustancialmente respecto al modelo anterior.

	Estimación de parámetros		***Efecto marginal sobre la prob.***		
	P (Y=1)	***P (Y=2)***	***P (Y=0)***	***P (Y=1)***	***P (Y=2)***
Tiempo de viaje	0.0038	0.0084**	-0.0004	-0.0006	0.0010
Elección del modo: no coche	0.8267***	0.8016***	-0.0481	0.0226	0.0254
Ventaja: Fact. Personales	1.6483***	5.0891***	-0.2238	-0.5066	0.7305
Ventaja: Fact. Sociales	1.2516**	4.0616***	-0.1772	-0.4159	0.5931
Ventaja: Fact. Externos	1.7232***	4.0953***	-0.1891	-0.3360	0.5251
Problema: Libertad	-1.2242***	-3.7827***	0.1664	0.3768	-0.5431
Problema: Horarios	-1.1975***	-3.5196***	0.1561	0.3400	-0.4961
Problema: Seguridad	-1.4721*	-4.6222***	0.2027	0.4647	-0.6674
Constante	1.0301***	1.4072***	-	-	-

$N = 2695 \quad R^2_{MCF} = 0.0861 \quad \chi^2(16) = 370.19\ (0.0000) \quad LnL = -1965.0442$

Niveles de significación: *** p < 0.01; * p < 0.05; * p < 0.10

Predicciones correctamente predichas: 68.9%

Tabla 6 – Estimación del modelo logit multinomial con tres categorías

Analizando las variables explicativas que resultan relevantes, se observa que las distintas ventajas y problemas declarados por los estudiantes son significativas. Además, como es de esperar, el signo del efecto marginal de estas variables es consecuente con su naturaleza, pues las ventajas contribuyen a un mayor nivel de predisposición a compartir, mientras los problemas reducen esta probabilidad.

Sin embargo, el valor de los efectos marginales sí que permite obtener una conclusión más relevante de cara al diseño de medidas que motiven el uso compartido del coche.

Así, en relación con las ventajas, se encuentra que son las asociadas a factores personales (ahorro económico o ganancias de tiempo) las que generan un mayor incremento (0.73

puntos porcentuales) en la probabilidad de compartir vehículo, siendo los factores externos (reducción de la congestión o de la contaminación) las que generan un menor impacto (0.52 puntos porcentuales). Por su parte, los problemas asociados con compartir el vehículo también arrojan resultados interesantes en el estudio de la magnitud de los efectos marginales relacionados con la última categoría considerada. En este caso, los problemas de seguridad son los que suponen un mayor desincentivo a compartir vehículo, con una caída de hasta un 66% en la probabilidad de viajar compartiendo. Sin embargo, los inconvenientes derivados de las esperas o los retrasos que podría llevar aparejado esta forma de movilidad cuentan con una disminución menor, aunque no deja de ser elevada -casi alcanza los 50 puntos porcentuales-.

En relación con los motivos de elección del modo de transporte actual, el único que resultó ser significativo fue la no disposición de vehículo, es decir, solo se encuentran diferencias significativas entre aquellos individuos que declaran no disponer de vehículo como razón principal para la elección del modo de transporte habitual frente al resto de modos. Además, la no disposición del coche supone un incentivo a abandonar el modo habitual y optar por viajar compartiendo el vehículo de otra persona. Este es un resultado interesante, si se tiene en cuenta que son los usuarios actuales del transporte público los que declaran en gran medida que el motivo principal de elegir ese modo de transporte es que no disponen de coche (se trata en cierta medida de una demanda cautiva del transporte público). Por último, el tiempo de viaje también resulta ser estadísticamente significativo cuando se toma la decisión planteada y, aunque la cuantía de las variaciones no sea elevada, ante incrementos en la duración, la probabilidad de no querer compartir vehículo se ve reducida.

La especificación de un modelo logit ordinal, por su parte, permite realizar el análisis de la probabilidad de elección de cada una de las alternativas de acuerdo con el esquema ordenado que inicialmente se diseñó para la encuesta. Por ello, la especificación ordenada podría ser considerada como la más adecuada dada la naturaleza del experimento, si bien se han especificado otros modelos, como ya se comentó, para ver las posibles discrepancias entre variables explicativas significativas, dependiendo del modelo estimado.

Los resultados derivados de la estimación del modelo ordinal (Tabla 7) con tres categorías permiten extraer las siguientes conclusiones. En cuanto a la significación individual de los parámetros, se concluye que todos resultan significativos al 99% de confianza, salvo dos de ellos que lo son al 95%. De igual manera, resultan ser significativos a nivel conjunto.

Este modelo, como el anterior, incluye variables referidas a ventajas y problemas que los individuos encuentran a la hora de viajar compartiendo vehículo y, al igual que en la especificación multinomial, las ventajas personales y los problemas asociados con la percepción de seguridad resultan los más importantes, si se considera la magnitud de sus efectos marginales como criterio de importancia. Esto llevo a pensar que, en cierta medida, las políticas que se lleven a cabo para potenciar el uso del vehículo compartido deben pasar por aspectos personales como el ahorro económico que le supone al individuo, además de incentivos como la reserva de plazas de aparcamiento para aquellos que se acojan a esta modalidad de movilidad.

Por otra parte, esta estimación incluye dos variables de sumo interés: asistencia a clase todos los días de la semana y contar con un mismo horario de entrada y salida todos los días.

Ambas variables indican, a luz de los valores de sus efectos marginales, que aquellos estudiantes que asisten a clase todos los días están más predispuestos a compartir vehículo y, a su vez, que aquellos que cuentan con un mismo horario durante la semana lectiva también muestran una actitud positiva ante la idea de compartir.

En conclusión, estas dos variables apuntan a que la frecuencia y regularidad horaria en sus estudios contribuye a aceptar nuevos modos de transporte como el propuesto en este trabajo.

	Estimación de parámetros	***Efecto marginal sobre la prob.***		
		P (Y=0)	***P (Y=1)***	***P (Y=2)***
Tasa de motorización	-0.6009***	0.0351	0.0816	-0.1167
Asistencia todos los días	0.1930**	-0.0113	-0.0262	0.0375
Disponibilidad de vehículo	0.3854**	-0.0225	-0.0523	0.0749
Tiempo de viaje	0.0066***	-0.0004	-0.0009	0.0013
Coste del viaje	-0.0705**	0.0041	0.0096	-0.0137
Ventaja: Fact. Personales	3.2791***	-0.1917	-0.4452	0.6369
Ventaja: Fact. Sociales	2.6036***	-0.1522	-0.3535	0.5057
Ventaja: Fact. Externos	2.2167***	-0.1296	-0.3010	0.4306
Problema: Libertad	-2.1344***	0.1248	0.2898	-0.4146
Problema: Horarios	-1.9082***	0.1115	0.2591	-0.3706
Problema: Seguridad	-2.6490***	0.1548	0.3597	-0.5145
$N = 2695 \quad R^2_{MCF} = 0.0860 \quad \chi^2(11) = 369.67\ (0.0000) \quad LnL = -1965.3056$ Niveles de significación: *** p < 0.01; * p < 0.05; * p < 0.10 Predicciones correctamente predichas: 68.7%				

Tabla 7 – Estimación del modelo logit ordinal con tres categorías

El tercer modelo considerado es el modelo logit binomial (Tabla 8). En este caso, la estimación se ejecuta considerando únicamente dos categorías de elección y, en consecuencia, realizando una nueva agrupación. Mientras se mantiene la unión de las categorías superiores, aquellas que expresan mayor predisposición, también se unen las dos categorías inferiores de la variable (en absoluto y en poca medida), obteniendo una única variable que indican la no predisposición a viajar compartiendo vehículo.

De esta forma, aún a pesar de la simplificación que pudiera darse en el análisis, se obtiene un modelo que, en términos generales, podría ser más sencillo de aplicar en algunos escenarios por su naturaleza dicotómica, lo que permite identificar, a priori, comportamientos más diferenciados: predispuesto o no predispuesto. Todos los parámetros incluidos en este modelo resultan ser significativos, también en términos conjuntos, y cuenta con un porcentaje de acierto del 70.6%.

La tasa de motorización, calculada como cociente entre el número de coches y el número de miembros del núcleo de convivencia del individuo, resulta ser significativa, como ya ocurría en el modelo ordinal y con la misma interpretación, esto es, los incrementos en la tasa suponen una disminución en la probabilidad de acudir al centro de estudios compartiendo un vehículo conducido por otra persona. En concreto, si se toma esta variable como variable proxy de la renta, esta viene a indicar la existencia de una correlación negativa entre renta y predisposición a compartir vehículo, pues aquellos individuos con una menor renta muestran mayor incentivo a emplear esta forma de movilidad.

	Coeficiente	***Efecto marginal***	***Odds-ratios***
Tasa de motorización	-0.6267***	-0.1205	0.5344
Asistencia todos los días	0.2031**	0.0390	1.2252
Todas las asignaturas en el turno de mañana	0.1690*	0.0325	1.1841
Disponibilidad de vehículo	0.4468***	0.0859	1.5633
Tiempo de viaje	0.0063***	0.0012	1.0064
Coste del viaje	-0.0818**	-0.0157	0.9215
Ventaja: Fact. Personales	3.8941***	0.7488	49.1106
Ventaja: Fact. Sociales	3.2209***	0.6193	25.0507
Ventaja: Fact. Externos	2.7633***	0.5314	15.8523
Problema: Libertad	-2.7561***	-0.5300	0.0635
Problema: Horarios	-2.5127***	-0.4831	0.0810
Problema: Seguridad	-3.3665***	-0.6474	0.0345
Constante	-0.0261	-	-
$N = 2695\quad R^2_{MCF} = 0.1052\quad \chi^2(12) = 357.51\ (0.0000)\quad LnL = -1520.0193$			
Niveles de significación: *** p < 0.01; * p < 0.05; * p < 0.10			
Predicciones correctamente predichas: 70.6%			

Tabla 8 – Estimación del modelo logit binomial

No obstante, este resultado no parece estar afectado por el coste que cada individuo paga por acudir al centro de estudio en el modo de transporte que emplea en la actualidad. Si se observa la contribución de la variable coste a la probabilidad, se concluye que esta es negativa, es decir, a mayor coste, el individuo tendría menos incentivos a compartir.

Este resultado es muy posible que venga derivado de que en su mayoría son los conductores habituales los que declaran un mayor coste por trayecto, al mismo tiempo que son los que muestran mayor reticencia a cambiar de modo, de ahí que el efecto del coste resulta ser desincentivador a la hora de optar por viajar como acompañante.

Además, en esta especificación son relevantes variables de tipo académico como las ya mencionadas en el modelo ordinal, con la salvedad de una nueva variable: tener todas las asignaturas concentradas en un mismo turno y, en concreto, en el turno de mañana.

Estos individuos muestran mayor probabilidad a compartir vehículo que aquellos que cuentan con asignaturas repartidas en turnos o concentradas en la tarde.

Por tanto, la concentración de las materias en un turno también influye en la decisión. Además, en este caso concreto, debe señalarse que en el entorno de los campus universitarios suele concentrarse un importante volumen de vehículos sobre todo en horario de mañana, lo que podría venir a explicar esta diferenciación entre la concentración por turnos dado que la mayor congestión en la entrada y salida de la ciudad se da durante la mañana.

5. CONCLUSIONES

En este trabajo se utilizan los datos de una encuesta de preferencias reveladas realizada en 2016 a una muestra de estudiantes de la ULL, en la que se incluían cuestiones acerca de la predisposición a viajar como acompañante. El propósito que se persigue es analizar cuáles son los principales factores que influyen en la predisposición a compartir de cara a fomentar el uso del vehículo compartido entre los universitarios.

Esta medida de política de transporte resulta de gran importancia para corregir los patrones de movilidad actuales, que se caracterizan por el uso predominante del coche en los desplazamientos a los centros de estudio. Además, se observa que la mayoría de los que se desplazan en coche lo hacen solos, lo que pone de manifiesto una gran cantidad de plazas ociosas en los vehículos que conlleva un uso ineficiente del parque automovilístico y, en consecuencia, un mayor impacto medioambiental per cápita. En consecuencia, fomentar políticas tendentes al uso del vehículo compartido por parte de los estudiantes no solo lleva aparejado un uso más racional de la capacidad del vehículo, sino una importante minoración de las emisiones derivadas del transporte por carretera en la isla

En este trabajo se ha planteado una batería de modelos de elección discreta, con el propósito de analizar la predisposición a viajar como acompañante de los estudiantes universitarios en sus viajes al centro de estudios, considerando diferentes aproximaciones al problema objeto de estudio. A partir de los resultados obtenidos se plantea una primera conclusión relacionada con la elección de la tipología del modelo. A pesar de que los diferentes modelos considerados comparten un grupo de variables, sí que, dependiendo del modelo empleado, se añaden unos u otros regresores significativos. Por tanto, parece que la tipología del modelo puede determinar distintas relaciones causales estadísticamente significativas.

Así pues, para el desarrollo de medidas de política orientadas a la movilidad, resulta conveniente chequear diferentes aproximaciones metodológicas más allá de la del modelo ordinal, que pudiera parecer la más adecuada a priori.

Asimismo, se ha observado como la capacidad predictiva y analítica del modelo varía según se considere un número u otro de alternativas sobre las que el individuo debe elegir. Por tanto, se recomienda comprobar, en base a un proceso iterativo, si las categorías inicialmente consideradas en el cuestionario se corresponden con las que los individuos identifican a la hora de tomar su decisión. Ello puede llevar, como en este caso, a que la agregación de determinadas categorías suponga una mejora de los modelos, permitiendo concluir que las categorías que consideran los individuos cuando hacen su elección no tienen por qué coincidir con las que fueron previamente establecidas por el investigador.

De entre las ventajas que los individuos declaran, sobresale la importancia que estos dan a aquellas relacionadas con factores meramente personales, esto es, su propio ahorro económico o de tiempo, o la reserva de plazas de aparcamiento para aquellos que acudan al centro bajo esta modalidad.

Este hecho permite establecer una nueva recomendación que vaya en la línea de incentivar aspectos personales frente a otro tipo de ventajas, pues su impacto en la conducta del individuo es mayor. No obstante, esto también permite valorar otra conclusión y es que las ventajas relacionadas con el medio ambiente (reducción de la contaminación y de la congestión, etc.) son las que producen un menor impacto en la predisposición a compartir vehículo y, por tanto, a pesar de los esfuerzos actuales que en esta materia se realizan, parece que la conciencia social sobre este asunto no es tal.

Ello, pone de manifiesto la necesidad de hacer una revisión en los mecanismos de comunicación de las políticas dirigidas a la concienciación medioambiental entre los jóvenes.

Otra medida que podría contribuir a la utilización del vehículo compartido es la reducción de la sensación de inseguridad a la que aluden como principal problema los individuos encuestados.

Esta sensación podría ser mitigada con la implantación de redes comunicativas, por ejemplo, mediante el uso de una app, que permita a los estudiantes contar su experiencia como usuarios de vehículo compartido e incluso que puedan valorar cuál ha sido su experiencia durante el viaje, etc.

En definitiva, visibilizar la seguridad que, en general, presenta el uso de este modo, en contra de la inseguridad percibida a priori.

Por último, otro aspecto relevante que permite recomendar acciones para potenciar el uso del coche compartido es la política académica.

En los modelos planteados, variables como la asistencia regular al centro de estudios (todos los días frente a días aislados) y la concentración de la docencia en un único turno (frente al reparto en turnos distintos) muestran importantes contribuciones a la probabilidad de optar por viajar en vehículo compartido, por ello, los centros universitarios, a través de la construcción de horarios más estables, pueden aportar notablemente a la generalización de una movilidad más sostenible entre los estudiantes.

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INICIATIVAS POLÍTICAS PÚBLICAS DEL TRANSPORTE DE CARGA URBANO SEGÚN EL SECTOR PARA LA CIUDAD DE BARRANQUILLA – COLOMBIA

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RESUMEN

La zona centro de la ciudad de Barranquilla, Colombia es un lugar predilecto por su comunidad debido a la gran variedad y accesibilidad económica de bienes y servicios, además de la concentración de los principales centros de comercio, almacenes mayoristas y diferentes grupos de interés como entes públicos y privados generando como consecuencia el incremento de altos niveles de contaminación ambiental, congestión vehicular, inseguridad y ocupación del espacio público que deterioran la calidad de vida de los residentes, transportistas, comerciantes, productores y consumidores.

El presente artículo es el resultado del trabajo de campo llevado a cabo en la zona centro con los principales actores con el propósito de realizar un análisis sobre la aceptación de diferentes políticas internacionales de transporte de carga. Los sectores analizados son calzado, parqueaderos, restaurantes, electrodomésticos, variedades.

Los resultados de la investigación arrojaron las tres políticas con mayor aceptación por parte de todos los actores, sin embargo, no existe unanimidad para elegir una política global, por lo tanto, se identifican los resultados de acuerdo con cada actor y sector.

1. INFORMACIÓN GENERAL

1.1 Introducción

Este trabajo está orientado a proponer soluciones a diversas problemáticas que son el resultado del transporte de carga urbana en el centro histórico de Barranquilla, esta área tiene una alta densidad de establecimientos que mueven mercancía para el funcionamiento diario del comercio de la ciudad.

En Colombia aún está muy insipiente la aplicación de nuevas políticas del transporte urbano de mercancías que se adapten a las necesidades de las zonas comerciales, por lo que surgen diversos problemas que dificultan el buen desempeño de estos procesos económicos como el incremento de contaminación ambiental, congestión vehicular, inseguridad y ocupación del espacio público que deterioran la calidad de vida de los residentes, transportistas, comerciantes, productores y consumidores.

La presente investigación tiene como propósito conocer cuál es la opinión de los diferentes actores acerca de las políticas planteadas con el fin de analizar viabilidad dichas políticas y concluir cuál se debería implementar.

1.2 Justificación

En la zona centro de Barranquilla las externalidades como congestión, contaminación, ruido están aumentando. Como resultado obtenemos el incremento de costos, tanto a los productos de consumo como a los transportistas. Cada vez que estas externalidades se incrementen representan un problema para la sociedad de manera que podría llegar a tornarse un escenario de colapso en esta zona, lo cual incide directamente en la economía al tratarse de un centro de comercio. Por lo tanto, utilizar políticas públicas para el transporte de carga urbano que han sido exitosas en el extranjero, se considera un buen ejercicio tanto académico como técnico, pero tal ejercicio no se puede sugerir e implementar sin analizar la operatividad y viabilidad de la política, por lo que es necesario hacer un análisis con los directamente afectados para conocer sus percepciones a partir de soluciones existentes.

En este sentido, se realizará la investigación y análisis mediante la información suministrada por los actores que intervienen en el comercio de la zona identificando así las posibles causas que ocasionan los problemas y un ranking de políticas potencialmente viables a implementar en la ciudad. De esta manera se busca cual sería la política de transporte más eficiente que disminuya las externalidades en esta zona, siendo de gran aporte para el desarrollo de la logística a nivel local.

1.3 Objetivo

1.3.1 Objetivo General

Analizar las diferentes perspectivas sobre la viabilidad de políticas para el transporte de carga urbano en el centro de Barranquilla.

1.3.2 Objetivos específicos

- Identificar los actores y sectores que hacen parte de la zona centro que resultan representativos para la investigación.
- Diseñar e implementar un instrumento que permita analizar la percepción de los actores ante las problemáticas de la logística urbana.
- Realizar un análisis comparativo con los actores y sectores de la zona centro sobre la aceptación de políticas.

1.4 Metodología

La metodología presentada en este artículo es de tipo cualitativa y cuantitativa. Para la ejecución y conclusión del proyecto de investigación se desarrollaron una serie de etapas:

1) Se realizó un inventario de cada uno de los negocios o lugares de la zona centro de Barranquilla y se caracterizaron, con el fin de identificar los principales sectores económicos de la zona. Ver Tabla 1.

2) Se usó como base la selección de políticas públicas del proyecto “Stakeholders perceptions to sustainable urban freight policies in emerging markets” que previamente desarrollaron (Amaya, Arellana, & Delgado-Lindeman, 2020).

    1. Crear bahías (estacionamientos junto al andén) para mejorar la carga y descarga de mercancía de camiones y reserva web de éstos.
    2. Crear estacionamientos para camiones y tracto mulas como centros de distribución para guardar y repartir mercancía.
    3. Crear un sistema de información con un único operador logístico que centraliza los pedidos y envíos.
    4. Peajes electrónicos para ingresar al centro de Barranquilla con exoneración a los propietarios, comerciantes, residentes, vehículos no contaminantes y con bajo nivel de ruido
    5. Prohibir el acceso a vehículos en ciertas zonas y peatonalización de zonas altamente comerciales (sólo se permite el paso de personas).
    6. Reubicar conjunto de almacenes de Ja misma actividad económica a un sector fuera de la zona centro.
    7. Micro-plataformas logísticas urbanas usando vehículos amigables con el medio ambiente (eléctricos o híbridos) como centro de distribución móvil (vehículos no convencionales: Uso de bicicletas, motos, etc.)
    8. Colaboración entre los transportistas o comerciantes para envío y recepción de carga colaborativa.
    9. Distribución nocturna de mercancía

3) Para la evaluación de las políticas se utilizaron técnicas como la recolección de información por medio de encuestas aplicadas a los principales actores y establecimientos de la zona centro de Barranquilla. El tamaño de muestra escogido se tomó según el número de negocios y establecimientos ubicados en dicha zona para el presente año; tratándose de una población finita y para lograr el tamaño ideal se hace uso de la siguiente fórmula propuesta por (Larry, 2017)

$$n = \frac{z^2\sigma^2 N}{e^2(N-1)+z^2\sigma^2} \tag{1}$$

$$n = \frac{(1{,}96)^2(0{,}5)^2(1163)}{(0{,}5)^2(1163-1)+(1{,}96)^2(0{,}5)^2} \tag{2}$$

$$n = 383 \tag{3}$$

Para el cálculo de la fórmula:

- n = es el tamaño de la muestra poblacional a obtener.
- N = es el tamaño de la población total, en este caso 1163 negocios y establecimientos en la zona centro.
- S = Representa la desviación estándar de la población. En caso de desconocer este dato es común utilizar un valor constate que equivale a 0.5.
- Z = es el valor obtenido mediante niveles de confianza. Su valor es una constante, por lo general se tienen dos valores dependiendo el grado de confianza que se desee siendo 99% el valor más alto (este valor equivale a 2.58) y 95% (1.96) el valor mínimo aceptado para considerar la investigación como confiable.
- e = representa el límite aceptable de error muestral, generalmente va del 1% (0.01) al 9% (0.09), siendo 5% (0.5) el valor estándar usado en las investigaciones, como lo demuestra (Larry, 2017)

4) Una vez obtenido el tamaño de muestra correspondiente al universo finito determinado, se procedió con la aplicación de las encuestas en la zona, para un total de 383 encuestas.
5) Por último, con la información obtenida en la investigación, se procedió a tabular, analizar e interpretar los resultados, con el fin de conocer la aceptación y viabilidad de cada una de las políticas por actor y sector.

2. RESULTADOS

Como resultado de la metodología aplicada, para establecer la clasificación y la cantidad de locales en la zona centro, en donde se agruparon los negocios que ofrecían productos o servicios de las mismas características, se elaboró el siguiente análisis.

Tipos de negocio	N° de locales	Porcentaje
Productos de almacén	187	16,08%
Partes de auto	156	13,41%
Textiles y confección	152	13,07%
Casas, lotes y locales vacíos	147	12,64%
Alimentos preparados	109	9,37%
Hotel/motel	57	4,90%
Productos electrónicos	48	4,13%
Bancos y giros	43	3,70%
Colegios, edificios e iglesias	41	3,53%
Ocio y entretenimiento	39	3,35%
Droguerías	30	2,58%
Mantenimiento y lubricante de vehículos	27	2,32%
Cuero y calzado	20	1,72%
Metales preciosos y casas de empeño	20	1,72%
Bodegas y almacenes	15	1,29%
Salón de belleza y estética	13	1,12%
Ferretería	12	1,03%
Muebles y cerámicas	11	0,95%
Venta de equipos	11	0,95%
Publicidad y café internet	9	0,77%
Centros de salud	6	0,52%
Loterías	5	0,43%
Entes del estado	4	0,34%
Agropecuarios	1	0,09%
Total general	1163	1

Tabla 1 Caracterización de los negocios de la zona centro de Barranquilla. Fuente: Elaboración propia.

En la tabla anterior se puede apreciar la participación de cada sector en el mercado. Con base en este resultado se hizo la priorización para realizar las encuestas a los tipos de locales con mayor porcentaje de participación en el mercado y a los diferentes actores que participan en su funcionamiento.

2.1 Políticas públicas

Del trabajo de campo realizado en la zona centro con la encuesta diseñada para que los actores formularan el ranking de las mejores políticas de acuerdo con la conveniencia de sus sectores (Calzado, parqueadero, restaurante, electrodomésticos, variedades) se analizaron los resultados generales y específicos de cada sector y actor.

Los resultados de la estimación se muestran en la figura 1. Para esto se utilizó un modelo de encuestas de las nueve políticas de logística urbana escogidas por los mismos actores y se empleó un procedimiento de integración numérica simultánea, mostrando la aceptación general de los diferentes actores (comerciantes, transportistas, productores y expertos) en los sectores analizados.

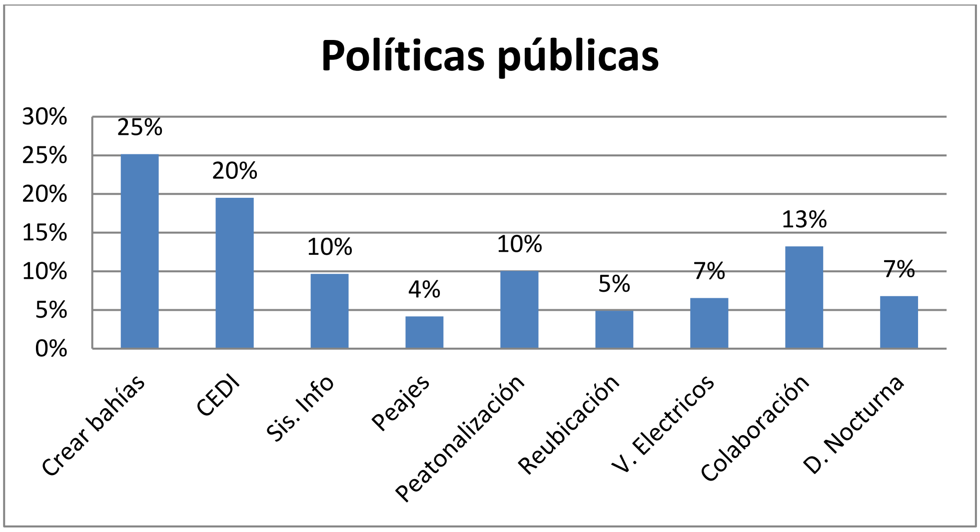

Fig. 1 – Ranking general de la aceptación de las políticas.
Fuente: Elaboración propia.

La figura 1 evidencia la aceptación de los diferentes actores sobre la viabilidad de las políticas de transporte de carga urbana, los resultados de la encuesta muestran que la política 1 fue escogida en los sectores analizados como la más viable a implementar en la zona centro con un porcentaje de aceptación del 25%, esta política consiste en crear bahías de estacionamientos junto al andén para mejorar la carga y descarga de mercancía de camiones y reserva web de estos espacios, con parquímetros o zonas azules.

Los resultados también muestran que segundo lugar los actores calificaron a la de creación de estacionamientos para camiones y tracto mulas como centros de distribución para guardar y repartir mercancía, con un porcentaje de aceptación del 20% y un 13% en tercer lugar del ranking para la política de colaboración.

2.2 Sector Calzado

Los almacenes de calzados dieron sus diferentes perspectivas sobre la viabilidad de las políticas de logística urbana que se encontraban en estudio.

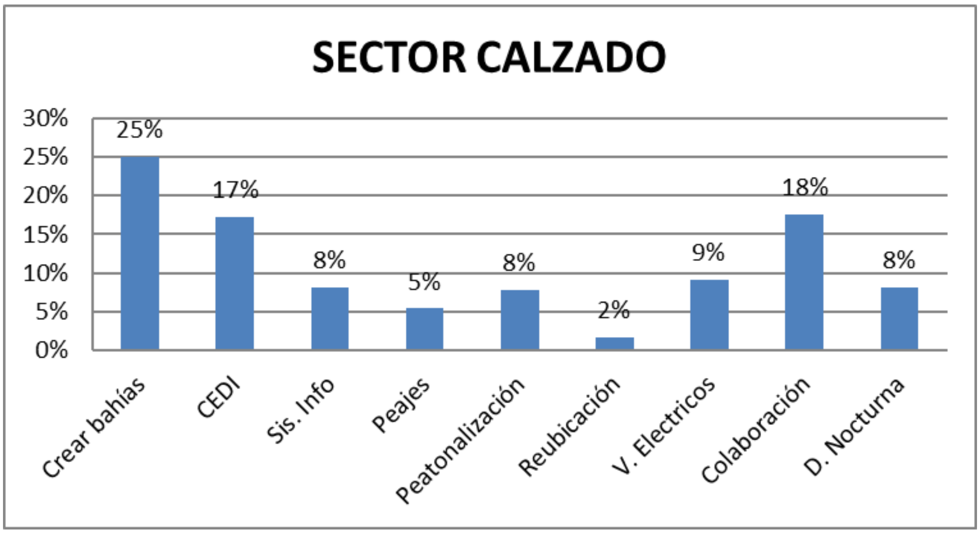

Fig. 2 – Ranking de la aceptación de las políticas, sector calzado.
Fuente: Elaboración propia.

Se evidencia el porcentaje de aceptación del Ranking de las políticas escogidas por su viabilidad según el sector de almacenes de calzado, la más aceptada es la creación de bahías.

2.3 Sector Parqueaderos

De los sectores analizados se encuentra los parqueaderos, los cuales dieron sus diferentes perspectivas sobre la viabilidad de las políticas de logística urbana que se encontraban en estudio.

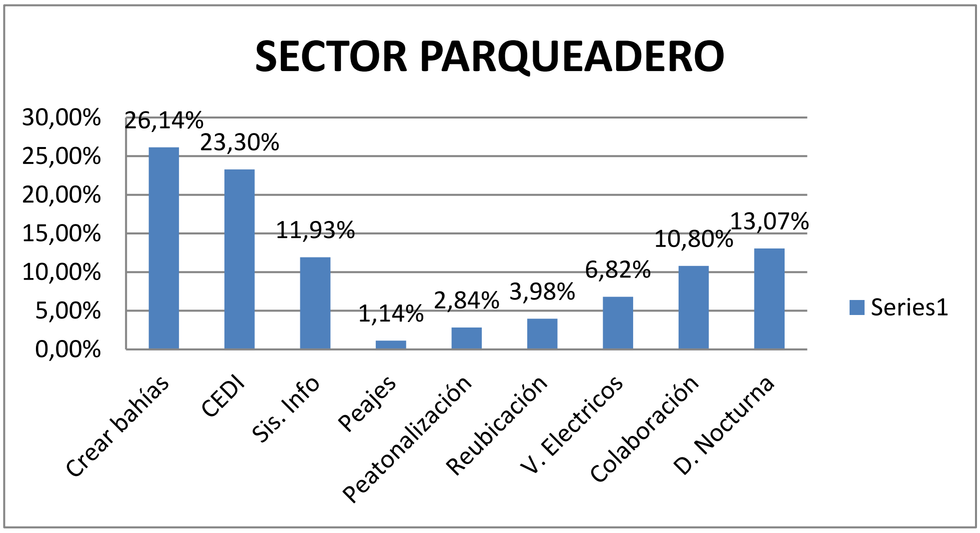

Fig. 3 – Ranking de la aceptación de las políticas, sector parqueaderos.
Fuente: Elaboración propia.

La figura 3 muestra los porcentajes de aceptación para cada política escogida, se concluye que para este sector tienen una mayor viabilidad la creación de bahías para mejorar la carga y descarga de mercancía con un porcentaje de aceptación del 26,14%; la creación de estacionamientos para camiones y tracto mulas como centros de distribución con un porcentaje de aceptación del 23,30% quedando en el ranking como segundo.

2.4 Sector Electrodomésticos

Los actores del sector de electrodomésticos mostraron sus diferentes perspectivas sobre cada una de las políticas de logística urbana propuestas, y categorizaron las que tenían mayor aceptación de acuerdo con las problemáticas presentadas en la zona en donde se encuentran localizados.

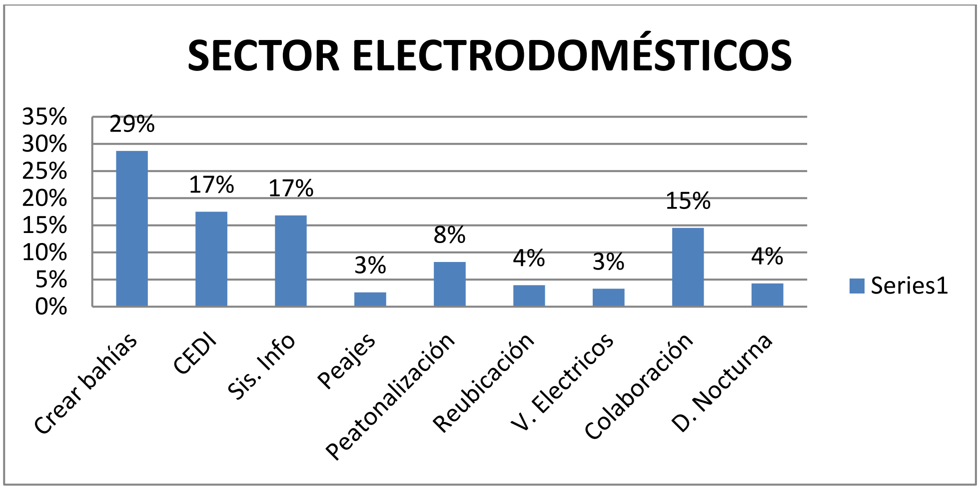

Fig. 4 – Ranking de la aceptación de las políticas, sector electrodoméstico. Fuente: Elaboración propia.

Teniendo en cuenta que por la ubicación en la que se encuentra el pequeño clúster de negocios de electrodomésticos, se presenta un alto flujo tanto vehicular como peatonal por lo que los espacios disponibles para un adecuado estacionamiento de camiones para la carga y descarga de mercancía es reducido. Es por esto por lo que la política que plantea la creación de bahías es considerada la mejor política por este sector con un porcentaje de aceptación del 29 %.

2.5 Sector Variedades

En este sector dedicado al comercio de variedades, dieron sus diferentes perspectivas sobre la viabilidad de las políticas que se encontraban en estudio.

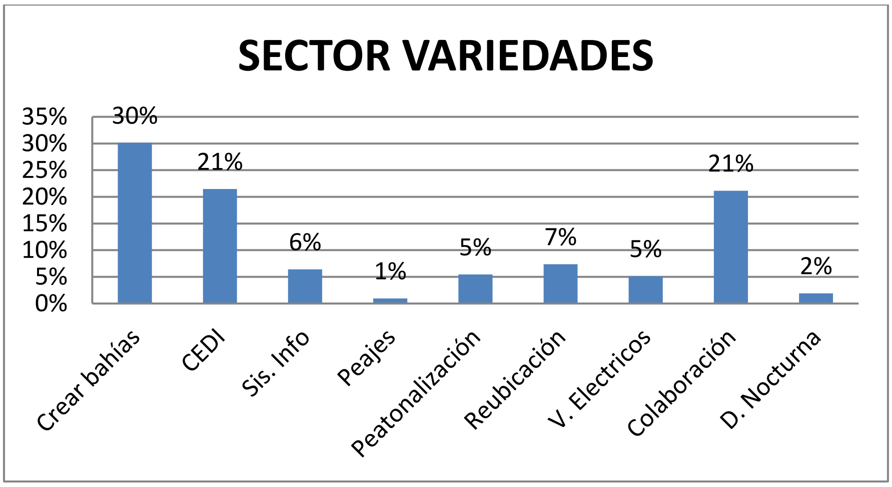

Fig. 5 – Ranking de la aceptación de las políticas, sector electrodoméstico.
Fuente: Elaboración propia.

Este sector mostró un nivel de aceptación elevado para la política "Crear bahías". Debido a que cuentan con una gran cantidad de artículos ofrecidos donde se hace necesaria la carga y descarga constante de mercancía, por lo cual asegurar un lugar de estacionamiento fijo, en los tiempos requeridos, optimizaría la operación.

2.6 Sector Restaurantes

El sector restaurante se diferenció de los otros sectores en cuanto a sus perspectivas sobre la política más viable.

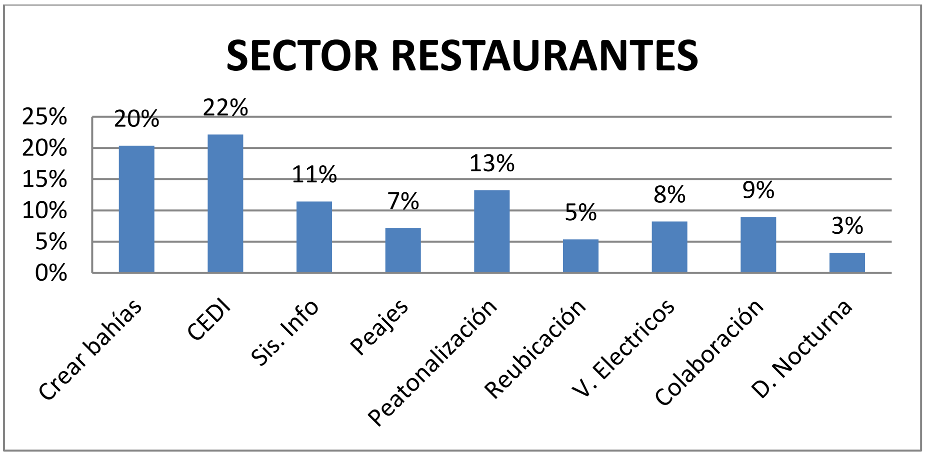

Fig. 6 – Ranking de la aceptación de las políticas, sector restaurantes.
Fuente: Elaboración propia.

En la figura 6 se observa que el primer lugar se encuentra la política 2, la cual propone crear centros de distribución permitiendo que un solo vehículo sea el encargado del despacho de mercancía en una misma zona.

En el segundo lugar se encuentra la política 1. Los actores la categorizaron como viable, debido a que disminuiría la congestión vehicular de su zona, dándole prioridad a los peatones, ya que, en muchas ocasiones, camiones de carga toman el espacio de la vía para parquear y obstruyen el ingreso a sus negocios o no los hace visible ante los peatones.

Fueron las políticas escogidas en general, ya que eran la solución a algunas problemáticas que sufren estos sectores, debido a que muchos de los clientes no tienen donde parquear cuando quieren adquirir o descargar mercancía, la mayoría de estos locales están ubicados en vías principales o secundarias y si no existen bahías de estacionamiento se les hace difícil el comercio, trayendo como resultado la congestión de las vías de la zona centro.

3. CONCLUSIONES

Para los sectores analizados, hay políticas con un buen nivel de aceptación para mitigar las problemáticas actuales, la viabilidad de éstas varía según las problemáticas y preferencias de cada sector. Esto se ve reflejado en el sector calzado, donde determinan como más viable la política de “Colaboración entre los transportistas o comerciantes” debido a que sus negocios están localizados en las vías donde se presenta más congestión vehicular, y la implementación de esta política les brindaría una disminución de camiones de carga a los diferentes negocios que se encuentran en la zona. Por otro lado, los sectores de parqueaderos, restaurantes, electrodomésticos y variedades prefieren la creación de bahías y los centros de distribución, manifestando que no solo supondría una disminución de congestión vehicular, sino que también aumentaría el flujo de clientes.

Es así como se puede concluir que las políticas de transporte de carga urbana con mayor viabilidad en los sectores analizados son la creación de bahías y creación de centros de distribución. Por tal razón se recomienda a los gremios que integran el sector público tener en cuenta estas políticas que cuales tuvieron gran aceptación en los participantes de la investigación para el mejoramiento del transporte de mercancía en cuanto a logística y movilidad se refiere.

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THE STRATEGIC VARIANCE ANALYSIS OF LAN AND TAM AIRLINES MERGER IN THE EARLY 2010's

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ABSTRACT

LAN and TAM used to be the flag carriers of Chile and Brazil, respectively until late 2000's in the airline industry. The merger of both into LATAM Airlines was part of the strategy to construct a major regional power of air transportation, an evolution from national companies to a Latin America brand. This research analyzes the merger of LAN and TAM, which in the second decade of 21st Century formed one of the largest passenger air transportation groups. The concept of Strategic Variance Analysis (SVA) is used in some academic environments to evaluate a company's operational revenue in two time periods, in this specific case, 2010-2013. The concept is easy to understand and relates the financial statements with businesses strategies approaches.

Previous studies in the American airline industry have been conducted with SVA method. This paper compares the financial situation of former TAM before the merger (2010), and LATAM (2013), after the merger. The financial, operational, and fuel data are gathered from the National Civil Aviation Agency of Brazil, reclassified, and applied to calculate SVA. Then, as the final conclusion, SVA demonstrates that this merger was good, however it was insufficient to cover the rise in fuel prices during those years.

1. INTRODUCTION

After the September 11, 2001 terrorist attacks, civil aviation faced hard financial moments around the world after. The demand for air transport dropped significantly in the following months due to the fear and uncertainties that surrounded flight security. That triggered a reputation crisis in air transportation market due to aviation security. While new measures were taken by the civil aviation authorities worldwide, aerial activity gradually regrew from the panic.

Even so, traditional airlines that had been in the market for many years, saw their (already harassed) profit margins reducing a lot, while new players arose at that time proposing new business models. Between 2000 and 2020, several of those traditional airlines, in pursuit of survival, merged to form stronger companies, such as Air France and KLM in 2004; Continental and United Airlines in 2010; British Airways and Iberia in 2011; Gol and Webjet in 2011; American Airlines and US Airways in 2013; and Alaska Airlines and Virgin America in 2016 (Table 1).

The low-cost/low-fare airlines model popularization, with an aggressive proposal of low operational costs and offering reduced fare air services, forced not only competition with the traditional companies but also with other means of transportation. The the market itself put pressure on older Airlines to operate in an even more efficient way, and to offer more competitive fares to face the new age, otherwise their market share would tend to decrease due to the low-cost competition.

Fluctuations of oil price directly influence airlines' operating results. In Brazil alone, *ABEAR* (the Brazilian Airlines Association) estimated that in 2012, 37.8% of national companies' operating costs were related to fuel, which was at its highest historically registered value (ABEAR, 2019). That demonstrates the weight this input represents for their balance sheets. The scenario for Brazilian airlines, most of whose revenue is in Brazilian Reals (BRL) whereas the costs are in United States Dollars (USD), is even worse; it means that the exchange rate component implies higher costs and lower profit margins for airlines.

The year 2020 has established a new era in aviation worldwide. The COVID-19 Pandemic, also known as Coronavirus Pandemic, has triggered the worst possible unforeseen scenario for aviation; even worse than the September 11, 2001 attacks. The air transportation market worldwide has been affected by COVID-19. Among the options to survive this hard moment are mergers and acquisitions. In the first semester of 2020, market rumors said that coming examples may be Azul and LATAM, Air Canada and Air Transat, Air Asia and Malaysia Air. Others have filed for Chapter 11 (United States), *Recuperação Judicial* (Legal Recovery – Brazil), Insolvency Law (United Kingdom), or Voluntary Administration (Australia), or the least undesirable option: bankruptcy. Some 2020 airlines with financial issues are LATAM, LATAM Argentina, Avianca, South Africa Airways, Flybe and Virgin Australia.

Merger	Year	Location	Description
Air China, China Eastern, China Southern	early 2000's	China	Ten state-owned Chinese airlines were merged into only three big groups.
Air France–KLM	2004	France and the Netherlands	Two flag carriers consolidated into Air France–KLM Group, keeping both brands.
Lufthansa–Swiss	2005	Germany and Swiss	Lufthansa purchased Swiss.
Cathay Pacific–Dragonair	2006	Hong Kong	Cathay Pacific, a major airline in the Asian market, purchased its competitor Dragonair.
TACA–Avianca	2009	Colombia and El Salvador	Avianca, the flag carrier of Colombia merged with TACA, one of the main airlines of Central America.
Delta–Northwest	2010	United States	Delta purchased Northwest.
United Airlines–Continental Airlines	2010	United States	Two major US airlines merged into a single company, preserving United Airlines name and Continental Airlines logo.
Gol–Webjet	2011	Brazil	Two low-costs airlines, Gol purchased Webjet, keeping only the Gol brand.
British Airways–Iberia	2011	United Kingdom and Spain	Two flag carriers consolidated into International Airlines Group (IAG), keeping both British Airways and Iberia brands.
LAN–TAM	2012	Brazil and Chile	Two major flag carriers merged into LATAM.
Azul–TRIP	2012	Brazil	Azul, a young airline at the time, purchased regional airline TRIP, keeping only the Azul brand.
American Airlines–US Airways	2013	United States	American Airlines merged with US Airways keeping only the American Airlines identity.
Alaska Airlines–Virgin America	2016	United States	Alaska Airlines acquired Virgin America, keeping only the Alaska Airlines identity.

Table 1 – Major airline mergers since 2000.

1.1 Problems and Objective

The main problem of this research is to respond to the following question: how to identify, in an objective way, the causes of LAN (Chile) and TAM (Brazil) merger's synergy (or lack of). Thus, the investigation is into whether this merger was financially successful, and what the causes of success or failure were.

The main objective is to evaluate the merger between LAN and TAM in 2010 using the Strategic Variance Analysis (SVA) method, developed by Horngren et al. (2000) and extended by Sopariwala (2003). The paper is focused on TAM's financial data provided by Brazil National Aviation Agency. LAN data are not used in this study.

Section 1 introduces the scenario of mergers and acquisitions in the airline market, in which LAN and TAM were major South American players at that time. Section 2 is a short story of LAN and TAM merger, focused on financial aspects. Section 3 is a theoretical framework and presents a literature review and goes into greater detail as to how SVA works. Section 4 gathers the necessary data to apply SVA to the LAN-TAM merger according to the concepts learned from the previous section. Section 5 is the final analysis of the operational results of the merger, and what those financial numbers can reveal about what happened during those 3 years. Section 6 is the conclusion and final remarks of the research. Some suggestions are made to apply the same study to other scenarios of recent aviation moments.

2. LAN AND TAM MERGER HISTORY

Both LAN and TAM used to have their differences, due to history, cultural organization, corporate strategies, and target markets. The focus of this study is on the merger period, however Table 2 is a summary of LAN and TAM individual characteristics before the merger.

In 2010, there were six Airlines in Brazil's passenger air transportation market: TAM, Gol, Webjet, Azul, Avianca and TRIP (ANAC, 2010). In August of the same year, the companies TAM and LAN made a public announcement of the merger, integrating both Brazilian and Chilean operations the following year. According to LAN's Vice-President, Enrique Cueto in an interview to a Santiago newspaper, *"in current values (2010), without the synergies, the combined value of both companies is around 11.5 billion dollars"* (Soto, 2010).

Larroulet & Ardiles (2018) summarize the idea behind this phase: *"One brand name, one continent, one network. There is no other airline in the world named after a continent (LATAM), and this makes it easier for passengers to fly across the region. LATAM is very attractive as a partner in Joint Business Agreements (JBAs), and therefore British Airways, American Airlines, or Qatar Airways, for example, are willing to form global alliances with LATAM"*.

Figure 1 shows a panorama of the South and Central American industry before (2010) and after the merger (2013).

In March 2011, Brazil's ANAC approved the merger agreement of both companies; also at that moment, the binding agreement between the Amaro Family (controller of TAM) and the Cueto Family (controller of LAN) was signed to combine both businesses (LATAM, 2019). The competition regulators of both countries approved the merger, although with some restrictions: in September, the *Tribunal de Defensa de la Libre Conpetencia – TDLC* (Court of Free Competition Defense) of Chile, and in December, the *Conselho Administrativo de Defesa Econômica – CADE* (Administrative Council for Economic Defense), of Brazil.

	TAM	**LAN**
Year	1961	1929
Origin	Brazilian Entrepreneur	Military
Range	Regional	National
Merger and acquisitions	Brasil Central LAPSA ABSA Pantanal	Ladeco Fast Air
Creations	TAM Mercosur TAM Cargo	LAN Perú LAN Argentina LAN Colombia LAN Ecuador LAN Express
Controller	Amaro Family	Cueto Family
Alliance	Star Alliance	One World
Focus	Brazil Argentina Paraguay Chile USA (Florida) Europe	Andean America Argentina Mexico USA (Florida and California) Australia/Pacific
Hubs	São Paulo Brasília Rio de Janeiro	Santiago Lima

Table 2 – Summary of TAM and LAN historical analysis.

In November 2011, LAN and TAM signed up in the Securities and Exchange Commission – SEC in the United States, to negotiate shares on the New York Stock Exchange. In January 2012, TAM's shareholders agreed to a shares swap at the rate of 0.9 LANs share for each TAM share (Fernández, 2012). In May of the same year, the *Comissão de Valores Mobiliários – CVM*, Brazil's stock market regulator (equivalent to United States SEC), authorized the swap of shares between the companies.

Finally, on June 22, 2012, the merger was concluded, and **LATAM Airlines Group S.A**. was born, the largest airline of Latin America. Fernández (2012) goes deeper into the chronological order of the happenings of that operation.

The main idea behind that merger can be summarized as:

- Establish a global airline, with a regional identification under the LATAM brand (meaning Latin American Airlines) and international partnerships (American Airlines, IAG and Qatar Airways);
- Increase competitiveness in Latin America against other major groups: Gol, Avianca and Copa Airlines;
- Cost reduction, focusing on fleet standardization and high profit markets (including North America and Europe);
- Invest in Latin American long-term economic growth;
- LAN needed a way to enter the highly regulated Brazilian market, then shared basically between Gol and TAM (Azul and Avianca Brasil were not that big yet).

Nonetheless, the benefits of the merger also brought with them some challenges. Successive economic crisis in South America, instable politics and high rates of poverty must be considered when planning long-term demand. Larroulet & Ardiles (2018) remind us not only of the high boarding fees in the region, and the fact that each country has a different regulatory framework which increases costs, but also that in South America in 2018, the ultra-low-cost model was almost non-existent.

Figure 1 – Major airlines in the South and Central American industry in 2010 (left) and in 2013 (right).

3. THEORETICAL FRAMEWORK

Firstly,n the specific LAN–TAM analysis of Nóbrega et.al (2016) and Melo & Borges (2017), there are only financial outcomes based on stock values, without going deeper into the reasons why the companies came up with those numbers. It would be more relevant to ask, for instance, what the factors that contribute to such numbers are. Did the merger meet its expected objectives?

Schosser & Wittmer (2015) go deeper and state that "LAN followed a multimarket strategy with regional hubs whereas TAM mainly operated the Brazilian market with a traditional hub-and-spoke business model. Hence, LAN generated more than half of its revenues with international flights whereas TAM relied heavily on the domestic market." This sentence demonstrates that different corporate strategies and/or cultural organization may have a quota of influence along the whole merger transaction. Their conclusions are very interesting because they compare the mergers in North America, Europe and Latin America, considering the possible influence of geographic aspects.
Some mergers and acquisitions studies have not been capable of accurately pointing out the reasons for the differences on financial results between pairs of years (for example).

Thus, SVA – Strategic Variance Analysis – can suggest the corporate strategy to be adopted by a company. The examples of Caster & Scheraga (2011, 2013), Mudde & Sopariwala (2008; 2010; 2014), and Rocha (2020) must be part of the theoretical framework that supports the sutdy.

3.1 Strategic Variance Analysis – SVA

This study adopts the Strategic Variance Analysis (SVA) as the technique to evaluate the difference of a company's financial results between two periods of time (usually years). To reinforce understanding, "variance analysis is the term applied to the process of specifying the reasons why actual profits in any given period differ from the expected or planned level of profits" (Shank et. al., 1977). It is important to highlight that the concept of SVA discussed here, has nothing to do with the traditional concept of variance applied to statistical analyses.

According to Horngren et al. (2000), the SVA considers the details of some strategic components: growth component, price-recovery component, and productivity component. Furthermore, Sopariwala (2003) extends the analysis and includes a fourth component, namely, capacity underutilization.

One of the ideas originating from SVA is to relate what the financial-operational numbers say about a company and its market strategies used in competition. Porter (2008) posited three major strategies to get competitive advantage: a) cost leadership, when a company pursues operational efficiency to lower its costs; b) product/service differentiation, a strategy focused on providing a product or service with qualities that somehow differ from those of the other competitors; and c) niche-seeking, where a small part of consumers, willing to pay higher prices, are seeking specific premium products/services, but are not served by producers/suppliers (this strategy is characterized by low sales volume and high profit margins.

Searches in traditional journal bases and scientific paper indexing services such as Scopus, Web of Science and Google Scholar about SVA return only a few results on the United States air transportation market. Some examples of research that applied SVA: studies produced by Caster & Scheraga. (2011 and 2013), who analyzed the environment of American aviation at that time, when seven major airlines were competing; the same authors also made an analysis of Alaska Airlines strategic transformation in 2010; Mudde & Sopariwala (2008; 2010; 2014) investigated the strategic execution of Southwest Airlines in 2005; they also developed a paper about the American Airlines case; and published a journal article about the US Airways and America West merger. Rocha (2020) applied SVA to the Brazilian airlines merger between Gol and Webjet.

Basically, SVA is a technical evaluation of the operational situation in a certain year in comparison with a previous year (not necessarily the immediately previous year), inspecting the financial-operational numbers of a company. Although Horngren et al. (2000) have developed this SVA concept for the manufacturing industry, Mudde & Sopariwala (2008; 2010; 2014) adapted the framework for the specific issues of the airline industry.

3.2 SVA Components

In the next set of equations, the subscript word *"actual"* refers to the least recent year analyzed, 2010, while the subscript *"expected"* refers to the most recent year, 2013. The word *"expected"* is used instead of the word planned, because the calculated values are not officially provided by the airline, but it is an expectation based on the previous year's numbers.

As mentioned previously, Mudde *et. al.* (2008) explain that the SVA must be done by breaking it down into four specific components. The **growth component** measures the change of operating revenue caused by variations in Revenue Passenger Kilometers (RPK), keeping sales price, input costs and input-output relationships constant). The variance of this component is caused by changes in market share or in market size. This component is calculated by equations from (1) to (4), from year i to year :

a. Revenue effect of the Growth Component:

$$variance_1 = (revenue_i / RPK_i) \times \left(RPK_j - RPK_i\right) \tag{1}$$

b. Fuel cost effect of the Growth Component:

$$variance_2 = (fuel\ cost/liter_i) \times (used\ fuel\ liters/ASK_i) \times (ASK_{i\ (actual)} - ASK_{j(expected)}) \tag{2}$$

c. Flight-related cost effect of the Growth Component:

$$variance_3 = (flight\ related\ cost/ASK_i) \times (passenger\ load\ factor_i) \times \left(ASK_{i\ (actual)} - ASK_{j(expected)}\right) \tag{3}$$

d. Passenger-related cost effect of the Growth Component:

$$variance_4 = (passenger\ related\ cost/passenger\ emplanements_i) \times \left(passenger\ enplanements_{i(actual)} - passenger\ enplanements_{j(expected)}\right) \tag{4}$$

The **price recovery component** evaluates the variance in the operating revenue due to variations in unit input costs and sales price, holding sales unit and input-output relationships constant. Horngren et al. (2000) suggest that this component indicates a product differentiation strategy: a positive value in the component of price-recovery means that the differentiation strategy produced enough power pricing to the company, so that the passengers were induced to pay a higher amount than the increased costs the company had.

This component is calculated by equations from (5) to (6), from year i to year j:

e. Revenue effect of the Price-Recovery Component:

$$variance_5 = (RPK_j) \times (revenue_j/RPK_j - revenue_i/RPK_i) \quad (5)$$

f. Fuel cost effect of the Price-Recovery Component:

$$variance_6 = (ASK_{j\ (expected)}) \times (used\ fuel\ liters/ASK_i) \times (fuel\ cost/liters_i - fuel\ cost/liters_j) \quad (6)$$

g. Flight-related cost effect of the Price-Recovery Component:

$$variance_7 = (passenger\ load\ factor_j) \times (ASK_{j\ (actual)}) \times (flight\ related\ cost/ASK_i - flight\ related\ cost/ASK_j) \quad (7)$$

h. Passenger-related cost effect of the Price-Recovery Component:

$$variance_8 = (passenger\ enplanements_{j\ (expected)}) \times (passenger\ related\ cost/passenger_i - passenger\ related\ cost/passenger_j) \quad (8)$$

The **productivity component** is the difference in operating revenue produced by variations in the input-output relationships, making sales price and input costs constant. Horngren *et. al.* (2000) indicate that this component may show a tendency of the company to choose a low-cost strategy. Thus, a positive value in productivity component indicates that the company gets its operating revenue from the increase in productivity. This component is calculated by equations (9) to (11), from year i to year j:

i. Fuel cost effect of the Productivity Component:

$$variance_9 = (fuel\ cost/liter)_j \times (ASK_{j(expected)}) \times ((used\ fuel\ liters/ASK)_i - (used\ fuel\ liters/ASK)_j) \quad (9)$$

j. Fuel (ASK) cost effect of the Productivity Component:

$$variance_{10} = (fuel\ cost/liter)_j \times (used\ fuel\ liters/ASK)_j \times (ASK_{j(expected)} - ASK_{i(actual)}) \quad (10)$$

k. Passenger-related cost effect of the Productivity Component:

$$variance_{11} = (cost/passengers\ enplanements)_j \times \left(passenger\ enplanements_{j(expected)} - passenger\ enplanements_{j(real)}\right) \quad (11)$$

Finally, the **capacity underutilization component** measures the difference in respect to the operating income caused by variations of costs of unused capacity between time periods. Sopariwala (2003) proposes that this component shows whether a company achieves success managing its used/unused relationship capacity. This component is calculated by equations (12) to (14), from year i to year j:

l. Variations in flight-related costs relating to unused capacities:

$$variance_{12} = \left(ASK_{j\ (actual)} - RPK_{j(actual)}\right) \times \left((cost/ASK)_i - (cost/ASK)_j\right) \quad (12)$$

m. Variations in flight-related costs of available capacities:

$$variance_{13} = (cost/ASK)_i \times \left(ASK_{i(actual)} - ASK_{j(actual)}\right) \quad (13)$$

n. Variations in flight-related costs of used capacities:

$$variance_{14} = (cost_i/ASK) \times \left(RPK_j - RPK_i\right) \quad (14)$$

If more than one airline is to be compared, it is recommended that the calculated values from (1) to (14) be normalized, dividing the variances by the Revenue Passenger Kilometers (RPK).

4. METHOD AND DATA

In alignment with the studies Caster *et. al.* (2011) conducted, the following information was gathered: **financial data** (revenue and expenses, depreciation, amortization, profit, etc.), **operational data** (revenue enplaned passengers, revenue passenger kilometers (RPK) and available seat kilometers), **fuel data** (total used liters, total fuel cost and average fuel cost per liter). These data are considered sufficient to conduct the analysis.

In order to situate the context in time, a 4 year time frame (2010-2013) was defined for this study: embracing the exact moment of the merger announcement, disclosed in 2010; and the period following the moment when the merger was concluded in 2012. The justification for this period is that the changes triggered by the merger needed a certain time to cause financial and operational impacts in the new company. The SVA is a study of situations at distinct moments (usually years) thus an analysis of the intermediate years was unnecessary.

The primary data sources are the ANAC Air Transportation Annuals (2010, 2013) and ANAC Statistical Data (2010, 2013), both available on the agency's website (only in Portuguese). The date used in this research had to be better organized in several tables, to make it easier to understand the calculation.

Table 3 shows the operational data of the former TAM (2010) and of the current LATAM (2013), while the fuel data for the two years are listed in Table 4. The concept "Enplaned Passengers' considers those who effectively boarded the aircraft and paid for the air ticket. The fuel data used could have been retrieved from the ANP – Agência Nacional do Petróleo (*National Oil Agency*) official website, but the Operational Statement (*DRO – Demonstrativos de Resultado Operacional*) provided the amount of used fuel (in liters) and the total cost spent with fuel. Dividing the first by the second was the way used to come up with the average fuel cost.

	2010	**2013**
Enplaned Passengers	31,515,633	35,902,761
Revenue Passengers Kilometers (RPK)	50,467,259,599.00	59,261,578,110.00
Available Seats Kilometers (ASK)	70,046,837,151.00	74,355,999,311.00

Table 3 – Operational Data, ANAC (2010, 2013).

	2010	**2013**
Used Fuel Liters	2,398,143,381	2,486,504,931
Total Fuel Costs (R$)	**3,374,858,840.00**	**5,278,656,660.00**
Average Fuel Cost (R$/l)	1.40	2.12

Source: *ANAC (2010, 2013)*

Table 4 – Fuel Data, ANAC (2010, 2013).

The financial data obtained from official ANAC Annuals were organized and reclassified in Table 5 according to two major groups: flight related costs (excluding fuel) and passenger related costs. This table is quite similar to the one used by Caster and Scheraga (2011).

	2010	2013
Crew	1,384,702,200.00	1,546,284,400.00
Maintenance	850,197,630.00	1,384,601,190.00
Airport and Air Navigation Fees	593,698,570.00	873,618,640.00
Leasing and Insurance	435,159,850.00	879,470,850.00
General and Administration Expenses	774,345,290.00	1,094,423,600.00
Flight Equipment Depreciation	577,785,770.00	544,245,020.00
Handling, Cargo and Ground Organization	716,700,360.00	902,985,810.00
Flight Related Costs (excluding fuel)	**5,332,591,680.00**	**7,225,631,523.00**
Onboard Services	304,267,100.00	349,673,870.00
Passenger Traffic Organization	1,747,068,690.00	1,758,836,390.00
Passenger Related Costs	**2,051,335,790.00**	**2,108,510,260.00**
Operating Revenue	**10,288,871,650.00**	**13,265,776,270.00**
Operating Expenses	**10,758,784,300.00**	**14,612,796,420.00**
Fuel Costs	3,374,858,840.00	5,278,656,660.00
Flight Related Costs	5,332,591,680.00	7,225,631,523.00
Passenger Related Costs	2,051,335,790.00	2,108,510,260.00
Operating Profit/Loss	**-469,912,650.00**	**-1,347,020,160.00**

Table 5 – Gathered and Reclassified Financial Data (R$), ANAC (2010, 2013).

The expenses were separated into two groups. The first, Flight Related Costs (excluding fuel), includes factors that directly influence the flight costs such as maintenance and ground organization. Although fuel is obviously related to the flight, following Caster and Scheraga’s (2010) proposal, this component was considered separately due to the traditionally high proportion of the expenses it represents. The second group, Passenger Related Costs, is limited to onboard services and passenger traffic organization, indirectly related to the flight, but directly related to passengers.

Then, some additional necessary data to run SVA were calculated based on Tables 3, 4 and 5, and displayed in Table 6: average revenue per RPK, passenger load factor, expected available seat kilometers (ASK), average RPK per passenger, expected enplaned passengers, average used liters per ASK, average related costs per ASK, average cost per enplaned passenger, idle or unused capacity (ASK) and expected idle or unused capacity (ASK).

	2010	2013
Operating Revenue	10,288,871,650.00	13,265,776,270.00
Revenue Passenger Kilometer (RPK)	50,467,259,599.00	59,261,578,110.00
Average revenue per RPK	0.204	0.224
Revenue Passenger Kilometer (RPK)	50,467,259,599.00	59,261,578,110.00
Available Seats Kilometer (ASK)	70,046,837,151.00	74,355,999,311.00
Passenger Load Factor (%)	72.05%	79.70%
Expected Available Seats Kilometers (ASK)		82,250,628,900.00
Revenue Passenger Kilometer (RPK)	50,467,259,599.00	59,261,578,110,00
Enplaned Passengers	31,515,633	35,902,761
Average RPK per Passenger	1601.34	1650.61
Expected Enplaned Passengers		37,007,493
Used Fuel Liters (l)	2,398,143,381	2,486,504,931
Available Seats Kilometer (ASK)	70,046,837,151.00	74,355,999,311,00
Average Used Liters per ASK	0.0342336	0.0334405
Flight Related Costs	5,332,591,680.00	7,225,631,523.00
Available Seats Kilometers (ASK)	70,046,837,151.00	74,355,999,311.00
Average Flight Related Costs per ASK	0.0761	0.0972
Passenger Related Costs	2,051,335,790.00	2,108,510,260.00
Enplaned Passengers	31,515,633	35,902,761
Average Cost per Enplaned Passenger	65.09	58.73
Revenue Passenger Kilometer (RPK)	50,467,259,599.00	59,261,578,110.00
Available Seats Kilometers (ASK)	70,046,837,151.00	74,355,999,311.00
Idle or Unused Capacity (ASK)	19,579,577,552.00	15,094,421,201.00
Expected Idle or Unused Capacity (ASK)		22,989,050,790.00

Table 6 – Processed Data used in SVA

The variance equations (1) to (14), were used to compile Table 6, based on data from Tables 3 to 6. For each SVA component, the values were summed to get the total of the component. In the end, the numbers of Table 7 indicate what the new company, LATAM, did strategically over the years along the merger process, and the factors that led them to profit or loss, according to further analysis in Section 6.

5. RESULTS

Table 7 displays the compiled results of SVA. Firstly, it is important to note that the airline increased its productivity between the year it announced the merger, and the year immediately after its conclusion. That is, after all, one of the objectives of a merger process. The productivity component generated more than R$ 1 billion of operating profit for the company, supported mainly by reduction of average cost per enplaned passenger (from R$ 65.09 to R$ 58.73); and by the increase of passenger load factors (occupancy rate) in the aircrafts (from 72.05% to 79.70). As a factor affecting productivity increase, it is worth mentioning that in the early 2010s, TAM phased out the four-engine Airbus A340 for long haul flights (Europe), and started operations with two-engine Boeing 777 (greater fuel efficiency).

Growth Component	
Revenue effect of the Growth Component	1,794,040,980
Fuel cost effect of the Growth Component	-584,891,615
Flight-related cost effect of the Growth Component	-669,134,512
Passenger-related cost effect of the Growth Component	-357,465,167
TOTAL	**182,549,686**

Price Recovery Component	
Revenue effect of the Price-Recovery Component	1,185,231,560
Fuel cost effect of the Price-Recovery Component	-2,027,329,290
Flight-related cost effect of the Price-Recovery Component	-1,250,422,530
Passenger-related cost effect of the Price-Recovery Component	235,367,655
TOTAL	**-1,857,152,605**

Productivity Component	
Fuel cost effect of the Productivity Component	138,293,904
Fuel (ASK) cost effect of the Productivity Component	865,173,904
Passenger-related cost effect of the Productivity Component	64,880,910,40
TOTAL	**1,068,348,720**

Capacity Underutilization Component	
Variations in flight-related costs relating to unused capacities	-318,492,287
Variations in flight-related costs of available capacities	-327,927,240
Variations in flight-related costs of used capacities	669,247,639
TOTAL	**22,828,112**

Table 7 – Strategic Variance Analysis TAM/LATAM (2010-2013) (R$)

The price recovery component of the TAM/LATAM merger stands out due to the huge negative value, a loss of R$ 2 billion. This component measures the capacity of an airline to increase fares, according to its increase in operational costs, holding all the rest constant.

It means that the fares charged to passengers could not cover the operational costs, coinciding with the rise of fuel prices throughout this period (from R$ 1,40 in 2010 to R$ 2,12 in 2013, an increase of more than 51%). Figure 2 shows a comparison of the component shares of the expenses. The fuel share increased by almost 5% in four years.

Another significant issue for a bad price recovery component was the increase of flight-related costs (from R$ 0.0761/ASK to R$ 0.0972/ASK, a variation of more than 27%). Table 5 demonstrates that aircraft leasing and insurance costs more than doubled. The handling, cargo and ground organization decreased by more than 4%. This result is interesting because until the year 2018 LATAM was the only airline in Brazil to self-provide the handling services; all the others used third-party companies. That seems to have been an advantage during those years.

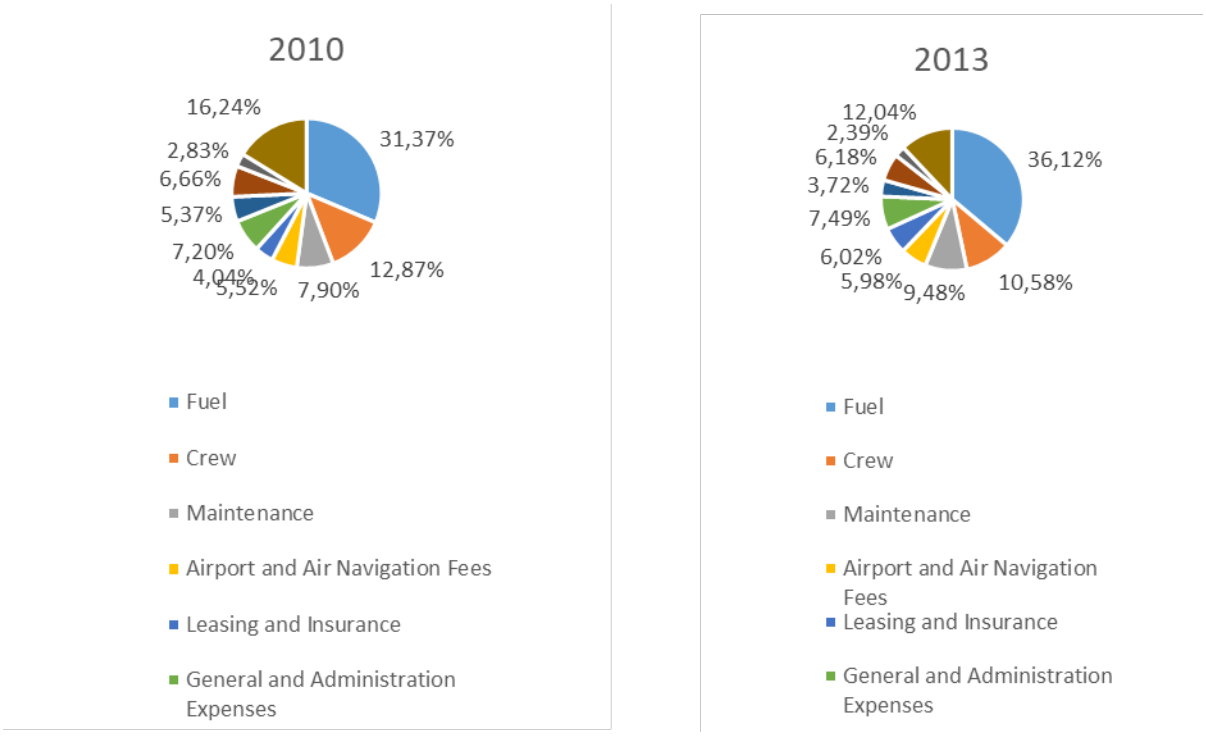

Figura 2 Pizza charts of each expense's share based on Table 5.

The growth component brought a little more than R$ 180 million of operating profit for LATAM, a reasonable value. The main ingredient which may explain this result is the increase of RPK in almost 9 billion flown-passengers-kilometers, influencing the increase of operating revenue in almost R$ 3 billion.

The capacity underutilization component showed a R$ 22 million increase for the company, which denotes that they were capable of reducing the underutilized capacity from more than 19.5 billion available-seats-kilometers to a little more than 15 billion. This ASK reduction implies that the airline succeeded in reducing its cost per unused ASK.

This study is a snapshot of TAM/LATAM’s situation before and after the merger, based on official reports published by the Brazilian regulatory agency of the air transportation market. This means that the financial data provided by ANAC are the only source taken into account.

Another issue is that the research would have been more effective if the data from LAN could have been retrieved from the Chile DGAC online platforms. The data provided for the period had fewer details than the data provided by the Brazilian ANAC, and fundamental information such as the amount of fuel consumed or the cost with maintenance was not available.

It may lack other market considerations such as the expansion of TAM’s main competitor, Gol, to South America and the Caribbean, the premium service offered by Avianca Brasil, or the expansion of Azul, applying effectively the hub-and-spoke model in Campinas Viracopos Airport.

Finally, ideally, the SVA should be applied to other airlines in order to give a broader dimension of the difference between 2010 and 2013 situations.

6. CONCLUSIONS

This research explored the numbers behind the LAN-TAM merger, applying the SVA method, which enabled identification, in the financial/operational balance sheets, of the causes of failure discussed in Section 5 – Results Analysis. As mentioned previously, Horngren *et al.* (2000) suggests that SVA is, *de facto*, more efficient if the data of all players of the industry are cross-referenced. Nevertheless, the SVA numbers, limited to the period between 2010 (merger announcement) and 2013 (the year after the consolidation of the new company), still managed to identify how, throughout the transition years, the expected benefits of the merger had already been overcame by high losses, although these data alone are not sufficient to affirm that the merger failed.

Among exogenous factors (increase of fuel price) and endogenous factors (increase in aircraft leasing and insurance costs, for example), the good productivity component performance emphasizes that a cost leadership strategy was adopted, which is quite reasonable because, naturally, it is one of the main objectives of an airlines merger. Thus, one conclusion that can be drawn is that the success of the productivity component was the fact that enabled LATAM to reduce its passenger-related costs.

On the other hand, a high magnitude price recovery component, but with negative value, indicates that product/service differentiation, was not LATAM’s strategy. It means that a slight increase in fares prices did not cover the operating costs, a recurrent problem in Brazil. In a historically low competition market such as Brazil’s airline industry, one is unlikely to come across a product/service differentiation strategy.

However, LATAM's evolution from a national airline to a transnational one took place with a huge operating loss. Immediately, it was identified with the increase of fuel costs in that time interval. In the early 2010s, the world faced a historical rise in oil prices that led to an increase in fuel costs; Brazil suffered more than other developing countries.

According to ANAC (2017), based on ANP, the average price of jet fuel (QAV) rose from R$ 1.13 per liter in August 2010 to R$ 2.06 per liter in March 2014. In an SVA perspective, this is *de facto* the main evidence of LATAM's huge operating loss, even though that on its own is not sufficient to justify the negative result.

By the end of the 2010 decade, the long-term geopolitical strategy of LATAM's merger, which started almost ten years before, finally seemed to have made its consolidation as the main "Latin American Airline" successful. Figures 3 and 4 display the top 20 airlines by RPK and absolute carried passengers in 2019 (IATA, 2020). It is important to highlight four major clusters with high level competition: United States, Europe, Middle East and China. LATAM is the only Latin American airline in the rankings (Figures 3 and 4).

The local competition in Latin America is quite intense with Azul, Gol, Avianca, Aeromexico and Copa Airlines. However, compared to them, as a global player, in 2019 LATAM was the only one to fly from Sydney to Johannesburg, from Los Angeles to Tel Aviv, from Ushuaia to Toronto, consolidating São Paulo, Santiago and Lima as major hubs.

Figure 3 – Top 20 airlines by Revenue Passenger-Kilometers (RPK) in 2019 according to IATA (2020).

Figure 4 – Top 20 airlines by absolute Carried Passengers in 2019 according to IATA (2020).

In future research, the SVA method can be expanded to other airlines at that time (Gol, Webjet, Azul, Trip and Avianca), comparing all the competitors in the market to provide a better understanding of the scenario.

Also, as this research applied SVA in a time interval that covered a relevant fact to TAM (its merger with LAN), it would be interesting to choose other periods associated to other important facts for Brazil's aviation: the concession and expansion of Guarulhos International Airport in 2013 (LATAM's main hub); the FIFA World Cup 2014; the checked baggage and the onboard food sale deregulation in mid-2017; Avianca Brasil's bankruptcy in 2019 and the COVID-19 Crisis in 2020.

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¿LOS SOBREVIVIENTES MAXIMIZAN SU UTILIDAD LUEGO DE UN DESASTRE?

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RESUMEN

Los modelos de distribución de ayuda humanitaria ayudan a asignar recursos escasos en contexto de desastre. Estos deben considerar, además de los costos logísticos, los costos de privación como una medida del sufrimiento humano para así evitar una asignación desigual de los suministros.

Las funciones de costo de privación (DCF) comúnmente se estiman utilizando métodos de elección discreta, suponiendo que los afectados buscan maximizar su bienestar tomando decisiones racionalmente. Sin embargo, después de los desastres, las personas están bajo estrés, presión y trauma, y pueden adoptar comportamientos que no sean compensatorios ni basados en utilidad. Este artículo cuestiona el uso de la maximización de la utilidad para estimar las DCF comparando sus resultados con un enfoque de minimización aleatoria del arrepentimiento y un método que combina reglas de decisión basadas en el arrepentimiento y la utilidad para representar los mecanismos de elección.

Se estimaron las DCF para diversos suministros críticos utilizando datos de preferencias declaradas de dos casos de estudio: Colombia y Ecuador. Los resultados sugieren que los costos de privación tienen valoraciones significativamente diferentes dependiendo del mecanismo de decisión utilizado; las DCF estimadas usando maximización de utilidad aleatoria arrojaron costos más altos.

Esto sugiere que, al menos durante la ventana de tiempo analizada, las personas aspiran a maximizar su bienestar. Además, los resultados muestran que los costos de privación dependen del contexto y no deben transferirse directamente. Finalmente, se muestra que las funciones de costos de privación para múltiples productos se pueden agregar por separado en la misma función objetivo al planificar las operaciones. Esta investigación es el primer intento de considerar diferentes heurísticas de elección para estimar DCFs, y es la primera en comparar datos de diferentes ubicaciones. Las implicaciones de estos hallazgos brindan a los administradores y planificadores de desastres nuevos desafíos y direcciones de investigación.

1.INTRODUCCIÓN

En medio de los desastres, los sobrevivientes a menudo enfrentan escasez de alimentos, agua y otros bienes esenciales durante períodos prolongados. Por ello, existe una mayor demanda de suministros esenciales y un aumento en el sufrimiento de las personas afectadas, debido a la falta de acceso a suministros críticos como alimentos o agua. Con estas necesidades en mente, en la literatura sobre gestión de operaciones e investigación de operaciones se han propuesto modelos de distribución de socorro para establecer la mejor manera de asignar recursos limitados en el contexto de desastres. Los desafíos asociados a los modelos existentes son la determinación de una función objetivo apropiada y la comprensión de las compensaciones entre los objetivos múltiples y conflictivos de la entrega de ayuda: eficiencia, eficacia y equidad.

Equilibrar estos objetivos y comprender cómo cada uno contribuye al alivio del sufrimiento es difícil, al igual que la modelación dichos objetivos cuantitativamente para que se puedan utilizar modelos de optimización (Gralla et al., 2014).

La mayoría de las metodologías disponibles utilizan funciones objetivo de logística comercial como base para la toma de decisiones, lo cual es inadecuado para fines humanitarios (Macea, et al., 2018). En este contexto, la mejor forma de asignar los escasos recursos es minimizando los costos sociales que, además de los tradicionales costos operativos, consideran los costos de privación de la población impactada por el desastre (Holguín-Veras et al., 2016). Los costos de privación son una valoración económica del sufrimiento que experimentan las personas que no tienen acceso a suministros críticos; encontrar un método apropiado para cuantificarlos es fundamental para los tomadores de decisiones (Shao et al., 2020).

Investigaciones recientes han propuesto experimentos de elección discreta y valoración contingente como métodos para estimar las funciones de costo de privación. En estos enfoques, se asume que los individuos afectados son racionales y tratarán de maximizar su bienestar a la hora de tomar decisiones.

Sin embargo, las personas afectadas por desastres toman decisiones en condiciones de estrés, presión y trauma, y se pueden esperar comportamientos que no son sistemáticos y racionales. Dado que el uso de supuestos de comportamiento poco realistas podría producir estimaciones de costos de privación sesgadas, esta investigación cuestiona las premisas de comportamiento racional, compensatorio y maximizador de la utilidad utilizadas para estimar las funciones de costos de privación en las metodologías actuales.

En este artículo, evaluamos diferentes heurísticas de elección, distintas a la maximización de la utilidad aleatoria para estimar las funciones de costo de privación de agua, alimentos y un kit que contiene ambos. Estimamos las funciones utilizando enfoques de minimización de arrepentimiento aleatorio (RRM por sus siglas en inglés) (Chorus et al., 2008), utilidad modificada aleatoria (RMU por sus siglas en inglés) (Chorus et al., 2013) y maximización de utilidad aleatoria (RUM por sus siglas en inglés) (Mcfadden, 1981) con datos recopilados en áreas afectadas por desastres previos para determinar el efecto de los supuestos de comportamiento en las funciones de costos de privación. El objetivo es comparar las funciones resultantes e identificar si tales supuestos se cumplen en el contexto de desastres.

El resto del artículo está organizado de la siguiente manera. La sección 2 incluye una descripción general de la literatura relevante; La Sección 3 presenta la metodología utilizada en este estudio; La sección 4 analiza el proceso de recopilación de datos junto con un análisis descriptivo de la muestra; La sección 5 describe las especificaciones y los resultados del modelo; y la Sección 6 analiza las implicaciones derivadas de los resultados. El artículo concluye en la Sección 7.

2. ESTADO DEL ARTE

Las operaciones humanitarias requieren interpretaciones innovadoras de la equidad en términos de asignación de recursos, brindando una respuesta eficaz y eficiente que apoye a la población impactada. La priorización efectiva de la entrega es crucial en este tipo de operaciones, incluso cuando es inevitable que algunas necesidades se satisfagan antes que otras (Balcik & Smilowitz, 2020). Sin embargo, como mencionan Gupta et al. (2016), la equidad no parece estar suficientemente cubierta en el campo de la toma de decisiones.

Últimamente, lograr la equidad ha sido una consideración fundamental en muchos estudios relacionados con la logística humanitaria (Balcik & Smilowitz, 2020). A pesar de tales esfuerzos, las funciones objetivo comúnmente formuladas en las investigaciones existentes sobre logística humanitaria descuidan los efectos del sufrimiento humano o los consideran únicamente mediante el uso de medidas indirectas y penalidades. Estos enfoques son limitados, ya que no pueden dar cuenta correctamente de los complejos efectos no lineales asociados con el sufrimiento humano experimentado por los beneficiarios de la ayuda a lo largo del tiempo (Holguín-Veras et al., 2012).

El concepto de costos de privación surgió en las operaciones de distribución de socorro para incluir el sufrimiento humano.
Si los costos reales de privación que enfrentan los individuos son significativos, las medidas aproximadas no pueden representar correctamente la complejidad y las características (por ejemplo, demandas no aditivas y naturaleza no lineal) de la privación.

Holguín-Veras et al. (2016) fueron los primeros en estimar funciones de costo de privación (DCF por sus siglas en ingles) para el agua potable utilizando el método de valoración contingente y proporcionaron una mejor manera de evaluar los impactos de la logística de entrega de ayuda.

Utilizando el mismo contexto, Macea et al. (2018) estimaron un DCF para agua potable a través de modelos de elección discreta. Estimaron modelos multinomiales de tipo logit y concluyeron que ignorar los efectos de la privación, o estimar incorrectamente su valor económico, resulta en una asignación inadecuada de recursos. Cantillo et al. (2018) estimó los costos de privación de un kit de alimentos básico, incluida el agua. Propusieron modelos RUM que incluían heterogeneidad de los gustos sistemática y aleatoria, y utilizaron modelos logit mixtos para reflejar cómo varía el impacto de las decisiones logísticas en función de las características socioeconómicas de los individuos. Macea et al. (2018) estimaron los DCF para un kit de alimentos básico utilizando modelos Logit mixtos y modelos híbridos con variables latentes que consideran la percepción del riesgo, la cultura de seguridad y la confianza en los sistemas de respuesta a emergencias. Finalmente, Delgado-Lindeman et al., (2019) estimaron la disposición individual a pagar para evitar el sufrimiento que experimentan los pacientes que no reciben asistencia inmediata durante una emergencia médica; utilizaron preferencias declaradas y modelos logit mixtos. A excepción de Holguín-Veras et al. (2016), todos los estudios de investigación mencionados anteriormente emplearon un método de elección declarada con modelos de elección discreta formulados utilizando un paradigma de maximización de la utilidad aleatoria para estimar los DCF, utilizando desastres en el contexto colombiano como caso de estudio.

Usando un enfoque diferente, Wang et al. (2017) propuso un nuevo método para cuantificar el sufrimiento humano, utilizando una escala de calificación numérica. Las funciones estimadas con los datos de la escala de calificación numérica se definen como funciones de nivel de privación y brindan información sobre el grado (en lugar del valor económico) del sufrimiento humano causado por la falta de acceso a un bien o servicio. No obstante, los niveles de privación no se pueden utilizar directamente con los costos logísticos en la misma función objetivo, y son más difíciles de calcular y analizar que los costos de privación (Shao et al., 2020).

Aunque la inclusión de una medida de sufrimiento es ideal, cuantificarlo sigue siendo complicado. No es posible desarrollar modelos precisos para representar sistemas que no se comprenden bien.

Una vez que comienzan las operaciones humanitarias, las personas afectadas suelen decidir entre esperar hasta que llegue la ayuda y trasladarse a otro lugar en busca de suministros esenciales para sobrevivir. El supuesto más común en este proceso está asociado con individuos que intentan maximizar su bienestar mientras están sujetos a ciertas restricciones socioeconómicas. En otras palabras, la situación se trata como un problema de maximización de la utilidad en el que los individuos siguen comportamientos racionales.

La literatura relevante no aborda adecuadamente la ansiedad psicológica, el estrés, la presión y sus efectos en la recuperación de desastres (Hu & Sheu, 2013). Se han realizado estudios para esclarecer los procesos de reacción al estrés traumático, aprendizaje y memoria, duelo, ansiedad y miedo (Cohen, 2008). Ante el peligro, los sistemas cognitivo y afectivo responden y las funciones de identificación / evaluación se centran en la supervivencia. Dado que las reacciones de estrés afectan el comportamiento según el tipo de evento traumático, es importante analizar si las especificaciones actuales de DCF podrían ser poco realistas desde una perspectiva conductual y, por lo tanto, arrojar estimaciones sesgadas. También es importante considerar el efecto que el contexto podría tener en las estimaciones de DCF y determinar si los resultados son transferibles entre contextos.

3. METODOLOGÍA

3.1 Enfoque econométrico

La pérdida de bienestar debido al impacto de un desastre se puede medir utilizando las funciones de costo de privación (DCF), que dependen del tiempo que las personas han pasado sin acceso a un bien o servicio (tiempo de privación). Los métodos de valoración económica tienen como objetivo estimar la disposición a pagar (WTP por sus siglas en inglés) de un individuo por un bien o servicio. Estas técnicas suelen recurrir a datos de preferencias reveladas (PR) o preferencias declaradas (PD).

Los experimentos de valoración contingente (CV) y de PD son las técnicas más utilizadas para estimar los DCF. Los costos de privación se pueden aproximar mediante modelos econométricos que estiman el cambio de utilidad (o arrepentimiento, como se detalla a continuación) producido por un aumento en el tiempo de privación. Dado un modelo de elección discreta estimado a partir de experimentos de PD, una vez estimados los parámetros que explican la elección de los individuos, es posible calcular los valores de la WTP utilizando la tasa marginal de sustitución o el cambio en el excedente del consumidor.

La tasa marginal de sustitución, que representa, en este caso, el valor subjetivo del tiempo de privación, se puede estimar mediante la Ecuación (1) (Ben-Akiva & Lerman, 1985; Rizzi & Ortúzar, 2003):

$$SVDT_n = \frac{\partial V_n / \partial DT_n}{\partial V_n / \partial I_n} \qquad (1)$$

donde Vn representa la utilidad sistemática (o arrepentimiento, como se detallará a continuación) del individuo n, DTn representa el tiempo de privación e In representa el ingreso.

El resultado es una medida de cuán dispuesto está el individuo a pagar por ahorrar tiempo de privación si la utilidad permanece constante.

El cambio total del bienestar (ΔW) producido por la privación podría calcularse como el producto de la SVDT y la variación del tiempo de privación. Como los costos de privación no son lineales y el SVDT no es constante en el tiempo, es necesario calcular ΔW para cada unidad de tiempo integrando entre los límites del tiempo de privación inicial (DT0) y el tiempo de privación final (DT1). También se puede estimar discretizando el atributo de tiempo y agregando cada unidad como se expresa en la Ecuación (2):

$$\Delta(W)_n = \sum_{DT_0}^{DT_1} WTP_n(DT) \qquad (2)$$

Las DCF deben ser monótonamente crecientes, no lineales y convexas con respecto al tiempo de privación (Holguín-Veras et al., 2013). Para estimar los DCF, es necesario especificar una transformación funcional (G) en el atributo de tiempo de privación; se implementó el tipo Box-Cox (Gaudry & Wills, 1978). La transformación de Box-Cox de una variable positiva x es continua para todos los valores del parámetro de potencia τ y se puede definir como (3):

$$x^{(\tau)} = \begin{cases} \frac{(x^{\tau}-1)}{\tau}, & si\ \tau \neq 0 \\ \log\ (x), & si\ \tau = 0 \end{cases} \qquad (3)$$

3.2 Enfoque de modelación

En este articulo estimamos los DCF siguiendo las tres heurísticas que se describen a continuación para identificar la que mejor se adapte al proceso de toma de decisiones de las personas en el contexto de desastres.

3.2.1 Maximización de la utilidad aleatoria (RUM).

Este paradigma asume que los individuos pertenecen a una población homogénea, actúan racionalmente y poseen información perfecta sobre las alternativas disponibles, eligiendo siempre la opción que maximiza su utilidad. La utilidad U_{ni} (Ver Ecuación 4) percibida por un individuo n al elegir la alternativa i, es una medida que se utiliza para agregar todas las características de la alternativa en una sola figura de mérito (Mcfadden, 1981).

$$U_{ni} = V_{ni} + \varepsilon_{ni} = \sum_k \beta_k x_{ik} + \varepsilon_{ni} \quad (4)$$

donde Vni representa la parte observada de la utilidad capturada por una combinación lineal de coeficientes βk asociados con k atributos x_k. εni se refiere al término de error que representa la parte no observada de la utilidad que se supone que es independiente e idénticamente distribuida (iid) siguiendo una distribución de valor extremo. Corresponde a la formulación más utilizada, denominada modelo Multinomial Logit (MNL) (McFadden, 1973). Dada la distribución supuesta del término de error, la probabilidad de elección de MNL para un modelo RUM se calcula utilizando la Ecuación (5).

$$P_{ni} = \frac{\exp(V_{ni})}{\sum_j \exp(V_{nj})} \quad (5)$$

3.2.2 Minimización del arrepentimiento aleatorio - RRM (Chorus et al., 2008)

El modelo basado en RRM postula que, al elegir entre alternativas, los tomadores de decisiones apuntan a minimizar el arrepentimiento aleatorio de forma anticipada. Esta hipótesis tiene sus raíces en la teoría del arrepentimiento (Bell, 1982; Loomes & Sugden, 1982), en la que el mecanismo de elección equivale a elegir la alternativa que se asocia con el arrepentimiento menos esperado.

El nivel de arrepentimiento aleatorio anticipado está asociado con la alternativa considerada i y está compuesto por un arrepentimiento sistemático Ri y un término de error aleatorio. El término de error representa una heterogeneidad no observada en el arrepentimiento. Ri se define como la suma de todos los arrepentimientos binarios asociados con la comparación de la alternativa considerada con cada una de las otras alternativas en el conjunto de opciones. (Chorus, 2010) propuso una aproximación suavizada del modelo de arrepentimiento como en la Ecuación (6):

$$RR_{in} = \sum_{j \neq i} \sum_m \ln\left(1 + \exp\left(\beta_m * \left[x_{jmm} - x_{imm}\right]\right)\right) + \varepsilon_{in} \quad (6)$$

Inspirado por el RUM, en el modelo RRM clásico, el negativo del término de error ε se asume iid tipo I Valor extremo distribuido, lo que resulta en la fórmula logit de forma cerrada para las probabilidades de elección (Ver Ecuación 7):

$$P_{in} = \frac{e^{-R_{in}}}{\sum_J e^{-R_{jn}}} \qquad (7)$$

La investigación ha encontrado que la minimización del arrepentimiento es un determinante particularmente importante del proceso de toma de decisiones cuando el tomador de decisiones percibe las opciones como complicadas y relevantes para su bienestar (Pieters & Zeelenberg, 2007).

3.2.3 Utilidad modificada aleatoria (RMU)

Chorus et al. (2013) propuso un marco integrado que establece que, si bien algunos atributos pueden procesarse utilizando la maximización de la utilidad, otros pueden procesarse utilizando otra regla como la minimización del arrepentimiento. Suponiendo que los primeros q atributos se procesan usando RUM, mientras que los atributos M - q restantes se procesan en términos de una regla RRM, la forma RMU para la alternativa i (donde el error aleatorio es idd valor extremo tipo I-distribuido) puede expresarse como en la Ecuación (8):

$$RMU_i = MU_i + \varepsilon_i = \sum_{m=1\ldots,q} \beta_m x_{im} - \sum_{m=q+1,\ldots,M} \sum_{j\neq i} ln\{1 + exp[\beta_m(x_{jm} - x_{im})]\} + \varepsilon_i \qquad (8)$$

Las probabilidades de elección que consideran la maximización de esta función de utilidad modificada a través de alternativas se pueden estimar usando la Ecuación (9):

$$P_i = \frac{exp(RMU_i)}{\sum_{j=1,\ldots,J} exp(RMU_j)} \qquad (9)$$

4.CASOS DE STUDIO

Diseñamos dos encuestas basadas en la revisión de la literatura y las condiciones que pueden afectar la preparación, los planes de respuesta y las privaciones después de los desastres. Las encuestas recopilaron características socioeconómicas de los encuestados, junto con sus elecciones en un conjunto de escenarios de preferencia declarados. Los escenarios contextualizaron a las personas en una situación de desastre en la que su hogar y los suministros disponibles han sido destruidos, lo que los ha llevado a enfrentar la privación de alimentos y agua. Cada individuo respondió nueve escenarios de elección.

Tuvieron que decidir si comprar alguno de los bienes esenciales disponibles (es decir, solo agua, solo alimentos o ambos si era posible), o esperar un poco más hasta que se les proporcionara ayuda de socorro gratuita.

La última opción haría que el individuo ahorrara dinero para otras necesidades, teniendo en cuenta que tenía limitaciones presupuestarias y ya ha experimentado algún tiempo de privación.

El único dinero disponible para los supervivientes era el dinero que llevaban en el bolsillo.

Las encuestas se refieren a dos casos de estudio diferentes. El primer caso fue en Colombia, en el contexto de inundaciones y deslizamientos de tierra. El segundo caso se refiere a un terremoto en Ecuador. Las encuestas se aplicaron en el otoño de 2019. La Tabla 1 muestra los niveles de atributos utilizados en el diseño.

Atributo	**Niveles de los atributos (Colombia)**	**Niveles de los atributos (Ecuador)**
Privación actual de agua y comida (hr)	4, 8, 16, 24	4, 8, 16, 24
Espera adicional por ayuda gratis (hr)	4, 8, 12	4, 8, 12
Presupuesto disponible	50000, 60000, 80000, 100000 (COP*)	20, 24, 32, 40 (USD)
Precio del agua	10000, 20000, 30000, 40000 (COP*)	4, 8, 12, 16 (USD)
Precio de la comida	20000, 30000, 40000, 50000 (COP*)	8, 12, 16, 20 (USD)

***1 USD = 3,395 COP**

Tabla 1 – Niveles de los atributos de la encuesta

Se recolectaron 3.474 observaciones en el caso colombiano, pero fueron eliminadas 567 porque estaban incompletas. La encuesta se aplicó en noviembre de 2019 en 5 municipios diferentes de la región caribeña del país: Barranquilla (34%), Cartagena (29%), Manatí (14%), Santa Lucía (13%) y Campo de la Cruz (11%). Esta región se considera propensa a desastres, ya que se ha visto afectada continuamente por desastres de este tipo durante el invierno y la temporada de lluvias del país.

En Ecuador se recolectaron 3.537 observaciones. Se eliminaron 1,227 debido a respuestas incompletas de la encuesta. La encuesta se aplicó en agosto de 2019 en 6 municipios diferentes: Jama (21%), Jipijapa (20%), Pedernales (18%), Esmeraldas (15%), Portoviejo (14%) y Guayaquil (12%). Esta región también se considera propensa a desastres, ya que anteriormente ha sido afectada por terremotos.

Los datos recopilados representan una amplia gama de características socioeconómicas de las poblaciones; el resumen se puede encontrar en la tabla 2.

	Colombia		Ecuador			Colombia		Ecuador	
Variable	**n**	**%**	**n**	**%**	**Variable**	**n**	**%**	**n**	**%**
Edad					**Ocupación**				
< 18	2	1%	12	3%	Estudiante	28	9%	828	25%
18-25	31	10%	131	35%	Empleado	96	30%	1008	30%
26-40	98	30%	100	27%	Independiente	117	36%	801	24%
41-65	170	53%	114	31%	Ama de casa	37	11%	315	9%
> 65	22	7%	13	4%	Desempleado	10	3%	171	5%
Género					Otro	35	11%	207	6%
Femenino	171	53%	229	62%	**Nivel de educación**				
Masculino	152	47%	141	38%	Primaria	25	8%	657	20%
Estrato socioeconomico					Bachillerato	103	32%	1161	35%
1 - 2	152	47%	-	-	Técnico	91	28%	27	1%
3 - 4	148	46%	-	-	Universitario	103	32%	1395	42%
5 - 6	23	7%	-	-	Ninguno	1	0%	90	3%
Ingreso					**# Personas en el hogar**				
Bajo	131	40.6%	250	68%	1	6	2%	153	5%
Medio	191	59.1%	113	31%	2	29	9%	342	10%
Alto	1	0.3%	7	2%	3	70	22%	774	23%
Cabeza de hogar					4	107	33%	837	25%
Si	121	37%	220	59%	5	62	19%	603	18%
No	202	63%	150	41%	>5	49	15%	621	19%

Tabla 2- Estadísticos de la muestra

5. RESULTADOS DE MODELACIÓN

Con los parámetros resultantes de cada formulación, estimamos las WTP para agua, alimentos y un kit de agua / alimentos. También estimamos los DCF correspondientes. A continuación, presentamos los resultados para cada heurística de elección y estudio de caso. Consulte el Apéndice para encontrar el diccionario de variables y las especificaciones del modelo para cada bien y heurística de elección.

5.1 Modelos de elección discreta

La Tabla 3 muestra los resultados de la estimación para el conjunto de datos de Colombia y cada tipo de modelo de elección. Los resultados indican que el costo asociado a los bienes ofrecidos, el presupuesto disponible y el tiempo que las personas están privadas de agua y alimentos son atributos importantes en la decisión de compra.

Además de esperar que los parámetros RUM tengan el mismo signo que los del RRM, es importante notar que los parámetros RUM tienen diferentes interpretaciones en comparación con la formulación RRM. En un modelo RRM, el parámetro resultante representa el cambio en el arrepentimiento causado por un aumento de una unidad en el valor del atributo de una alternativa no elegida en comparación con el valor del atributo de la opción elegida (Masiero et al., 2019).

En el modelo RMU, la interpretación depende de si el atributo se formula como basado en la utilidad o basado en el arrepentimiento.

	RUM		**RRM**		**RMU**	
Parámetro	**Estimación**	**Test t robusto (0)**	**Estimación**	**Test t robusto (0)**	**Estimación**	**Test t robusto (0)**
$\boldsymbol{ASC}_{agua}$	-0.915	-3.263*	0.974	3.993*	-0.915	-3.263*
$\boldsymbol{ASC}_{comida}$	-0.094	-0.300	0.160	0.574	-0.094	-0.300
$\boldsymbol{ASC}_{agua\&comid}$	0.923	2.636*	-0.859	-2.718*	0.923	2.636*
$\boldsymbol{ASC}_{\boldsymbol{ninguno}}$	0.000	-	0.000	-	0.000	-
$\boldsymbol{\beta}_{\boldsymbol{costo}}$	-0.111	-2.451*	-0.051	-2.620*	-0.111	-2.451*
$\boldsymbol{\beta}_{presupuesto}$	0.089	2.286*	0.048	2.575*	0.089	2.286*
$\boldsymbol{\beta}_{esperaAgua}$	-0.461	-5.456*	-0.231	-5.454*	-0.231	-5.455*
$\boldsymbol{\beta}_{esperaComida}$	-1.363	-8.649*	-0.682	-8.630*	-0.681	-8.648*
$\boldsymbol{\lambda}_{agua}$	2.314	17.263*	2.311	17.199*	2.314	17.262*
$\boldsymbol{\lambda}_{comida}$	2.471	21.227*	2.472	21.210*	2.471	21.226*
Rho	0.4434	-	0.4433	-	0.4434	-
LL	-2091.57	-	-2091.69	-	-2091.57	-
AIC	4201.15	-	4201.4	-	4201.15	-

Tabla 3 – Parámetros estimados (Colombia) Nota: nivel de confianza *95%

La Tabla 4 muestra los resultados de la estimación para el caso de Ecuador. Al igual que en el contexto colombiano, el costo asociado a la compra de los bienes, el presupuesto disponible y el tiempo de privación resultaron ser atributos importantes en la decisión de compra.

En ambos contextos los signos del costo, los tiempos de espera tanto para el agua como para los alimentos y los parámetros presupuestarios fueron consistentes y esperados. También se encontró que los parámetros λ de la transformación box-cox asociados con el agua y los alimentos en ambos contextos eran significativos, lo que refuerza la naturaleza no lineal de los costos de privación.

	RUM		RRM		RMU	
Parámetro	**Estimación**	**Test t robusto (0)**	**Estimación**	**Test t robusto (0)**	**Estimación**	**Test t robusto (0)**
$\boldsymbol{ASC}_{agua}$	-1.095	-3.207*	1.224	3.627*	-1.094	-3.208*
$\boldsymbol{ASC}_{comida}$	-1.722	-5.273*	1.847	5.830*	-1.719	-5.266*
$\boldsymbol{ASC}_{agua\&comi}$	-0.003	-0.008	0.132	0.423	-0.0015	-0.004
$\boldsymbol{ASC}_{\boldsymbol{ninguno}}$	0.000	-	0.000	-	0	-
$\boldsymbol{\beta}_{\boldsymbol{costo}}$	-0.032	-3.511*	-0.014	-3.650*	-0.032	-3.517*
$\boldsymbol{\beta}_{presupuesto}$	0.025	2.418*	0.014	2.653*	0.024	2.413*
$\boldsymbol{\beta}_{esperaAgua}$	-1.455	-8.258*	-0.738	-8.196*	-0.728	-8.294*
$\boldsymbol{\beta}_{esperaComida}$	-0.675	-6.234*	-0.338	-6.163*	-0.337	-6.249*
$\boldsymbol{\lambda}_{agua}$	1.286	11.386*	1.267	11.056*	1.283	11.395*
$\boldsymbol{\lambda}_{comida}$	2.198	14.336*	2.192	14.120*	2.199	14.368*
Rho	0.3217	-	0.3215	-	0.3217	-
LL	-2163.28	-	-2163.68	-	-2163.28	-
AIC	4344.56	-	4345.36	-	4344.56	-

Tabla 4 – Parámetros estimados (Ecuador) Nota: nivel de confianza *95%

Después de comparar los resultados de las tres formulaciones del modelo y ambas muestras, podemos ver que las log-verosimilitudes finales, los indicadores Rho y AIC son prácticamente iguales entre las formulaciones. La literatura respalda que las diferencias en el ajuste del modelo y el rendimiento predictivo entre los modelos RUM, RMU y RRM suelen ser pequeñas (Chorus et al., 2014), lo que también se confirma con nuestros hallazgos. Además, no existe consenso en la literatura sobre qué formulación de modelo proporciona el mejor ajuste, ya que los resultados son diversos. Sin embargo, las implicaciones derivadas de los modelos, como los pronósticos de participación de mercado y las estimaciones de la disposición a pagar, pueden variar sustancialmente (Chorus et al., 2014), como se mostrará a continuación.

5.2 Funciones de costo de privación (DCFs)

Se calcularon los costos de privación generados cada hora para una ventana de tiempo de 36 horas de privación (tiempo sin comer, beber o ambas). Luego, se acumularon los valores para graficar las DCF para cada bien y para cada formulación del modelo. Para calcular los costos de privación se usaron los parámetros resultantes en la sección 5.1 y las especificaciones de cada heurística de elección (ver Apéndice).

La Figura 1 muestra las curvas de costo de privación por privación de agua para ambos contextos estudiados. En general, las curvas RUM arrojan mayores costos de privación en ambos casos para la ventana de tiempo completo analizada, seguida de la estimación de

RRM y finalmente de las estimaciones de RMU. En las primeras horas de privación, los costos asociados tienden a ser similares entre las tres especificaciones, pero se vuelven más diferenciados a medida que aumenta el tiempo de privación. A medida que pasa el tiempo, es más conservador usar RUM dado que arroja estimaciones más altas, lo que sugiere que si las personas maximizan su bienestar, reconocen un valor más alto de su privación. Como se señaló en la sección anterior, se confirma la no linealidad de las DFC (esperada por definición), dados los parámetros de transformación box-cox resultantes (λ). En cada una de las tres heurísticas de elección, los costos de privación estimados resultaron ser más altos en el caso de Ecuador. Este resultado podría explicarse por las diferencias en contextos socioeconómicos, por el tipo de desastre enfrentado, indicadores de percepción, entre otros aspectos, todos los cuales deben ser analizados en profundidad en futuras investigaciones.

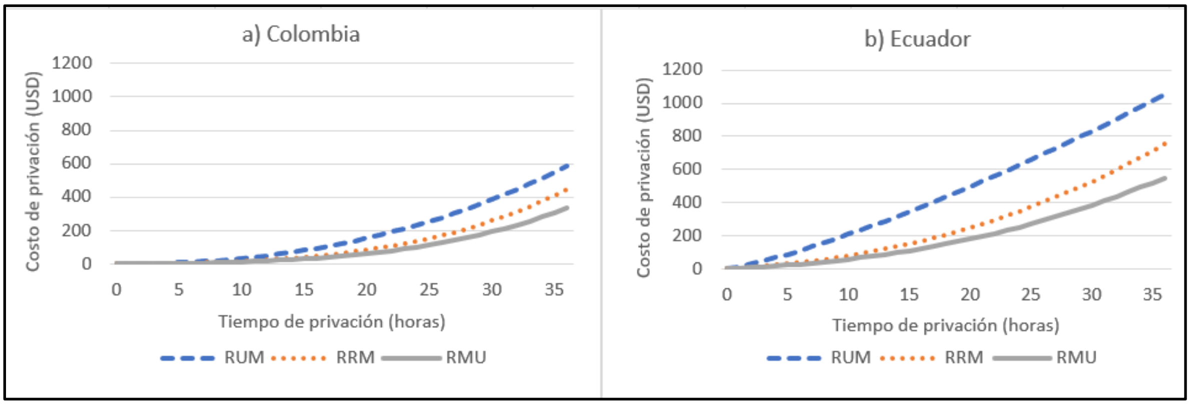

Figura 1 – DCF del agua

La Figura 2 muestra las curvas de costo de privación asociadas con la privación de alimentos para ambos casos de estudio. Aquí, la forma de los DCF es más similar entre los dos contextos y, como se encontró antes, la estimación de RUM siempre arroja costos de privación más altos, seguidos por las estimaciones de RRM y RMU, respectivamente.

Al contrario de lo que sucedió con las estimaciones de agua, los costos de privación son significativamente más altos para la muestra colombiana. Los resultados anteriores sugieren que los colombianos consideran que los alimentos son más críticos que el agua, dada la magnitud de los costos de privación asociados con cada bien analizado. Lo contrario ocurre cuando se analizan las decisiones que toman las personas en Ecuador. Este resultado sugiere que se debe analizar el efecto del tipo de producto, junto con el contexto en el que ocurre el desastre.

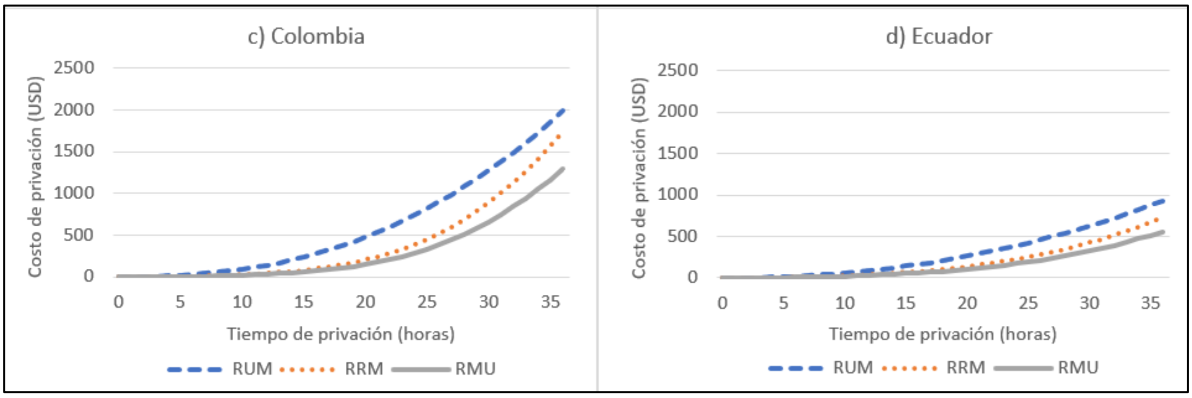

Figura 2- DCF de comida

La Figura 3 muestra las curvas de costo de privación asociadas con la privación de agua y alimentos simultáneamente (como un kit). Considerando que en el presente análisis el efecto de la privación de agua se consideró independiente del efecto de la privación de alimentos, la estimación conjunta del costo de privación de agua y kit de alimentos resultó ser la suma de los costos de privación de agua y comida. En general, las funciones estimadas para el estudio de caso colombiano son un poco más convexas y arrojan valores más altos, lo que confirma que el contexto local juega un papel en la estimación de las funciones de costos de privación. Por lo tanto, no se aconseja la transferibilidad directa de la estimación del DCF, incluso si las áreas en estudio pertenecen a la misma región geográfica (De Vries & Van Wassenhove, 2020), incluso entre países con características socioeconómicas similares.

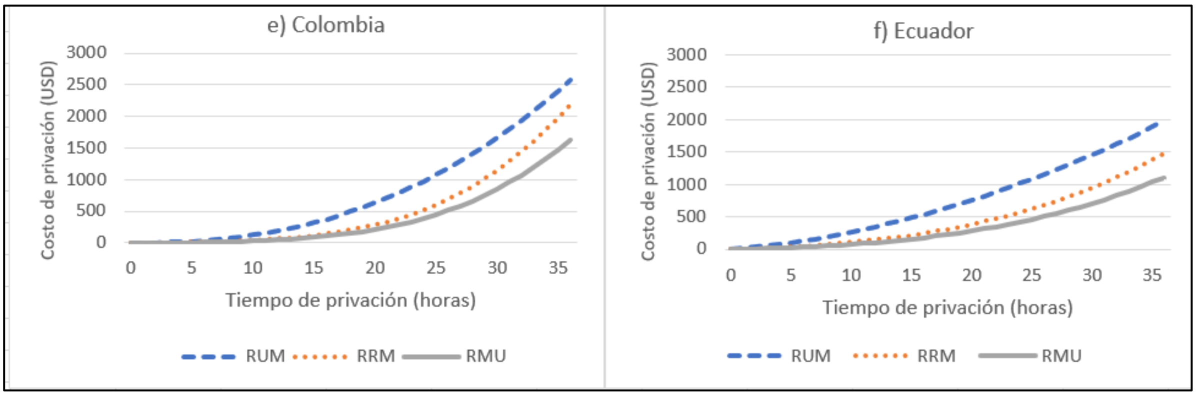

Figura 3- DCF de kit (agua y comida)

6. IMPLICACIONES DE LOS RESULTADOS

Este es el primer estudio que estima DCF para bienes esenciales fuera del contexto colombiano, y el primero en evaluar el efecto que la heurística de elección utilizada puede tener sobre las estimaciones resultantes.

En todos los casos considerados, la estimación basada en la heurística de elección RUM siempre arrojó valores de costo de privación más altos, lo que sugiere que, al menos para la ventana de tiempo analizada y para las condiciones propuestas en este estudio, el uso de esta heurística de elección sigue siendo la opción más recomendada. Como muestran Holguín-Veras et al. (2013), cuando las funciones de costos de privación sobrestiman los costos del sufrimiento humano, los patrones de entrega de las ayudas están determinados por los valores de los costos de privación, lo que garantiza que todas las personas de la comunidad afectada reciban ayuda.

Al final, una sobreestimación de los costos de privación no cambiará el orden en que se atenderán los puntos de distribución (POD), donde se ubica la población afectada. Sin embargo, dado que los parámetros de los modelos y el ajuste entre las formulaciones eran casi iguales, no hay suficiente evidencia para sugerir qué heurística de elección describe mejor el comportamiento de elección de los individuos. Cabe destacar que los resultados no desacreditan las estimaciones actuales de las funciones de costos de privación, ni sugieren que no sean válidas.

Resultados adicionales de este estudio muestran diferencias significativas en las estimaciones del costo de las privaciones entre los estudios de caso de Colombia y Ecuador, lo que respalda la conclusión de De Vries & Van Wassenhove (2020) de que la rentabilidad de las operaciones de logística humanitaria es muy específica del contexto. Por lo tanto, este estudio confirma empíricamente que la generalización de los resultados es crucial y no se recomienda la transferibilidad directa de la estimación de DCF. Esto plantea grandes desafíos para las organizaciones de socorro, ya que no deben utilizar un DCF para desarrollar planes de distribución de socorro en un país o ubicación geográfica que sea diferente del lugar donde se recopilaron los datos para las estimaciones. Esto agrega una nueva tarea a las organizaciones de ayuda. Si se quieren desarrollar planes equitativos, se necesitan DCFs y, con ello, se deben recopilar y analizar datos para estimarlos.

Además, los resultados sugieren que incluso la percepción de qué bien es más crítico después de los desastres depende del contexto. En el estudio colombiano, la falta de alimentos produce mayores costos de privación que la falta de agua, contrario al estudio ecuatoriano, en el que el agua parecía ser más crítica para los individuos en el contexto analizado.

Finalmente, las funciones de costo de privación estimadas para un kit de alimentos + agua resultaron ser la suma de las funciones de costo de privación para agua y alimentos por separado. Esto confirma empíricamente que, y las funciones se pueden incluir una por una en la misma función objetivo para optimizar el diseño de los planes de distribución de la ayuda.

7. CONCLUSIONES

En este artículo, se utilizaron modelos de elección discreta como método de valoración económica para estimar las funciones de costo de privación de bienes críticos (es decir, agua, alimentos y un equipo que contenga ambos) en el contexto de un desastre. Se diseñó e implementó una encuesta en dos casos de estudio diferentes. Presentamos un conjunto de escenarios de preferencia declaradas que fueron respondidos por personas de Colombia en el contexto de inundaciones y deslizamientos de tierra, y de Ecuador, en el contexto de un terremoto. En cada escenario de elección, las personas tenían que elegir entre comprar agua, comprar alimentos, comprar ambos artículos (si era posible con el presupuesto) o esperar más tiempo para que llegara la ayuda gratuita, dadas algunas limitaciones presupuestarias.

Los modelos de elección se formularon evaluando tres heurísticas de elección: maximización de utilidad aleatoria (RUM), minimización del arrepentimiento aleatorio (RRM) y utilidad modificada aleatoria (RMU). El objetivo fue comparar resultados y analizar cuál refleja mejor el comportamiento de las personas en situaciones de desastre y las diferencias en los costos de privación estimados.

En términos del ajuste de los modelos, los resultados fueron muy similares entre las heurísticas de elección, por lo que no se pueden sacar conclusiones sobre qué mecanismo de elección explica mejor el comportamiento de elección de los individuos. Las diferencias significativas en las estimaciones entre los dos estudios de caso sugieren que las funciones de costos de privación dependen del contexto.

Además, varían en función del bien / oferta analizada. En este estudio, la disposición a pagar por el agua y los alimentos después de un desastre fue bastante diferente en los dos países. En Ecuador, la privación de agua parece ser más crítica que en Colombia. Si bien el resultado anterior podría explicarse en parte porque el experimento colombiano consideró escenarios de inundaciones, al final sugiere que el contexto del desastre podría jugar un papel relevante en el proceso de toma de decisiones.

Los alimentos, por el contrario, fueron valorados casi el doble en el contexto colombiano en comparación con los valores obtenidos para Ecuador.

Además, las diferencias no son solo una cuestión de contexto. Dependiendo del desastre, los costos de privación por producto básico pueden variar ampliamente. Por lo tanto, la investigación adicional debe centrarse en estimar las funciones de costos de privación para diferentes artículos y al mismo tiempo considerar diversos escenarios de desastres.

Los hallazgos también sugieren que, para los contextos estudiados, RUM sigue siendo la opción heurística más recomendada para estimar los DCF. Como se muestra en la literatura anterior (Holguín-Veras et al., 2013), usar este enfoque arroja valores económicos más altos, y usar una función que sobreestima los costos reales de privación no cambiará el orden en que los puntos de distribución (POD). Por lo tanto, se podrían desarrollar planes de distribución de socorro.

Finalmente, como se muestra en el kit que contiene agua y alimentos, las funciones de costos de privación para múltiples productos no requieren estimaciones complejas. El DCF de cada bien podría incluirse por separado en la misma función objetivo al diseñar planes de distribución de socorro.

Despite the rigor of the research, this study has some limitations. Given this is the first study that proposes DCFs estimations using alternative choice heuristics, the results are not conclusive, and require further research. More research focused on different choice heuristics, critical supplies, and with data collected in various disaster contexts is needed to gather more evidence. Nonetheless, the findings discussed here provide key insights into the choice behavior of individuals after disasters. We empirically confirm that DCFs should not be transferable, as it was found that an individual's willingness to pay varies with the type of supply and the context in which the decision is being made. Studies collecting data in multiple countries and disaster types are recommended for future research to help identify the geographical and socio-economic effects of deprivation cost functions.

A pesar del rigor de la investigación, este estudio tiene algunas limitaciones. Dado que este es el primer estudio que propone estimaciones de DCF utilizando heurísticas de elección alternativas, los resultados no son concluyentes y requieren más investigación. Se necesita más investigación centrada en diferentes heurísticas de elección, suministros críticos y con datos recopilados en varios contextos de desastres para recopilar más evidencia. No obstante, los hallazgos discutidos aquí brindan información clave sobre el comportamiento de elección de las personas después de los desastres. Confirmamos empíricamente que los DCF no deberían ser transferibles, ya que se encontró que la disposición a pagar de un individuo varía con el tipo de suministro y el contexto en el que se toma la decisión. Se recomiendan estudios que recopilen datos en varios países y tipos de desastres para futuras investigaciones a fin de ayudar a identificar los efectos geográficos y socioeconómicos de las funciones de costos de privación.

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ANEXO

Definición de las variables y notación

Variable	Descripción	Variable	Descripción
ASC_a	Constante específica del agua	β_p	Parámetro del presupuesto
ASC_c	Constante específica de la comida	$Pres_a$	Presupuesto disponible luego de comprar agua
$ASC_{a\&c}$	Constante específica del kit (agua y comida)	$Pres_c$	Presupuesto disponible luego de comprar comida
ASC_n	Constante especifica de no comprar	$Pres_{a\&c}$	Presupuesto disponible luego de comprar agua y comida
β_c	Parámetro del costo	$Pres_n$	Presupuesto disponible luego de no comprar. Igual al presupuesto total
$Cost_a$	Costo del agua	β_{ea}	Parámetro de la espera por agua
$Cost_c$	Costo de la comida	β_{ec}	Parámetro de la espera por comida
$Cost_{a\&c}$	Costo del kit de agua y comida	Esp_{actual}	Tiempo de privación actual: tiempo que llevan sin comer ni beber
$Cost_n$	Costo de no comprar. Definido como cero	Esp_{adi}	Tiempo adicional de privación que deben esperar para recibir ayuda gratuita
λ_a	Parámetro box cox para el tiempo de privación del agua	λ_c	Parámetro box cox para el tiempo de privación de la comida

Formulación de los modelos

RUM	Agua (a)	$V_a = ASC_a + \beta_c * Cost_a + \beta_p * Pres_a + \beta_{ea} * \frac{Esp_{actual}{}^{\lambda_a} - 1}{\lambda_a} + \beta_{ec} * \frac{Esp_{adi}{}^{\lambda_c} - 1}{\lambda_c}$
	Comida (c)	$V_c = ASC_c + \beta_c * Cost_c + \beta_p * Pres_c + \beta_{ec} * \frac{Esp_{actual}{}^{\lambda_c} - 1}{\lambda_c} + \beta_{ea} * \frac{Esp_{adi}{}^{\lambda_a} - 1}{\lambda_a}$
	Agua y Comida (a&c)	$V_{\text{a\&c}} = ASC_{\text{a\&c}} + \beta_c * Cost_{\text{a\&c}} + \beta_p * Pres_{\text{a\&c}} + \beta_{ec} * \frac{Esp_{actual}{}^{\lambda_c} - 1}{\lambda_c} + \beta_{ea} * \frac{Esp_{actual}{}^{\lambda_a} - 1}{\lambda_a}$
	Ninguno (n)	$V_n = ASC_n + \beta_{ec} * \frac{Esp_{adi}{}^{\lambda_c} - 1}{\lambda_c} + \beta_{ea} * \frac{Esp_{adi}{}^{\lambda_a} - 1}{\lambda_a}$

RRM	Agua (a)	$V_a = ASC_a + \log(1 + exp(\beta_c * (Cost_c - Cost_a))) + \log(1 + exp(\beta_c * (Cost_{a\&c} - Cost_a))) + \log(1 + exp(\beta_c * (Cost_a - Cost_a))) + \log\left(1 + exp\left(\beta_p * (Pres_c - Pres_a)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_{a\&c} - Pres_a)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_a)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c})\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c}\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c})\right)\right)$
	Comida (c)	$V_c = ASC_c + \log(1 + exp(\beta_c * (Cost_a - Cost_c))) + \log(1 + exp(\beta_c * (Cost_{a\&c} - Cost_c))) + \log(1 + exp(\beta_c * (Cost_a - Cost_c))) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_c)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_{a\&c} - Pres_c)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_c)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \left(\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c}\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c})\right)\right)$

	Agua y Comida (a&c)	$V_{a\&c} = ASC_{a\&c} + \log\left(1 + exp\left(\beta_c * (Cost_a - Cost_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_c * (Cost_c - Cost_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_c * (Cost_a - Cost_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_c - Pres_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_{a\&c})\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * \left(\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \left(\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \left(\frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c}\right)\right)\right) + \log\left(1 + exp\left(\beta_{ec} * \left(\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c}\right)\right)\right)$
	Ninguno (n)	$V_n = ASC_n + \log\left(1 + exp\left(\beta_c * (Cost_a - Cost_n)\right)\right) + \log\left(1 + exp\left(\beta_c * (Cost_c - Cost_n)\right)\right) + \log\left(1 + exp\left(\beta_c * (Cost_{a\&c} - Cost_n)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_a - Pres_n)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_c - Pres_n)\right)\right) + \log\left(1 + exp\left(\beta_p * (Pres_{a\&c} - Pres_n)\right)\right) + \log\left(1 + exp\left(\beta_{ea} * (\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a})\right)\right) + \log\left(1 + exp\left(\beta_{ea} * (\frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a})\right)\right) + \log\left(1 + exp\left(\beta_{ea} * (\frac{{Esp_{act}}^{\lambda_a} - 1}{\lambda_a} - \frac{{Esp_{adi}}^{\lambda_a} - 1}{\lambda_a})\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c})\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c})\right)\right) + \log\left(1 + exp\left(\beta_{ec} * (\frac{{Esp_{act}}^{\lambda_c} - 1}{\lambda_c} - \frac{{Esp_{adi}}^{\lambda_c} - 1}{\lambda_c})\right)\right)$

RMU	Agua (a)	$V_a = ASC_a + \beta_c * Cost_a + \beta_p * Pres_a - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c}\right)\right)\right)$
	Comida (c)	$V_c = ASC_c + \beta_c * Cost_c + \beta_p * Pres_c - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right)$
	Agua y Comida (a&c)	$V_{a\&c} = ASC_{a\&c} + \beta_c * Cost_{a\&c} + \beta_p * Pres_{a\&c} - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{act}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{act}^{\lambda_c}-1}{\lambda_c}\right)\right)\right)$

	Ninguno (n)	$V_n = ASC_n - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}{}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}{}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{adi}{}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}{}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ea} * \left(\frac{Esp_{act}{}^{\lambda_a}-1}{\lambda_a} - \frac{Esp_{adi}{}^{\lambda_a}-1}{\lambda_a}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{adi}{}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}{}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}{}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}{}^{\lambda_c}-1}{\lambda_c}\right)\right)\right) - \log\left(1 + exp\left(\beta_{ec} * \left(\frac{Esp_{act}{}^{\lambda_c}-1}{\lambda_c} - \frac{Esp_{adi}{}^{\lambda_c}-1}{\lambda_c}\right)\right)\right)$

FERROCARRILES
RAILWAYS

LA RED DE VÍA MÉTRICA EN GALICIA

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RESUMEN

La construcción de líneas ferroviarias en España a lo largo de la segunda mitad del siglo XIX sigue, en general, una configuración radial, uniendo Madrid con los principales puertos y centros urbanos de la costa española. Al objeto de satisfacer las demandas de movilidad en ejes transversales, pronto se planteó la necesidad de realizar una serie de tramos paralelos a la costa.

En este contexto, los antecedentes de la línea de vía métrica Ferrol – Gijón, de 321 km de longitud, se remontan al *Plan General de Ferrocarriles* (1864), aunque habría que esperar al *Plan de Ferrocarriles Estratégicos del Estado* (1883) para que se formalizase. Las obras se iniciaron en 1921, casi 20 años después de la redacción de su primer estudio. El último tramo fue inaugurado en 1972, medio siglo después de iniciadas las obras.

El trazado de esta línea, prácticamente paralelo a la costa, discurre salvando las estribaciones de la Cordillera Cantábrica y el Macizo Galaico, que descienden hacia el mar, mediante 34 túneles y 30 puentes realizados a lo largo de los 154 km de línea que discurre en Galicia. La línea Ferrol – Ribadeo tiene 52 estaciones y apeaderos

La extinción de la entidad pública empresarial *Ferrocarriles Españoles de Vía Estrecha* (*FEVE*), como consecuencia del Real Decreto-ley 22/2012, pareció definir el inicio de un paulatino proceso de deterioro de la oferta de los servicios prestados sobre la red de vía métrica del Norte de España y, en particular, los que se ofrecen sobre esta línea que, aunque actualmente están amparados bajo una obligación de servicio público (OSP), parecen tener un futuro incierto.

En la presente ponencia se analizan, entre otras, cuestiones relacionadas con su trazado, la situación de las paradas, el diseño de los servicios o la oferta en competencia, que permitirían explicar algunos aspectos de la actual situación y que dificultan hacer más competitivos los servicios prestados.

La construcción de líneas de ferrocarril de vía ancha en España se va desarrollando a lo largo de la segunda mitad del siglo XIX siguiendo una configuración básicamente radial, es decir, uniendo Madrid con los principales puertos y centros urbanos de la costa española. A esta pauta no fueron ajenos los principales puertos de la costa cantábrica y atlántica, a donde llegan las líneas ferroviarias que los comunican con Madrid: Bilbao (1863), Santander (1866), Gijón (1874), A Coruña (1875), Vigo (1878), Avilés (1890) o Ferrol (1913) (García Raya 2006).

Pronto se planteó la necesidad de construir líneas que permitieran satisfacer las demandas de movilidad en ejes transversales, más difíciles de atender por una red radial.

Ya en el Plan General de Ferrocarriles, redactado en cumplimiento de la ley de 13 de abril de 1864, se contempló entre los anteproyectos de la Junta Consultiva de Caminos, Canales y Puertos una conexión entre Santander y Zumárraga (Guipúzcoa) por Bilbao, en la red de Norte (A. D. 1864), y otra de Ribadeo a Oviedo por la costa, Lugo a Ribadeo y Santiago a Ferrol por A Coruña, en la red del Noroeste (Ministerio de Fomento 1905). Se trata de tramos que formarían parte de un corredor ferroviario costero que debía enlazar Galicia con el golfo de Vizcaya.

El primer tren de la Compañía del Ferrocarril de Santander a Bilbao que unió Santander con Zoroza circuló el 3 de julio de 1896. La prolongación desde Zoroza a Bilbao entró en servicio el 30 de julio de 1898. Dicho ramal finalizaba en el centro de la villa, con la estación modernista de Bilbao-Concordia.

A partir de 1905 comienza la explotación del tramo de Santander – Llanes (Compañía del Ferrocarril Cantábrico), cuyos servicios se prolongan hasta Oviedo a través de la Compañía de los Ferrocarriles Económicos de Asturias.

La construcción y progresiva entrada en servicio de estas líneas, junto con los favorables resultados económicos de las compañías ferroviarias que las explotaban, animó a completar el corredor ferroviario costero a lo largo de la cornisa cantábrica hasta Galicia. Este tramo ya se había planteado en 1883, en el Plan de Ferrocarriles Estratégicos del Estado (Ley de 27 de julio de 1883), para comunicar las zonas de productoras de carbón y las factorías armamentísticas asturianas (Trubia y Oviedo) con el arsenal de Ferrol. Por esta razón, el proyecto de Ferrocarril Ferrol – Gijón es igualmente conocido como “el Estratégico”.

Esta línea también se había incluido en el Plan de Ferrocarriles Secundarios de 1888 (apareciendo como Ferrocarril de Somorrostro a Ferrol), en el de 1893 y en el de 1905. En este último, la línea Ferrol – Gijón aparece descompuesta en los siguientes tramos, con sus longitudes estimadas (Ministerio de Fomento 1905) (Se consideraban ferrocarriles estratégicos los que, con independencia del servicio que prestaban a otros intereses generales, atendían directamente necesidades o conveniencias de la defensa nacional).

- Ferrol, por Santa Marta de Ortigueira, al Barquero (70 km).
- Barquero, por Viveiro, a Ribadeo (74 km).
- Ribadeo a Pravia (106 km).
- Pravia a Gijón (40 km).

Cabe señalar que la definición del trazado no estuvo exenta de dificultades, debido a las discusiones promovidas por los ayuntamientos que quedaban fuera de su trazado. Las variantes del Eo y de Pravia fueron motivo de vehementes debates, llegando las discusiones al Parlamento, como una cuestión de interés nacional.

Los estudios del que también se conoció como Ferrocarril de la Costa fueron llevados a cabo por la Sociedad Iberia Concesionaria, creada en 1902 en Bilbao, con el objetivo de desarrollar esta línea. Dicha Sociedad recibió la autorización para llevar a cabo estas tareas mediante la Real Orden de 17 de marzo de 1902. El anteproyecto fue realizado por los ingenieros José Borés y Romero y Luis Vasconi y Cano, y se presentó el 20 de abril de 1906. En él, entre otras cuestiones, se comentaban las ventajas que esta línea tendría para Galicia y Asturias (se estimaba que beneficiaría a más de un millón de habitantes en su área de afección) al objeto de que fuera declarado ferrocarril de servicio general (Heredia Flores 2017).

Con motivo de la presentación del anteproyecto, la Real Orden de Guerra de 17 de noviembre de 1906 consideraba que, dada la importancia estratégica de la línea, especialmente entre Pravia y Ferrol, sería conveniente que una comisión mixta de ingenieros civiles y militares estudiase las modificaciones precisas para proteger la línea contra posibles ataques de una escuadra o tropas de desembarco, y dotase a las obras de fábrica de mecanismos o dispositivos que permitieran su inutilización en caso de necesidad. Especialmente interesante fue la recomendación de que la línea se proyectase de manera que, a pesar de estar diseñada para vía métrica, pudiese, por sus características de planta y perfil, igualar la capacidad y velocidad que ofrecería una línea de vía ancha (Gómez Martínez 1999).(Como ferrocarriles secundarios se consideraban aquellos destinados al servicio público, con motor mecánico de cualquier clase, que no estuvieran comprendidos en la red de servicio general, tal como se había definido y establecido en la Ley de 1877).

Tras la incorporación de la línea al *Plan de Ferrocarriles Secundarios* de 1907, en 1908 (mediante Real Orden de 14 de mayo) se abrió el concurso que fijaba los requisitos que debía reunir el proyecto, entre los cuales cabe señalar:

- Vía métrica.
- Trazado por Ortigueira, Viveiro, Ribadeo, Pravia y Avilés.
- Pendiente máxima: 20 milésimas.
- Radio de curva mínimo: 120 m.
- Velocidad comercial de los trenes: 25 km/h.

La única empresa que presentó un proyecto fue la *Sociedad Iberia Concesionaria*, que lo hizo el 30 de enero de 1909. El presupuesto de construcción de la línea se estimó en cerca de 75 millones de pesetas. Tras las modificaciones precisas, el proyecto se aprobó, mediante Real Orden, el 10 de enero de 1914. La *Sociedad Iberia Concesionaria* fue la adjudicataria de la concesión.

Las obras se sacaron a concurso en tres ocasiones (12 de noviembre de 1915, 7 de noviembre de 1919 y 15 de junio de 1920), quedando en todas ellas desierto el concurso. Puesto que la concesionaria no pudo reunir el dinero suficiente para ejecutarlas, el Gobierno tomó la decisión de, a través de los presupuestos generales de 1920-1921, subastar la construcción de las secciones de mayor interés para los viajeros. La línea fue dividida en las siguientes secciones:

- Ferrol – Mera
- Mera – Ortigueira
- Ortigueira – Foz
- Foz – Ribadeo
- Ribadeo – Los Cabos (entre Pravia y Soto del Barco)
- Los Cabos – Gijón

Se decidió subastar la construcción de los tramos extremos, es decir, Ferrol – Mera y Los Cabos – Gijón (Gómez Martínez 1999).

La subasta para la construcción de las obras de explanación y fábrica del primer tramo de la sección de Ferrol a Mera se adjudicó el 25 de septiembre de 1921. Las obras se iniciaron ese mismo año.

En 1928 la línea fue incluida en el *Plan Preferente de Ferrocarriles de Urgente Construcción* (también conocido como *Plan Guadalhorce*, llamado así en honor del ministro de Fomento, Rafael Benjumea y Burín, conde de Guadalhorce). A pesar de ello, tendrían que transcurrir 44 años para que se inaugurase el último tramo puesto en servicio. Gómez Martínez (Gómez Martínez 2005) atribuye a las siguientes causas este dilatado periodo de construcción:

- El Estado se encargó de la construcción de la línea Ferrol – Gijón, cosa que no ocurrió con la mayoría de las líneas ferroviarias construidas hasta la fecha, en las que la construcción y explotación las llevó a cabo una empresa con capital privado. La intervención del Estado hace que los procesos burocráticos (reformados y modificaciones parciales de proyectos, desfase de los presupuestos, rescisiones de contratos, licitación y adjudicación de nuevos, etc.) se eternicen.

- La Guerra Civil, que interrumpió las obras hasta principios de los años cuarenta. Terminada la contienda, y aunque desde el Gobierno había interés en concluir las obras por ser Ferrol la ciudad natal del jefe del Estado, la necesidad de liquidar obras antiguas, redactar presupuestos adicionales o reformar los ya realizados, junto con la carestía de materiales y la escasez de fondos públicos, dilataron una vez más la ejecución de las obras.

En la tabla 1 se muestran las fechas de inauguración de los diferentes tramos en que se dividió la construcción de la línea Ferrol – Gijón.

Longitud [km]	**Tramo**	**Inauguración**
7,0	Aboño - Gijón	1 octubre 1950
24,3	Pravia - Avilés	11 septiembre 1956
45,9	Ferrol - Mera	29 enero 1962
57,8	Luarca - Pravia	13 septiembre 1962
6,66	Mera - Ortigueira	7 septiembre 1964
33,3	Ortigueira - Viveiro	24 junio 1966
67,0	Viveiro - Vegadeo	21 junio 1968
58,4	Vegadeo - Luarca	6 septiembre 1972

Tabla 1. Cronología de las inauguraciones de los tramos de la línea Ferrol – Gijón. (Gómez Martínez 2005).

El general Franco inauguró la totalidad de la línea, el 6 de septiembre de 1972. El coste final de la misma ascendió a 4.250 millones de pesetas de 1972, lo que supone un coste por kilómetro de 13,2 millones de pesetas. La línea, con una longitud de 321 km, tiene 121 túneles, numerosos viaductos, puentes y obras de paso, 27 estaciones y gran cantidad de apeaderos. Habían transcurrido más de 50 años para que finalizara su construcción, quedando unidas las ciudades de Ferrol y Gijón por ferrocarril de vía métrica.

A partir de 1972 se llevan a cabo diferentes actuaciones de mejora de la infraestructura ferroviaria (sobre puentes, túneles, instalaciones fijas, etc.), electrificación (el tramo Pravia – Avilés en 1986, y el Cudillero – Pravia en 1994), renovación de la vía (entre Avilés y Soto del Barco en 1996; entre Soto del Barco y Pravia, y entre Ribadeo y Vegadeo en 1997), señalización y enclavamientos.

2. SITUACIÓN ACTUAL DE LA LÍNEA FERROL – RIBADEO

2.1 Infraestructura

El tramo que se desarrolla en Galicia de la línea Ferrol – Gijón (321 km), tiene una longitud de 154 km, siendo sus estaciones extremas las de Ferrol y Ribadeo (figura 1). El trazado de esta línea, prácticamente paralelo a la costa, se caracteriza por la presencia de numerosos viaductos para salvar los valles que se forman como consecuencia de las estribaciones de la Cordillera Cantábrica y el Macizo Galaico que descienden hacia el mar. Por lo general, se trata de obras de fábrica con dos tipologías diferenciadas: viaductos formados por arcos ojivales, en el lado gallego, y de arcos de medio punto, en el sector asturiano.

Desde su inauguración, esta línea fue explotada por la entidad pública empresarial *Ferrocarriles Españoles de Vía Estrecha* (*FEVE*). De acuerdo con el Real Decreto-ley 22/2012, de 20 de julio, por el que se adoptan medidas en materia de infraestructuras y servicios ferroviarios, *FEVE* se extinguió el 31 de diciembre de 2012, momento en el que fundamentalmente *Adif* y *Renfe Operadora* asumieron sus derechos y obligaciones, así como la titularidad de sus bienes. El material móvil y la explotación de los servicios de transporte pasaron a ser gestionados por *Renfe Operadora*, mientras que la gestión de la infraestructura se encomendó a *Adif*.

Está integrada en la *Red Ferroviaria de Interés General* (*RFIG*), de acuerdo con la Orden FOM/710/2015, de 30 de enero, por la que se aprueba el Catálogo de líneas y tramos de la Red Ferroviaria de Interés General (BOE nº 97, de 23 de abril de 2015). Por ello, su gestión y mantenimiento corresponden al *Administrador de Infraestructuras Ferroviarias* (*Adif*), de acuerdo con la disposición adicional primera de la Ley 38/2015, de 29 de septiembre de 2015, del Sector Ferroviario (BOE nº 234, de 30 de septiembre de 2015). Entre Ferrol y Pravia el código de identificación de la línea es el 740.

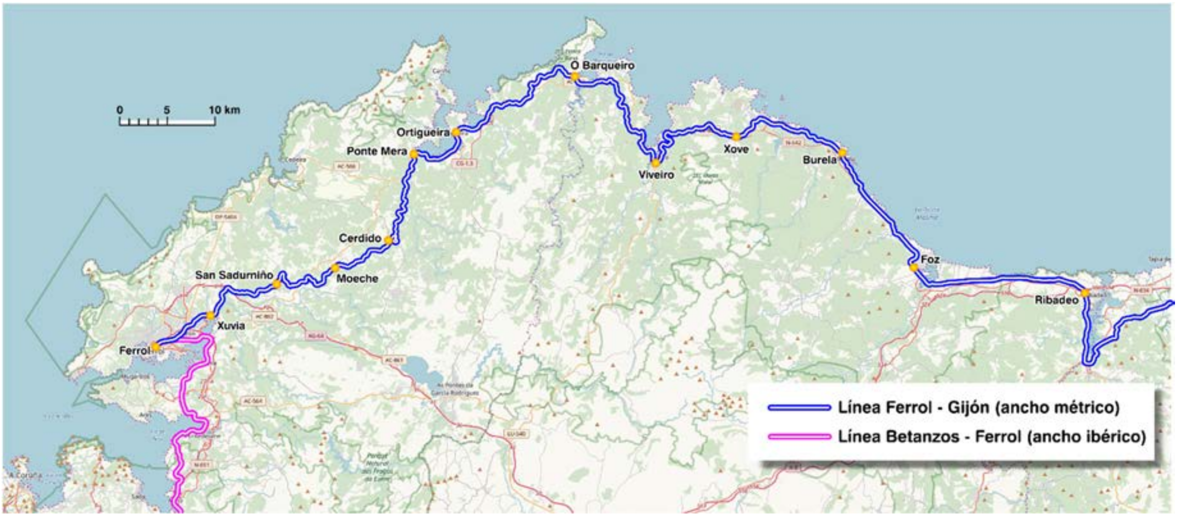

Figura 1. Trazado general de la línea Ferrol – Ribadeo, con sus estaciones principales.

2.1.1 Tipo de línea y ancho de vía

La infraestructura ferroviaria de la línea Ferrol - Gijón en la sección Ferrol - Ribadeo puede caracterizarse esquemáticamente por los siguientes aspectos:

- Vía única, sin electrificar.
- Ancho de vía métrico (1.000 mm).
- La superestructura está constituida, en general, por carril de 45 kg/m sobre traviesas de hormigón monobloque y balasto silíceo.
- En el tramo Ferrol – Ribadeo existen 34 túneles, numerados correlativamente. Totalizan 7.041 m de longitud, siendo el mayor de ellos de 813 m.
- Existen 30 puentes en el tramo Ferrol - Vegadeo, con una longitud total de 1.844,6 m. El más largo es el que salva el río Sor cerca de O Barqueiro (A Coruña), con una longitud de 241 m.
- Por lo que se refiere a pasos inferiores, existen 114, de los cuales 24 son mayores de 6 metros de luz.

2.1.2 Cargas máximas

De acuerdo con la *«Declaración sobre la Red 2021»* de *Adif* (Administrador de Infraestructuras Ferroviarias 2021), la carga máxima por eje es de 15,0 t y por metro lineal de 8,0 t.

2.1.3 Rampas características

De acuerdo con la *«Declaración sobre la Red 2021»* de *Adif*, los valores de las rampas características existentes en la línea Ferrol – Ribadeo se muestran en la tabla 2.

Tramo	**Rampa característica** [mm/m]
Ferrol → Cerdido	20
Ferrol ← Cerdido	20
Cerdido → Ortigueira	16
Cerdido ← Ortigueira	20
Ortigueira → Xove	15
Ortigueira ← Xove	17
Xove → Ribadeo	15
Xove ← Ribadeo	15

Tabla 2. Valores de las rampas características en la línea Ferrol – Ribadeo. (Administrador de Infraestructuras Ferroviarias 2021).

En la figura 2 se muestra el perfil longitudinal de la línea a partir de las cotas de sus diferentes estaciones y apeaderos.

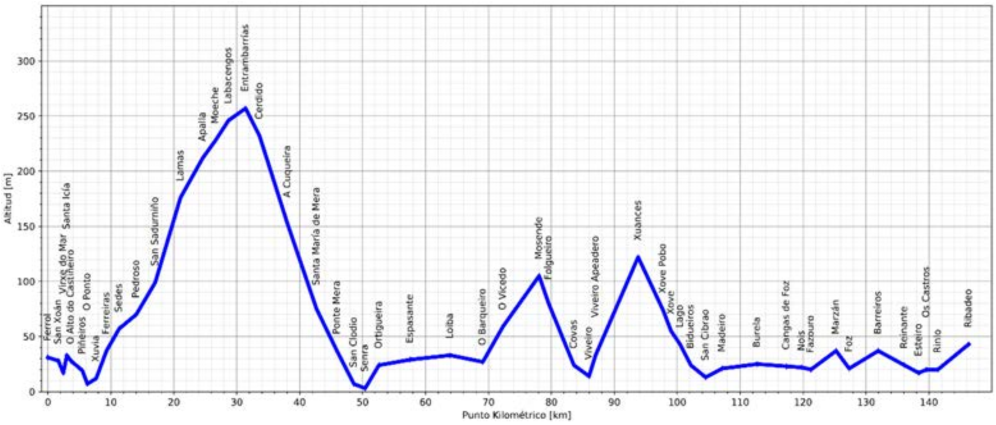

Figura 2. Perfil transversal aproximado de la línea Ferrol – Ribadeo.

Como puede apreciarse en la citada figura, el perfil se quiebra en los pasos de ría a ría, que lo hacen más difícil desde el punto de vista de la tracción:

- **Paso de la ría de Ferrol a la de Ortigueira.** En el ascenso desde Xuvia, la línea se pliega a la falda de los montes do Castro, la Pereiruga, Pedroso, O Pico, Moimentos, As Fervenzas, A Chousa, A Croa, Rapadoiro, Pousadoiro y Outeiro, hasta alcanzar el apeadero de Entrambarrías. Desde dicho punto, comienza el descenso hacia la ensenada de Mera, en la ría de Ortigueira, con un lazo inicial sobre el rego do Loureiro, y siguiendo a media ladera, paralelo al cauce del río Mera. Es la zona donde la línea tiene las mayores rampas características (20 milésimas), tanto en la zona Ferrol – Entrambarrías, como cuando se asciende desde Ortigueira hacia dicho apeadero.

- **Paso de la ría de O Barqueiro a la de Viveiro**, a través de O Vicedo, Mosende y Folgueiro.

- **Paso de la ría de Viveiro a la de Lieiro (San Cibrao)**, pasando por Xuances, Xove, Lago y Bidueiros.

En el primer caso, el trazado sigue una hipotética línea recta entre Ferrol y Ortigueira. Se trata de una zona de orografía irregular, caracterizado por las estribaciones montañosas de la sierra de la Faladoira. Con respecto a los dos últimos casos se deben a que el trazado sigue la línea de costa. En su desarrollo, encuentra las estribaciones de la cordillera Cantábrica, que llega con sus crestas a la costa, formando entre ellas valles que al entrar en el mar forman rías. La línea debe superar estas crestas para llegar a los puertos que albergan las rías.

Este trazado, tan ajustado a la orografía de terreno, obliga al empleo de curvas de radio reducido, que limitan la velocidad de circulación como se verá en el siguiente epígrafe.

2.1.4 Velocidades máximas

En la figura 3 se indican los valores de las velocidades máximas de circulación que se pueden alcanzar en esta línea.

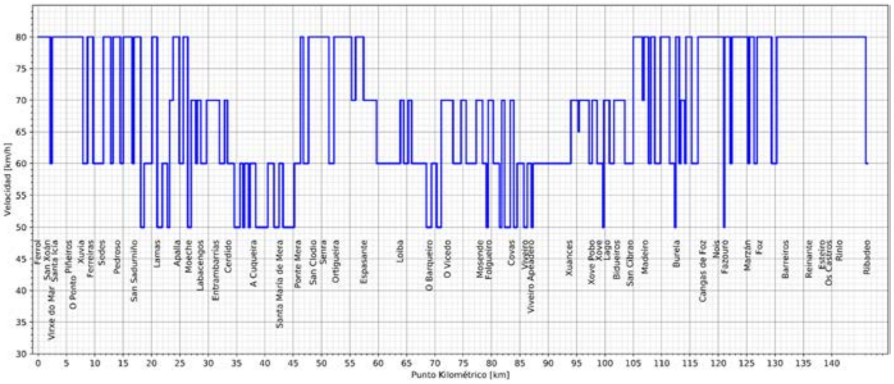

Figura 3. Velocidades máximas en la línea Ferrol - Ribadeo para trenes tipo N ($a_{csc} \leq$ 0,65 m/s^2).

Se puede apreciar cómo en cada tramo, aunque tenga un valor de la velocidad máxima común (por ejemplo, 80 km/h), existen múltiples zonas en las que es preciso reducir dicha velocidad (a 60 o 50 km/h). No es infrecuente que, aunque dichas zonas tengan una longitud relativamente reducida, la marcha de los trenes se vea afectada por dichas limitaciones.

2.1.5 Longitud máxima de los trenes

En la tabla 3 se presentan las longitudes máximas de los trenes, tanto de viajeros como de mercancías, admitidas en esta línea, de acuerdo con lo que indica la *«Declaración sobre la Red 2021»* de *Adif*. En ambos casos, se incluye la longitud máxima especial, para cuya utilización es necesario solicitar autorización expresa a la *Dirección de Gestión de Capacidad de la Dirección General de Circulación y Gestión de Capacidad* para los trenes Regulares u Ocasionales y a la *Dirección de Tráfico (H24)* para los trenes inmediatos.

Tipo de tren	Tramo	Parámetro	Valor [m]
Viajeros	Ferrol – Ribadeo	Longitud máxima básica	36
		Longitud máxima especial	250
Mercancías	Ferrol – San Sadurniño	Longitud máxima básica	160
		Longitud máxima Especial	290
	San Sadurniño – Ribadeo	Longitud máxima básica	200
		Longitud máxima especial	380

Tabla 3. Longitud máxima de los trenes en el tramo Ferrol – Ribadeo. (Administrador de Infraestructuras Ferroviarias 2021).

Al respecto de estos datos, cabe destacar dos ideas:

- Como puede comprobarse en la tabla 3, las longitudes básica y especial de los trenes de mercancías es ligeramente inferior en la sección Ferrol – San Sadurniño que en la comprendida entre San Sadurniño y Ribadeo. Parece razonable que la longitud máxima de los trenes fuera la misma en ambas secciones, al objeto de no limitar la capacidad de transporte de los trenes en la primera (por ejemplo, procedentes del puerto de Ferrol).

- La longitud máxima básica y especial de los trenes de mercancías en la sección Ribadeo – Pravia es, respectivamente, de 250 y 360 m. También en este caso parece que sería deseable que dichas longitudes fueran las mismas a lo largo de toda la línea Ferrol – Gijón, aunque habría que analizar con un detalle que excede el alcance de este documento, entre otras cuestiones, las capacidades de tracción de *Renfe Operadora* en dicha línea y la demanda de tráfico de mercancías existente y futura.

2.1.6 Sistemas de seguridad

De acuerdo con el documento *«Declaración sobre la Red 2021»* de *Adif*, el bloqueo de los trenes desde Ferrol a Cudillero se realiza mediante bloqueo telefónico (BT).

Desde el año 1997, la línea Ferrol – Gijón tiene operativo el sistema ASFA (Anuncio de Señales y Frenado Automático) analógico.

El Real Decreto 1513/2018, de 28 de diciembre, por el que se modifica la disposición transitoria única del Real Decreto 664/2015, de 17 de julio, por el que se aprueba el Reglamento de Circulación Ferroviaria, establece que:

> *«A partir del 1 de enero de 2019 en las líneas de ancho ibérico y estándar europeo y del 1 de julio de 2021 en la red de ancho métrico no se admitirá la circulación de trenes con el sistema ASFA analógico, debiendo sustituirse los equipos embarcados con dicho sistema por otros con el sistema ASFA digital».*

2.1.7 Estaciones y apeaderos

En la tabla 4 se muestran las estaciones y apeaderos que se sitúan a lo largo de la línea Ferrol – Gijón, en la parte de Galicia.

Denominación		Tipo	Situación [PK]
A Coruña	Ferrol	Estación	0,00
	San Xoán	Apeadero	1,65
	Virxe do Mar	Apeadero	2,44
	Santa Icía	Apeadero	3,00

	O Alto do Castiñeiro	Apeadero	3,65
	Piñeiros	Apeadero	5,47
	O Ponto	Apeadero	6,26
	Xuvia	Estación	7,66
	Ferreiras	Apeadero	9,30
	Sedes	Apeadero	11,30
	Pedroso de Narón	Apeadero	14,03
	San Sadurniño	Estación	17,04
	Lamas	Apeadero	21,06
	Apalla	Apeadero	24,60
	Moeche	Apeadero	26,63
	Labacengos	Apeadero	28,69
	Entrambarrías	Apeadero	31,40
	Cerdido	Estación	33,62
	A Cuqueira	Apeadero	38,08
	Santa María de Mera	Apeadero	42,68
	Ponte Mera	Apeadero	45,92
	San Clodio	Apeadero	48,62
	Senra	Apeadero	50,40
	Ortigueira	Estación	52,59
	Espasante	Apeadero	57,56
	Loiba	Apeadero	63,91
	O Barqueiro	Apeadero	69,10
Lugo	O Vicedo	Apeadero	72,30
	Mosende	Apeadero	78,05
	Folgueiro	Apeadero	79,56
	Covas	Apeadero	83,58
	Viveiro	Estación	85,98
	Viveiro Apeadero	Apeadero	87,02
	Xuances	Apeadero	93,78
	Xove Pobo	Apeadero	97,74
	Xove	Estación	99,02
	Lago	Apeadero	100,44
	Bidueiros	Apeadero	102,16
	San Cibrao	Apeadero	104,51
	Madeiro	Apeadero	107,15
	Burela	Estación	112,71
	Cangas de Foz	Apeadero	117,35
	Nois	Apeadero	119,77
	Fazouro	Apeadero	121,24
	Marzán	Apeadero	125,24

	Foz	Apeadero	127,32
	Barreiros	Apeadero	131,94
	Reinante	Apeadero	136,09
	Esteiro	Apeadero	138,38
	Os Castros	Apeadero	139,60
	Rinlo	Apeadero	141,43
	Ribadeo	Estación	146,31

Tabla 4. Estaciones y apeaderos de la línea Ferrol – Ribadeo.

Puede parecer que este elevado número de paradas conlleve una notable accesibilidad de los servicios ferroviarios sobre el territorio. Sin embargo, con frecuencia estas instalaciones se encuentran relativamente alejadas del núcleo principal de población, hecho que en ocasiones se agrava como consecuencia del estado de los accesos a las mismas.

3. SERVICIOS OFERTADO

3.1 Viajeros

En la actualidad, sobre la línea Ferrol – Ribadeo – Gijón circulan servicios de la entidad pública empresarial *Renfe Operadora*, tras la desaparición de *Feve* en aplicación del Real Decreto-Ley 22/2012, de 20 de julio, por el que se adoptan medidas en materia de infraestructuras y servicios ferroviarios.

Estos servicios, como otros prestados en la red de ancho métrico, fueron declarados obligaciones de servicio público (OSP) mediante Acuerdo de Consejo de Ministros de 28 de diciembre de 2012, por el que se declararon las obligaciones de servicio público del transporte ferroviario de viajeros de *“Media distancia”*. Esta declaración se realizó en cumplimiento del Real Decreto Ley 22/2012 antes citado, de tal forma que *Renfe Operadora* continuaba prestando, entre otros, los servicios ferroviarios de transporte de viajeros sobre la red de ancho métrico que en ese momento se venían prestando.

Es preciso destacar que en la línea Ferrol – Gijón se prestan los únicos servicios ferroviarios de cercanías que se ofrecen actualmente en Galicia. Se trata de los servicios Ferrol – Ortigueira, identificados como la línea C-1f.

La tabla 5 resume la oferta de trenes de viajeros establecida entre Ferrol, Ribadeo y Oviedo (se presenta la situación de la oferta en 2019, antes de la afección a la misma por la pandemia de la COVID-19).

Serv./día	Día	Origen	Destino	Horario	Observaciones
17 (8)	L-V (S-D)	Ferrol	Xuvia	7.25 --- 21.20 (8.20 --- 21.20)	13 (4) Serv. Cercanías L-V (S-D)
17 (8)	L-V (S-D)	Xuvia	Ferrol	7.39 --- 22.01 (8.20 --- 21.20)	13 (4) Serv. Cercanías L-V (S-D)
8 (5)	L-V (S-D)	Ferrol	Ortigueira	8.20 --- 20.05 (8.20 --- 19.05)	4 (1) Serv. Cercanías L-V (S-D)
8 (5)	L-V (S-D)	Ortigueira	Ferrol	6.35 --- 20.28 (8.43 --- 20.28)	4 (1) Serv. Cercanías L-V (S-D)
4	L - D	Ferrol	Ribadeo	8.20, 10.45, 15.30, 19.05	
4	L - D	Ribadeo	Ferrol	6.55, 11.34, 15.00, 18.40	
2	L - D	Ferrol	Oviedo	8.20, 15.30	
2	L - D	Oviedo	Ferrol	7.30, 14.30	

Tabla 5. Servicios ofrecidos en la línea Ferrol – Ribadeo (Oviedo), en 2019.

Los elementos básicos que configuran la oferta de servicios ferroviarios en la línea, desde un punto de desplazamiento regional e interregional, se presentan en la tabla 6. Además, en la tabla 7 se compara la oferta de transporte público que se realiza por ferrocarril y carretera en relaciones de ámbito provincial o regional.

Tipo servicio	Tiempo	$V_{comercial}$	Precio
Cercanías Ferrol – Xuvia	12 min	39 km/h	1,65 €
Cercanías Ferrol – Ortigueira	1 h 16 min	42 km/h	3,15 €
Ferrol – Ribadeo	3 h 5 min	47 km/h	11,15 €
Ferrol – Oviedo	7 h 11 min	43 km/h	24,10 €

Tabla 6. Características de los servicios ferroviarios que se prestan en la línea Ferrol – Ribadeo (Oviedo). Tiempos correspondientes al mejor servicio en cada tipo. Precios billete sencillo (2019).

Modo	Ser./día	Longitud	Paradas	Tiempo	$V_{comercial}$	Precio
Ferrol → Ortigueira						
Ferrocarril	8 (5)	52,6 km	23 (0)	1 h 16 min	42 km/h	3,15 €
Autobús	3 (1)	55,1 km		58 min	57 km/h	5,20 €
Automóvil		55,1 km		1 h 2 min	53 km/h	
Viveiro → Ribadeo						
Ferrocarril	4 (4)	60,3 km	21 (9)	1 h 7 min	54 km/h	4,75 €
Autobús	8 (2)	59,6 km	19	1 h 38 min	36 km/h	4,65 €
Automóvil		59,6 km		1 h	60 km/h	
Ferrol → Ribadeo						
Ferrocarril	4	146,3 km	51 (13)	3 h 5 min	47 km/h	11,15 €
Autobús*	3	149 km		3 h 30 min	43 km/h	13,45 €
Auto por autovía		131 km		1 h 23 min	94 km/h	
Auto por carretera		149 km		2 h 36 min	57 km/h	
Ferrol → Oviedo						
Ferrocarril	2	310,3 km	90 (35)	7 h 11 min	43 km/h	24,10 €
Autobús**	1	355 km	12	5 h 45 min	62 km/h	33,60 €
Auto por autovía		262 km		2 h 36 min	101 km/h	
Auto por carretera		283 km		5 h 5 min	56 km/h	

Tabla 7. Comparación de la oferta de transporte público por ferrocarril y carretera en el corredor Ferrol – Ribadeo (Oviedo), en 2019.

Tiempos correspondientes al mejor servicio. Precios tarifa general. Servicios diarios en día laborable. En FC, Se indican paradas totales (de ellas, el número de discrecionales entre paréntesis). En autobús, los servicios con estación – estación.

* Autobús con transbordo en Viveiro: Ferrol → Viveiro → Ribadeo

**Autobús con transbordo en A Coruña: Ferrol → A Coruña → Vilalba → Ribadeo → Oviedo.

Resultados automóvil procedentes de Google Maps.

Con los datos expuestos en las citadas tablas, cabe realizar las siguientes observaciones:

a) **Servicios de cercanías:** Entre Ferrol y Ortigueira se realiza una oferta de servicios ferroviarios con mayor número de expediciones y a un precio más reducido que la que se efectúa mediante autobús. En un recorrido de algo más de 50 km, los servicios ferroviarios realizan 23 paradas, lo que favorece su accesibilidad, aunque sea a costa de dilatar los tiempos de viaje.

   A pesar de la potencial accesibilidad de estos servicios debido a sus múltiples paradas, debe destacarse el hecho ya mencionado de que la ubicación de numerosos apeaderos, alejados de los núcleos principales de población, y/o su acceso, no facilitan el uso del ferrocarril. Este comentario es extensivo a otras secciones de la línea.

b) **Servicios de ámbito comarcal o provincial:** Entre Viveiro y Ribadeo la oferta que se efectúa a través del ferrocarril presenta características muy similares a la que se realiza con autobús. En esta relación concreta, la tarifa general es 10 céntimos más cara en tren, es decir, un 2%; o el número de paradas por ferrocarril (21, de las cuales 9 son discrecionales) es parecido al que realizan los servicios de autobús (19). Los servicios ferroviarios tienen un tiempo de viaje más reducido. No obstante, en días laborables se ofrecen en autobús el doble de expediciones que por ferrocarril, ocurriendo justamente al contrario en días no laborables.

c) **Servicios regionales:** Si se considera, por ejemplo, el servicio Ferrol – Ribadeo, la oferta realizada por ferrocarril presenta la notable ventaja de ser única, ya que este recorrido no es posible llevarlo a cabo en autobús si no es realizando transbordo con los servicios de otra empresa en Viveiro. Este hecho, aparte de la desfavorable percepción que tiene por parte de los potenciales usuarios, también origina un tiempo de viaje mayor en autobús, al tener que considerar el tiempo de espera entre un servicio y el siguiente en la estación de autobuses. Desde un punto de vista de servicio ferroviario regional típico, tienen un número mayor de paradas (en este servicio concreto, 51, de las cuales 13 son discrecionales). Ello se traduce en una mayor accesibilidad territorial de los servicios ferroviarios, si bien a costa de un notable incremento de los tiempos de viaje.

d) **Servicios interregionales:** Tal vez el más característico que se desarrolla sobre esta línea sea el que une Ferrol y Oviedo. Sorprenden las numerosísimas paradas que realiza (90, de las cuales 35 son discrecionales), muy por encima de las esperables en este tipo de servicios. A título de ejemplo, Pyrgidis indica que en servicios interurbanos convencionales normalmente se produce una parada del orden de cada 75 km (Pyrgidis 2016). Este hecho perjudica los tiempos de viaje, en este caso, si cabe, de forma más acentuada. De hecho, parece que el tren desarrolla un servicio de proximidad extendido a lo largo de la línea Ferrol – Oviedo.

3.2 Mercancías

En la tabla 8 se detallan los trenes de mercancías que habitualmente circulaban por la línea Ferrol – Gijón en 2019.

Mercancía	Operador	Origen	Destino	Última circulación
Aluminio	Renfe Operadora	Xove	Ariz	En servicio
Madera	Renfe Operadora	Xove	Ariz	En servicio
Madera	Renfe Operadora	Xove	Ariz [→ Lasarte-Empalme]	2019
Contenedores	Renfe Operadora	Ferrol	Ariz	Desconocida
Madera	Renfe Operadora	Cerdido	Aranguren	Desconocida
Madera	Renfe Operadora	Cerdido	Barreda	Desconocida
Madera	Renfe Operadora	Cerdido	Lasarte-Empalme	Desconocida
Madera	Renfe Operadora	Xuvia	Navia	Desconocida
Varilla	Renfe Operadora	Xove	Burtzeña (Lutxana)	Desconocida

Tabla 8. Trenes de mercancías en la línea Ferrol - Ribadeo.

Con respecto a los servicios de mercancías de *FEVE*, cabe apuntar que no constituyendo un gran número de expediciones, sin embargo se trata de servicios rentables, al tratarse del transporte de grandes masas (aluminio, madera, acero en diferentes formas, etc.) a distancias relativamente grandes (por ejemplo, entre Galicia y el País Vasco).

3.3 Utilización de los servicios ferroviarios de viajeros

Resulta muy difícil hallar información publicada sobre la evolución de los viajeros que han utilizado los servicios ferroviarios ofrecidos hasta 2012 por *FEVE* y, especialmente, a partir de dicho año, por *Renfe Operadora*. Por esta razón, para algunos años no ha sido posible conseguir el número de viajeros que utilizan determinados servicios ferroviarios de ancho métrico.

Esta dificultad se ha incrementado en los últimos años, toda vez que con la desaparición de *FEVE* también desaparece su Informe Anual, un documento en el que podía seguirse la evolución de numerosas variables de la Empresa (entre ellas, los viajeros transportados). Los informes económicos y de actividad de *Renfe Operadora* no contemplan el suficiente nivel de desagregación de la información para poder obtener los datos antes citados.

Por otra parte, la reducción del personal de intervención en los trenes y la ausencia de cerramiento en las estaciones, al objeto de llevar a cabo la cancelación de los billetes mediante máquinas automáticas, ha originado en estos últimos años (según las denuncias de sindicatos, colectivos de usuarios, etc.), un incremento del número de viajeros que utilizan estos servicios de transporte sin billete y que, por lo tanto, no aparecen reflejados en los resultados de explotación.

En la figura 4 se muestra la evolución del número de viajeros que utilizan los servicios de cercanías entre Ferrol y Ortigueira, junto con su tendencia (calculada mediante el ajuste de los datos con que se cuenta mediante regresión lineal. El área sombreada representa el intervalo de confianza al 95%).

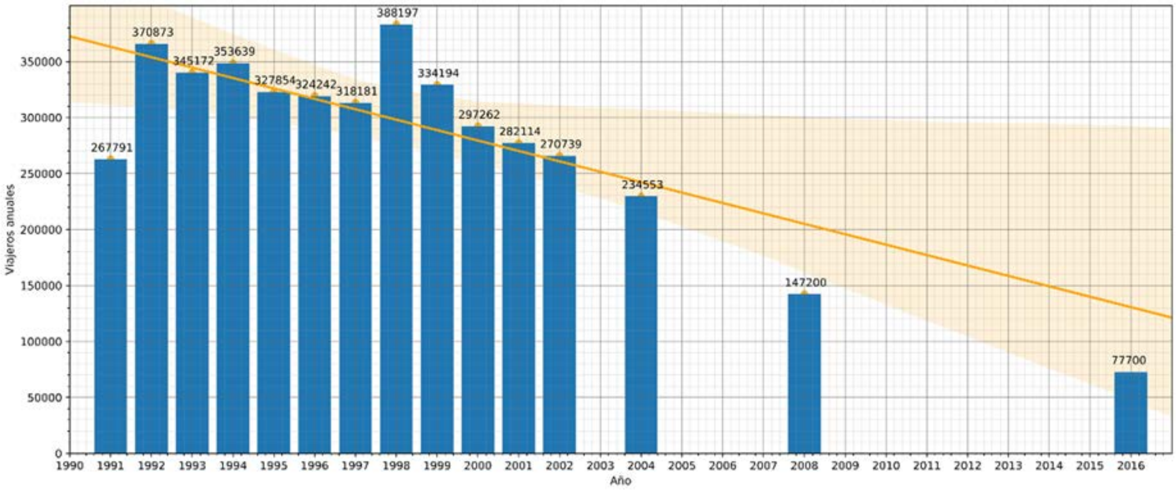

Figura 4. Evolución del número de viajeros anuales de Feve / Renfe Operadora, en servicios de cercanías entre Ferrol y Ortigueira.

En la figura 5 se presenta la evolución del número de viajeros que utilizan los servicios regionales en el corredor Ferrol – Ribadeo.

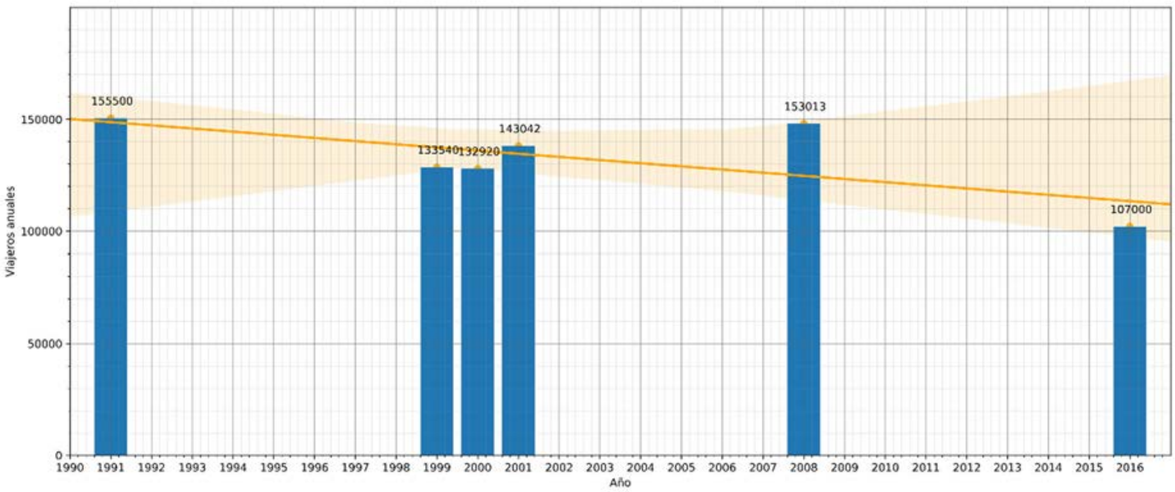

Figura 5. Evolución del número de viajeros anuales de Feve/Renfe Operadora, en servicios regionales entre Ferrol y Ribadeo.

Finalmente, en la tabla 9 se muestra el movimiento de viajeros en las estaciones del tramo Ferrol - Ortigueira en los años 2000 y 2001. Aunque se trata de datos que no se corresponden, en cuanto a su volumen, con la realidad actual, parece interesante reflejarlos en este documento para comprobar que del orden del 70% de los usuarios de los servicios de vía métrica en Galicia utilizaban la relación Ferrol – Ortigueira. En dicha relación, aproximadamente el 85% de los viajeros se movían entre las estaciones del tramo Ferrol – Xuvia.

Estación	Salidas		Llegadas		Total movimiento		
	2000	2001	2000	2001	2000	2001	% variación
Ferrol	131.104	125.792	141.607	135.246	272.711	261.038	-4,28
Santa lcía	25.082	22.829	21.483	19.601	46.565	42.430	-8,88
Virxe do Mar	9.657	9.343	8.533	8.390	18.190	17.733	-2,51
Piñeiros	30.576	26.802	26.621	23.675	57.197	50.477	-11,75
O Ponto	10.093	8.720	8.682	7.837	18.775	16.557	-11,81
Xuvia	34.313	30.536	33.110	28.976	67.423	59.512	-11,73
Ferrerías	3.666	3.613	3.644	3.359	7.310	6.972	-4,62
Sedes	4.629	4.322	4.311	4.112	8.940	8.434	-5,66
Pedroso	28.328	30.310	28.420	30.612	56.748	60.922	7,36
San Sadurniño	4.972	5.625	5.118	5.656	10.090	11.281	11,80
Lamas	1.092	1.236	1.066	1.177	2.158	2.413	11,82
Apalla	488	432	434	360	922	792	-14,10
Moeche	1.243	1.017	1.487	1.301	2.730	2.318	-15,09
Labacengos	2.221	1.817	2.376	1.865	4.597	3.682	-19,90
Entrambarrias	215	281	234	296	449	577	28,51
Cerdido	4.602	4.042	4.579	3.893	9.181	7.935	-13,57
Cuqueira	501	482	454	443	955	925	-3,14
Santa María	642	681	543	619	1.185	1.300	9,70
Ponte Mera	2.202	2.130	2.494	2.767	4.696	4.897	4,28
San Clodio	1.708	1.692	1.299	1.506	3.007	3.198	6,35
Senra	408	448	348	305	756	753	-0,40
Ortigueira	12.096	13.209	12.617	13.360	24.713	26.569	7,51
Total	**277.448**	**262.267**	**276.411**	**261.808**	**553.859**	**524.075**	**-5,38**

Tabla 9. Movimiento de viajeros en las estaciones entre Ferrol y Ortigueira durante los años 2000 y 2001.(Meixide Vecino y otros 2007)

4. LA MODERNIZACIÓN DE LA LÍNEA

Como ha podido verse en los párrafos anteriores, las características de la línea Ferrol – Ribadeo impiden ofrecer servicios ferroviarios competitivos. Por esta razón, parece lógico plantear una modernización de la línea.

A pesar de la lógica de este planteamiento, debe señalarse que las líneas de *FEVE* quedaron fuera del *Plan de Transporte Ferroviario* (1987). En el *Plan Director de Infraestructuras* (1993) las actuaciones a desarrollar se centraron en mejorar la oferta de cercanías. Será precisamente la mejora de los servicios de cercanías (que, como se ha visto, representaban en Galicia la mayor parte de los viajeros transportados), lo que justificó la introducción de la propuesta de duplicación de la vía entre Ferrol y Xubia dentro de las actuaciones del *Plan de Infraestructuras* (2000), duplicación que finalmente no se llevó a cabo.

Con el *Plan Galicia* (2003), se planteó la construcción de una línea de Alta Velocidad del Cantábrico, que se mantuvo tanto en el *Plan Estratégico de infraestructuras y Transporte* (2005) como en el *Plan de Infraestructuras, Transporte y Vivienda* (2012).

Las dificultades de llevar a cabo tal proyecto, condujeron a que *Feve* explorase en el 2009 la posibilidad de adaptar el trazado de la línea Ferrol – Gijón – Santander para velocidades máximas de 160 km/h, con material móvil de cajas inclinables. El coste estimado de las actuaciones a desarrollar fue lo suficientemente elevado como para que no se tomase en consideración esta alternativa por el momento.

5. ELEMENTOS PARA UN DIAGNÓSTICO

De acuerdo con un informe realizado en 2009, en el marco del *National Transport Master Plan 2050* de la República de Sudáfrica (Rail Working Group 2009), el 16,6% de la longitud de las líneas ferroviarias que existen en el mundo son de vía estrecha (anchos de vía entre 914 y 1.067 mm), mientras que el ancho estándar (1.435 mm) está implantado en el 60,2% de la red ferroviaria mundial. Los anchos mayores (de 1.520 a 1.676 mm) están implantados en el 23,2%.

España cuenta con la red de vía estrecha más extensa de Europa, superando las de Suiza o Italia. Esta red no es homogénea. Frente a las subredes que, por ejemplo, se extienden por Cataluña, la Comunidad Valenciana o el País Vasco, las líneas que se desarrollan en la España septentrional (la línea Ferrol – Bilbao y la que une La Robla/León con Valmaseda) conectan municipios con baja densidad de población. Excepto las capitales de provincia y sus cercanías (Santander y Asturias), cuya densidad de población supera los 500 hab/km^2, los municipios conectados por ambas líneas tienen entre 10 y 100 hab/km^2 (Morillas-Torné 2014).

Esta baja densidad de población hace muy difícil justificar una explotación ferroviaria orientada al transporte de viajeros. De hecho, la línea La Robla/León – Valmaseda se construyó con la finalidad de transportar el carbón de las minas de León a las industrias de Vizcaya. Sin embargo, en el caso de la línea Ferrol – Gijón no existía tal justificación, como se ha visto. Esta insuficiente demanda potencial ya se puso de manifiesto antes de que se concluyeran las obras, tal y como señala un informe de la empresa *SOFRERAIL* (*Société*

Francaise d'Etudes et de Réalisations Ferroviaries) encargado en 1963 por la Comisaría del Plan de Desarrollo Español (Gómez Martínez 2005):

> *"Los resultados muy desfavorables obtenidos para las perspectivas de explotación de la línea Ferrol-Gijón inducen a recomendar el abandono inmediato y definitivo de las obras en la sección central Ortigueira - Luarca en donde no se han comenzado aún ningún trabajo de superestructura. La prosecución de la explotación en las secciones extremas Ferrol - Ortigueira y Luarca - Avilés debería ser objeto de un estudio especial, a emprender desde ahora dentro del marco general de las líneas de tráfico reducido y de la coordinación de los transportes y según los métodos recomendados en el estudio hecho por SOFRERAIL por cuenta de la RENFE. Sin esperar los resultados de dicho estudio, se deberían estudiar y aplicar medidas de simplificación de la explotación en estas secciones".*

Esta situación se vio además agravada por una falta de inversiones que permitieran mejorar ciertos servicios (por ejemplo, entre ciudades). En la modernización del Ferrocarril en España, que se inicia con el *Plan de Transporte Ferroviario* (1987), las inversiones que *Feve* precisaba quedaron fuera del mismo, tal y como su presidente, Martínez-Vilanova, reconocía en una entrevista (Muñoz Rubio 2005):

> *«… un problema muy importante durante estos años. De cara al exterior, en las discusiones presupuestarias ha constituido una limitación – diría incluso que una posición de debilidad – el que se negociara las cantidades destinadas a FEVE fuera de las ya comprometidas por el PTF».*

Debe además subrayarse que esta situación fue sensiblemente diferente en las redes de vía estrecha que pasaron a ser de competencia autonómica, en las que se realizaron inversiones, incluso en líneas de débil tráfico (Llevat i Vallespinosa 1996).

La extinción de *FEVE* al finalizar 2012 y la asunción de la gestión por parte de *Adif* y *Renfe Operadora*, unida a la situación que arrastraba la operación ferroviaria, tuvo un efecto imprevisto: la explotación de los servicios que, de forma más o menos precaria, se había ido manteniendo, empezó a tener problemas de regularidad por averías del material móvil y la práctica inexistencia de unidades para poder reemplazar a las averiadas. A pesar de que la situación ha ido mejorando y *Renfe Operadora* ha sacado a concurso la adquisición de nuevo material móvil, no deja de ser una nueva advertencia acerca de la precaria salud de los servicios ferroviarios de vía métrica prestados en la línea Ferrol - Gijón y del incierto futuro de esta línea, tal y como se conoce en la actualidad.

6. LA NECESIDAD DE ACTUAR

La situación que ha alcanzado la red ferroviaria de vía métrica y, en particular, la línea Ferrol – Gijón, requiere actuaciones. Por esta razón, debería redactarse y poner en marcha un plan que permita actualizar esta red y sus servicios.

No debe olvidarse que, como ya en 1979 afirmaba Moseley (Moseley 1979):

> *"El transporte rural representa la sangre que da vida a las comunidades rurales. Tiene un papel vital en el acceso al trabajo y a los servicios."*

Satisfacer la necesidad de transporte público en el ámbito rural siempre ha sido un arduo objetivo. La densidad de población es baja y, como consecuencia, la demanda de transporte también suele ser baja. En general, las soluciones convencionales de transporte público no son capaces de atender este tipo de demandas de una forma eficiente. Los ferrocarriles rurales son particularmente ineficaces en este aspecto, si bien con frecuencia son apreciados por los residentes frente a otras alternativas de transporte (Utsunomiya 2018).

Si se analiza el problema en términos meramente económicos, el cierre de algunas líneas o tramos podría parecer inevitable, ya que la inversión necesaria para mejorar los servicios en estas líneas no se justificaría, al ser demasiado alto en comparación con la reducida demanda.

Debe recordarse aquí la frase de John Stuart Mill, "*Ningún problema económico tiene una solución puramente económica*". Por ello, parece razonable que, sin eludir ninguna posibilidad, la toma de decisiones sobre estas líneas se base en un modelo que contemple diferentes criterios, no únicamente las pérdidas anuales, y que debería responder a preguntas como qué servicios se mantienen, cómo deben configurarse, qué mejoras requiere la infraestructura para poder ofrecer dichos servicios, etc.

Si ello es posible, resulta especialmente útil establecer previamente un estándar para seleccionar, en cada caso, el modo de transporte más adecuado para satisfacer una determinada demanda de transporte (Kurosaki y Alexandersson 2018).

La tecnología sigue ofreciendo soluciones para reducir los costes de mantenimiento de la infraestructura ferroviaria (Bugarín, Novales, y Orro 2004; Muramoto 2017), así como el desarrollo de vehículos ferroviarios mejor adaptados a estas condiciones de operación tan particulares. Todo ello debería contribuir a un descenso de los costes, reduciendo el saldo negativo de explotación.

Finalmente, en párrafos anteriores se han mencionado las redes de vía estrecha de Suiza e Italia. Son dos realidades, entre otras, de las que pueden obtenerse interesantes experiencias. En esta línea, cabe señalar también los cambios recientes que se han producido en el sistema de ferrocarriles locales de Japón (Utsunomiya 2016). Entre ellos, debe destacarse la puesta en marcha de servicios turísticos, cuya expansión está ayudando a compensar la disminución de la demanda en desplazamientos cotidianos. Además, estos servicios turísticos, que se difunden entre los visitantes extranjeros, ayudan a la promoción de productos locales, como el pescado fresco, verduras o productos elaborados de forma artesanal, colaborando en la revitalización de la economía de las comunidades locales.

Por otra parte, en el marco de la lucha contra la despoblación rural, se están definiendo planes maestros para la red de transporte público local, con el fin de revitalizar el transporte público y la sociedad locales. Con este tipo de medidas, desde 2013 no se ha cerrado ninguna línea de ferrocarril en Japón.

Se trata de algunas referencias que se presentan como ejemplo, que en todo caso requerirán de un estudio pormenorizado para analizar hasta qué punto son factibles y eficaces en el caso concreto de la red de vía métrica de Galicia.

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TOWARDS THE NUMERICAL GROUND-BORNE VIBRATIONS PREDICTIVE MODELS AS A DESIGN TOOL FOR RAILWAY LINES: A STARTING POINT

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ABSTRACT

In recent decades, High-Speed Railway (HSR) lines have become one of the most extended and environmental-friendly ways to plan new mass transport networks. These systems are directly influenced by its operational speed generated dynamic effects and the areas where it runs through. This necessarily requires to predict ground-borne vibrations generated by trains passing-by populated areas and its influence zone.

Trends in ground-borne measurements, prediction models, and isolation systems are usually performed for maximum operation speed. This method implies the maximum dynamic forces which are suitable for structural calculations (generally developed in time domain) but not necessary for vibration related issues (emission and/or transmission). Additionally, these studies are mainly focused on urban areas where maximum operational speed are frequently far from railways service's top speeds.

Related to frequency domain, it is known that upper frequencies are not the most disturbing ones. In fact, European structural standards usually cut frequencies off at 30 Hz, so much relevant information for vibrational prediction is ignored due to it does not influence structural issues.

Moreover, current common predictive numerical models usually apply punctual loads (birth & death) that are disposed to run in certain speed conditions. This method, which is considered valid for time domain analysis, are identified to be incomplete for frequency domain components due to its discontinuous application of loads.

The implementation of contact theories in the wheel-rail interface implies a continuous load application, refining the obtained results but increasing computational cost.

In this study, different scenarios are compared varying inner and boundary conditions of a model, with the aim of validate results and optimize resources by obtaining a parametrical influence study that will show how different assumptions and cases could condition ground-borne vibrational studies results.

1. INTRODUCTION

1.1 Ground-borne vibrations generated by railways. State of the Art.

It is known that railways running along the track produces important vibrations -noise & vibration Pollution- not only in the track but its surroundings, as well as air-borne and structural noise. Assuming the common ‘noise & vibration’ binomial, it is capital to note that two different concepts are then considered.

Regarding the air-borne noise, so many consolidated and standardized methods are sufficiently defined in order to guaranty its measurement and/or prediction models. However, vibrational measurement or prediction modelling is not as standardized due its inner complex phenomena, because its transmission is made along non-homogeneous materials -ground and soils- which is definitely more difficult to analyse or mitigate.

Some particular characteristics about railway related vibrations are:

- Short term events

- Intermittent and repeated sequences due to bogies and axles passing-by. Frequency spectra variable depending on operational issues.
- Moving forces applied
- Non-linear events
- Conditioned by:
    - Track typology -slab or ballasted tracks-
    - Subgrade typology -earthworks, structures, tunnel-
    - Soil characterization
    - Track grade of maintenance

Vibrations are initially generated by wheel–rail contact, subsequently this wave propagates through track components, subgrade and soils to surrounding buildings. Vibrations effects are basically originated by:

- Rolling stock moving loads (quasi-static) and produced deformations
- Wheel and/or Rail unevenness effect
- Punctual track defects
- Axles passing-by effect
- Other track components effect

Aforementioned, one of the major needs for vibrations prediction is to accurately define the transmission media between the source and the receptor. Following image shows common way of generated vibration. As could be seen there, once vibrations are running along soil, any kind of discontinuity as layers or punctual issues, must affect the wave transmission and subsequently, the immission results.

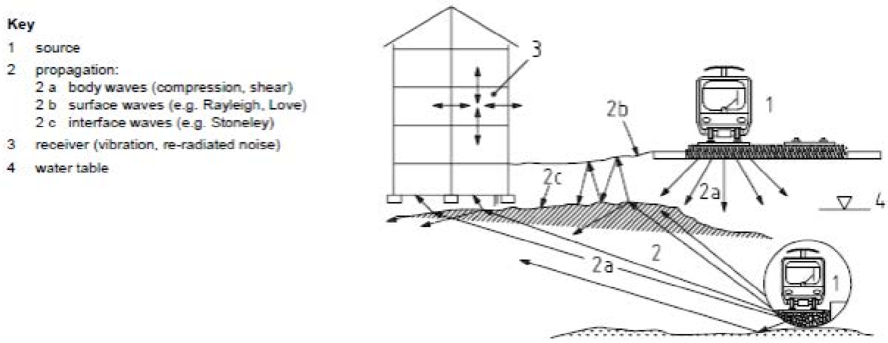
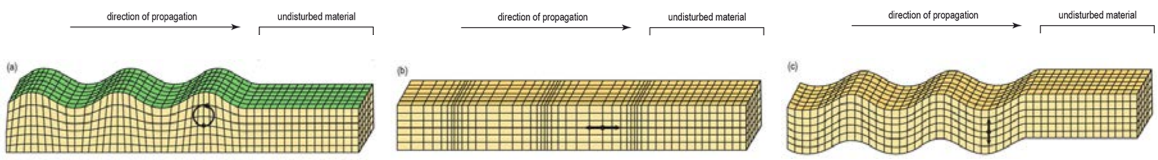


Figure 1. Generation, transmission and immission scheme. Source: ISO 14837-1:2005 Standard

Additionale, each transmitted wave along the soil is mainly divided into three typologies, a) Surface waves, b) P-Waves and c) S-Waves. The following Table shows the main ones and its shape:



a) b) c)

Figure 2. Rayleigh, P & S waves. Source: http://www.kgs.ku.edu/Publications/PIC/pic37.html

Additionally, other capital parameter to completely analyse how these waves moves and its possible attenuation, is to study not only Time domain but Frequency domain.

- Geometrical attenuation: reduction produced by the distance between the source and the measure point. It is not related to frequency domain.
- Material typology attenuation: reduction produced by traversed materials properties. This is directly related to frequency response.

It is important to note that, nowadays, this kind of vibration phenomena is not sufficiently known or modelled due to a non-possible media total characterization.

Vibrational energy arises in structures from its foundations and is distributed througthout it as structural noise and vibrations. In fact, it is common to use empirical formulations.

1.2 Effect of vibrations on humans

With the aim of developing a regulating standard for railway vibrations, structural issues and its influence over humans should be studied. It is capital to analyse possible harmful effects.

Firstly, with the aim of determining the most annoying situations, not only time domain must be done, but a deep frequency domain study must be realized to obtain enough information to evaluate its consequences.
Secondly, one of the most used concepts to analyse frequency domain and ponder it, is the Root Mean Square acceleration -RMS- weighting, that penalizes the identified most harmful frequencies for humans.

Then, due to the wide range of perceptible frequencies, it is not possible to analyse it one by one, thereby it is necessary to agglutinate the spectrum in bands -1/3 octave bands-. Moreover, this bands could be ranged from 1 to 250 Hz for human’s perception .

Finally, based on scientific literature and experience, some reference values are the following:

- Generally, the natural frequency of the most common structures is between 5 and 30 Hz.
- The most annoying frequencies for humans are under 8 Hz.
- Although railways-related vibrations do not show a clear and defined spectrum, maximum energy peaks are generally between 40 and 80 Hz.

2. VIBRATIONAL PREDICTION STUDIES

When carrying out vibrational prediction studies or measurements some stages should be completed before starting works to reach a proper characterization of the existing situation. Previous background and the applicable standards should be determined depending on the location. This process will determine affections and/or existing limit values.

Otherwise, a structural evaluation along the surroundings of the track must be done to identify possible affections. Note that some variances could appear when analysing possible environment affection depending on applicable standard values.

In order to obtain reference values, it is necessary to obtain the existing vibrational values by at-field measuring. Every possible existing source such as surrounding tracks, roads, industrial facilities, and others will be considered.
Once the base plane is fully characterised, a future scenario modelling and prediction is started. With the aim of optimizing time scale and computational cost, a two-step sequence is generally performed:

1. First approach. Analytical models are used to reach some initial rough numbers of vibrational conditions. This kind of modelling does not need important computational resources or time to make a first approach for fencing possible structural affections.
2. Numerical modelling. With the aim of considering the most reliable prediction by modelling existing subgrade, soil or surrounding structures, a numerical specific model is developed.

Finally, some possible necessary solutions for attenuation would be tested to select the optimized system for each detected case. The following list shows presented process:

1. Background and applicable standards
2. Obtain Reference Values
3. Potential affections pre-analysis
4. Future situation analytical modelling
5. First modelling results and initial affections proposal
6. Ad-Hoc soil and structures characterization
7. Detailed numerical modelling
8. Results study and affections refinement
9. Corrective and absorption solutions where necessary are proposed

3. EXISTING STANDARDS

Only European ISO recommendations or guidelines are standardized, so each country and/or region apply its own standard.

Most extended Methods are generally related to a called *K* parameter, which was regulated by ISO 2631-2 (1989). Note that this parameter was deleted in the most recent versions of the standard.

4. MODERN PREDICTIVE MODELS

Due to recent consciousness about these vibrational issues and the increase of operational speeds with High-Speed Railways, deeper studies are necessary to predict future possible effects.

Consequently, vibrational predictive models come up as a tool to simulate railways passing-by and the vibration phenomena generated, and identify possible planification not only for new lines but for track maintenance or renewal.

In recent times, different models arose with this aim. These models are commonly subdivided into independent submodels that are finally interrelated. As represented in Figure 3, three different models are involved in the process: Vehicle model, Subgrade model and surrounding structures model (in case of existing).

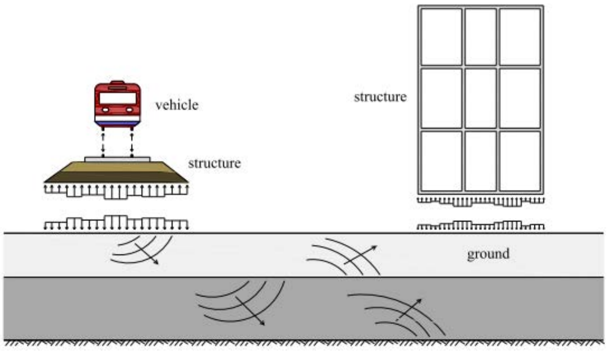


Figure 3. Submodels pipeline to complete a prediction model (Correia dos Santos et al., 2017)

4.1 Vehicle Modelling

For rolling stock modelling, the 'Quarter-car' model is the most extended. It is a Discrete Elements formulation to compose the vehicle model as shown in Figure 4.

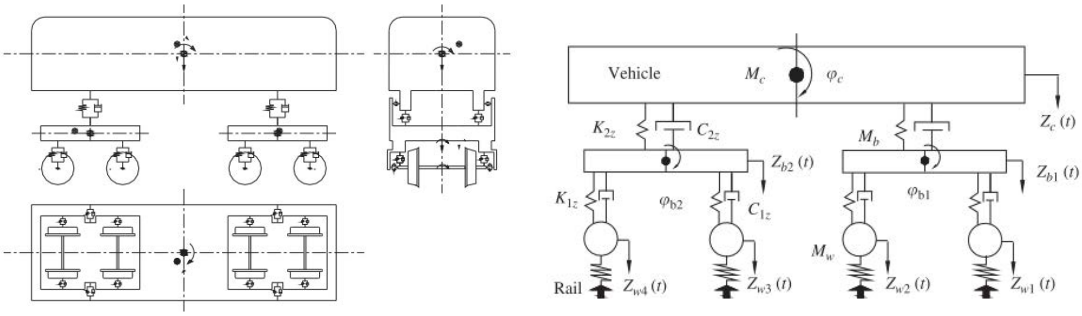


Figure 4.- Comparison between vehicle -left- and its mechanical model -right- (Xin & Gao, 2011)

These representations assume each element of rolling stock as vehicle car mass, suspended mass, unsprung mass, axles or bogies distribution.

4.2 Subgrade Modelling

Regarding track and terrain modelling, two main trends are generally developed depending on the analysis stage or needed accurate. These typologies are the analytical ones and the numerical ones.

4.2.1 Analytical Models

Analytical models (Koziol et al., 2008; Metrikine & Vrouwenvelder, 2000; Salvador et al., 2011) solve the wave equation for a 2-Dimension terrain and assuming viscoelastic layers and linear behavior soils.

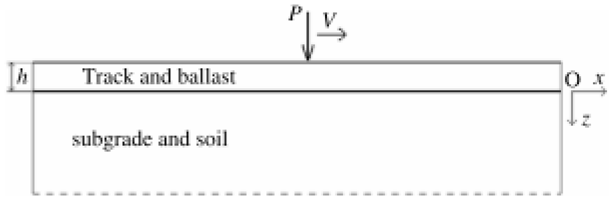


Figure 5.- Diagram for the track & soil model (Salvador et al., 2011)

These kinds of models are also able to consider the static load of the rolling stock and its harmonic without needing high computational resources or processing time.

In contrast, these models are severely limited to be considered a reliable tool to make accurate predictions to be used for planning new infrastructures because they are not able to model non-linear scenarios and punctual situations.

It could be concluded that the use of Analytical models is advisable for a vibrational first approach, initials pre-dimensioning, and/or relative comparisons between comparable track systems due to many analyses could be done in a short-term period.

4.2.2 Numerical Models

Numerical models are based in Finite Elements Method (FEM) and/or Boundary Elements Method (BEM) (Dijckmans et al., 2014; François et al., 2014; Galvín & Domínguez, 2007; Galvín & Romero, 2014; Gupta et al., 2006; Lombaert & Degrande, 2009; Romero et al., 2010, 2013), that provide precise time-domain track responses and their surroundings for accurate future planning predictions, assuming a 3-Dimension model.

Numerical models are feed through track elements geometry & materials specific properties as well as soil layers and environmental elements. These mentioned models mainly subdivided into the rolling stock FEM model and the track & soil BEM model. FEM-BEM coupling is made by Hertzian contact by applying an extra component of rail unevenness.

Usage of BEM reaches several computational savings respect FEM models by avoiding internal mesh points when calculating, and time-domain results are consciously validated by on-site measurements.

In contrast, it is necessary to note that the coupling of models is made by a discontinuous loads time-domain sequence to represent the train movement (loads birth-death process). Figure 6 shows how loads are modelled as punctual at each point depending on time. This discrete loading method commonly ballast the obtained Frequency-domain results due to the instant change of situations.

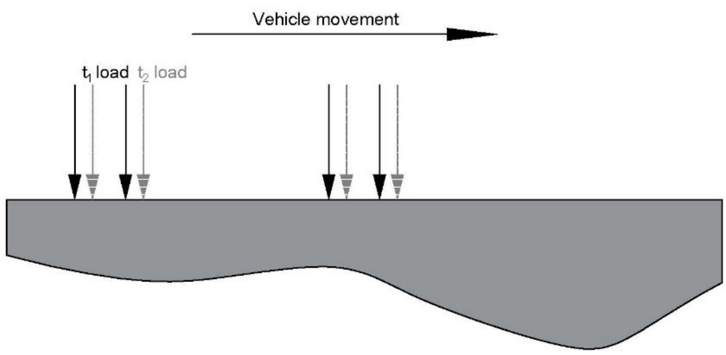


Figure 6. Common practice of numerical model's vehicle loads representation (own elaboration)

5. CONCLUSIONS

Prediction models are nowadays positioning as the elemental tool in railway networks planification and operation. These elements are able to clarify the track surroundings influence of vibrations generated by trains passing-by and also to evaluate possible means to absorb and attenuate these vibrations.

Regarding numerical models' possible future research, there is much work to do, because there are no common standards in the EU or different countries that clearly characterize this necessary process.

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USING DATA ANALYTICS & MACHINE LEARNING TO DESIGN BUSINESS INTERRUPTION INSURANCE PRODUCTS FOR RAIL FREIGHT OPERATORS

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ABSTRACT

This paper discusses a case study in which publicly available data of a rail freight transportation firm has been gathered, cleansed, and analyzed in order to: (*i*) describe the data using statistical indicators and graphs; (*ii*) identify patterns regarding several Key

Performance Indicators; (*iii*) obtain forecasts on the future evolution of these indicators; and (*iv*) use the identified patterns and the generated forecasts to propose customized insurance products that reflect the current and future freight transportation activity. The paper illustrates the different methodological steps required during the extraction and cleansing of the data --which required the development of Python scripts--, the use of time series analysis for obtaining reliable forecasts, and the use of machine learning models for designing customized insurance coverage from the identified patterns and predicted values.

1. INTRODUCTION

Data has become an essential element for the operational development and economic growth of many organizations throughout the world. As organizations across the world reach a level of economic abundance, their capacity to efficiently and effectively manage data has become a matter for concern (Parr-Rud, 2012). As a result, organizations from all industries and fields, and those which contribute to an emerging economy are welcoming innovative solutions and methods for managing their volumes of data. For instance, organizations from the railroad freight transportation sector in the United States (U.S.) have experienced substantial data growth throughout the years. This valuable information can be used for identifying factors which can prevent an organization from reaching and maintaining economic growth. According to Samson and Previs (1999), the first train freight transport service contracted in the U.S. took place in 1827. Shipments of cargo were less frequent, and hence, the volume of standard goods being transported were minimal during this period. As a result, risks and incidents that occurred during transportation were minimal. On the other hand, train freight carrier services extend beyond transporting standard items and commodities. Train freight carriers have also committed to cautiously and effectively transport dangerous goods (DG) and hazardous materials (HAZMAT) which are essential for world economies. These materials are employed for powering vehicles, homes, and businesses, and for producing pharmaceuticals, sterilizers, disinfectants, fertilizers, and pesticides. In addition, these highly demanded items require cautious and effective handling and containment. Moreover, train freight carriers have encountered unforeseen challenges during transportation of standard items, DG, and HAZMAT. Increased risks of accidents, loss of goods, and adverse environmental consequences have been the most significant challenges. Therefore, sustaining risks awareness initiatives by assessing and anticipating risks which could occur during train shipments could prepare freight carriers for these unforeseen events. For this reason, the design of Business Interruption Insurance products for protecting the train freight industry from unforeseen circumstances and calamities is imperative.

The proposed insurance product or mechanism would parametrically pay (i.e., based on the collected data over time) when the actual performance falls below the agreed performance thresholds with respect to an established forecast. This type of mechanism would obviate the need to conduct any type of claim or forensic analysis and therefore permit the insured to recover without delay and without the peril of legal disputes.

Substantial data growth which is attributed to the railroad freight transportation sector implies that there is a high demand for the services provided by railroad freight operators.

Therefore, such organizations can profit from the abundance of valuable information extracted from databases by using data analytics not only for examining data, but also for attempting to identify patterns and for forecasting future events. In consideration of the foregoing, this paper will address the use of data analytics and machine learning methods for designing Business Interruption Insurance Products. As a result, data from a U.S. public train freight transportation organization has been extracted and analyzed by employing statistics and graphs. In addition, forecasts were processed for identifying patterns regarding key performance indicators (KPIs), and for supporting the design of business interruption insurance products aimed at safeguarding losses during train freight transportation.

Currently, data analytic methods could be considered the most efficient and effective solution for managing data (Ji and Wang, 2017). In the same manner, machine learning has contributed to the optimization of data analytic methods.

In order to create new knowledge and accomplish the goal of this study, the development of a forecasting model based on historical data that establishes the baseline performance of the freight business at the time of underwriting the policy is proposed. The predicted performance would then be compared with current performance developments.

The presented forecast method could be used for supporting the devising of customized parametric insurance policies that trigger a payout once verifiable conditions aimed at safeguarding losses during train freight transportation are satisfied. These policies could be devised by stipulating a payout that considers the real transported goods against expected transported goods over a certain period of time. In this manner, the policy would behave as a compensation for aggregate drops rather than as a payout for a momentary drop in transported cargo at a particular point in time.

The Methodology illustrates data extraction and cleansing based on the development of Python scripts, and consists of descriptive and predictive data analytics. Subsequently, time series analysis for forecasts on the evolution of these indicators have been provided, which together with previous results, are used with machine learning models for proposing customized insurance products based on identified patterns and predictive values, and for reflecting the current and future freight transportation activity. Subsequent to the Introduction, this paper is arranged as follows: Section 2: Literature Review presents a synopsis of related topics; Section 3: Problem Definition describes the problem contextualization; Section 4: Methodology introduces the tools and methodology for gathering and analyzing the data; Section 5: Results and Discussion provides a data and forecasting analysis of the future; and to conclude, Section 6: Conclusions and Further

Developments highlights the main conclusions of this investigation and proposes future research guidance.

2. LITERATURE REVIEW

The freight transportation industry continuously encounters risks such as loss of cargo due to business interruptions. Addressing these risks has posed challenges in carrying out logistics processes. Risk management has existed for decades and has been essential for logistics processes and systems. When transportation companies are faced with cargo losses, the consequences directly affect the cargo owners. For this reason, companies acquire cargo insurance that provides protection and entitlement to monetary compensation (Wu et al. 2017). Business interruptions affect both the insurance sector and global industries (Mizgier et al. 2018), forcing insurance companies to replace their business models with those that meet financial obligations as a result of an accident (Ganapathy, 2017).

However, few studies have focused on business interruption insurance although it has significant optimization and digitization potential through the use of big data and data analytics (Dong and Tomlin, 2012; Ganapathy, 2017). This literature review presents an overview of existing work on business interruption insurance and data analytics for the freight transportation industry.

According to Gagatsi et al. (2014), the devising of transportation insurance policies is an intricate process requiring extraordinary diligence from all stakeholders and affected economic sectors. Moreover, business interruption insurance products protect against losses incurred during company operational interruptions as a result of unexpected events occurring within their own sites or the suppliers' facilities. Business interruption insurance products are devised to include clauses describing explicit coverage limitations that define three crucial elements: (*i*) the premium which represents the price paid by the interested company for obtaining insurance coverage; (*ii*) the coverage limit which represents the maximum amount paid by the insurer in case of a loss; and (*iii*) the deductible which represents the monetary value of the loss absorbed by the insured company. Prior to establishing prices for customized business interruption insurance products, insurance providers must access the facilities of prospective insurance holders for assessing possible loss values (Dong and Tomlin, 2012).

Keller et al. (2018) have reported that data analytics has played a fundamental role in insurance policies allowing them to evolve from "intuitive bets" on the future to an industry based on logic calculus and decision making. They also considered that recent advances in big data analytics, artificial intelligence, and the internet of things promise to transform the role of data by understanding risks and protecting insurance product holders by providing compensation for incurred losses. According to Frees (2015), "insurance is a data-driven industry" which is linked to data and models of uncertainty. Insurance is also of a random nature, given by the very concept of payment, compensation, risks, as well as their grouping and dispersion. Understanding its benefits leads to the relationship of all factors involved giving rise to stochastic models that have correlations for measuring dependencies between random outcomes. A statistical data analysis pioneer who aimed at investigating the distribution of business interruption products was Zajdenweber (1996) from the French

Insurance Syndicate. Zajdenweber (1996) analyzed the consequences of Pareto's alpha exponent law when the tail was close to one on the actuarial risk. Pareto's law asserts that 80% of outputs results from 20% of all inputs. This implies that premium calculations for 100% insurance coverage require an uppermost limit corresponding to the highest potential loss. He also concluded that the insurer and reinsurers' financial stability requires funds for coping with annual fluctuations and unforeseen events. Dong and Tomlin (2012) explored the relationship between business interruption products and operational measures such as inventory and emergency sourcing as strategies for managing business disruption risks.

Moreover, an endogenous insurance pricing model was used for providing reliable insurance coverage and for supporting operational decisions. The results highlighted the importance of linking effective decision making and risk management practices into operational processes.

According to Frees (2015) description of the contributions of analytical and statistical methods for insurance market operations, analytical predictions are advanced data mining tools. Among the applied methodologies are the neural networks, the classification trees, and non-parametric regression statistical methods. An example of this is the methodology for calculating the Fuzzy net present value proposed by Neto et al. (2012). The net present value verifies the viability of purchasing a business interruptions insurance product for an offshore production unit. Moreover, it is the result of the discounted cash flow which gives rise to uncertainty with the available information. In Zurich, Switzerland, Mizgier et al. (2018) developed a collaborative project between Zurich Insurance and the Swiss Federal Institute of Technology. A large amount of data concerning business interruption claims from various data sources was extracted and analyzed. The results enabled Zurich Insurance to design and implement a relevant business interruption insurance service proposition for customers.

In the case of business interruption products for the freight transport industry, Zhen et al. (2016) proposed a model based on the work of Dong and Tomlin (2012). This model characterized the relationship between transport recovery and business interruption insurance when transport costs were uncertain and when transport recovery was deemed an endogenous factor. In the same manner, Li et al. (2018) developed a fine-grained transport insurance prototype based on blockchain and internet of things technologies. The insurance premium was evaluated on the basis of vehicle use and driver behavior. The insurance and payment model were implemented using an Ethereum framework by saving data from mobile sensors. Wang et al. (2018) contributed to the literature for the high-value transportation disruption including the value declared by the customer, the optimal insurance premium, and the strategy preference problem of the express logistics providers. Two types of contracts were developed, the additive and the multiplicative, which depend on actual probability of disruption where it is critical for the express logistics providers to be aware of the actual value of the load in order to maximize its profits. This proposal benefits both the transport company and the insured customers. In addition, studies have been based on data analysis that propose management improvements and support decision making in freight transport cases involving business interruption insurance. For example, Tatarinov and Kirsanov (2019) built an information support system aimed at managing the road transportation of dangerous goods based on a systematic approach that relies on guidance documents and that employs information and communication technologies for transmitting information from moving vehicles to duty vehicles. This system includes the load insurance during the transport by road organization stages. Wu et al. (2017) also addressed the management of logistics risks based on knowledge discovery in databases procedures with business analytics of descriptive, predictive, and prescriptive analysis to address load loss incidents. In relation to business interruption insurance, they conceived strategic cargo loss insurance policies where they used insurance company claim databases for not only preventing the financial losses caused by incidents, but also to avoid jeopardizing the company's competitiveness. Currently, investigative research on business interruption insurance and data analytics for the freight transportation industry remains limited and inadequate. Nonetheless, the insurance industry seems to be clear about the importance of integrating big data and data analytics into activities such as product development, portfolio analysis, underwriting operations, pricing, and loss and control. As insurers venture beyond the analysis of structured transaction data to incorporate external data of all kinds, the combination and analysis could be challenging (Breading and Garth, 2014).

3. PROBLEM DEFINITION

The case study in this research is a recognized train freight transportation company servicing the U.S. railroad industry. Its railways cover thousands of miles across the U.S. eastern contiguous territory. It operates up to 1,300 trains per day, and it transports some 6.5 million carloads of products per year. Moreover, HAZMAT constitutes 7.5% of the company's yearly cargo. As with all organizations, train freight transport has not been exempted from encountering challenges in the course of its organization's development. Train freight carriers that assess, anticipate, and are informed of the various risks which could occur during train shipments are less affected by unforeseen circumstances.

More recently the managing of emerging or accelerated data growth has become a trending concern. Train freight transport companies generate and store excessive volumes of data in their organization's internal database. Consequently, the data becomes valueless if it is not analyzed. However, by employing the analyzed railway transportation data through descriptive and predictive analytics, a forecasting model was developed. This forecasting model supports the devising of customized insurance policies by calculating the probability of transportation statistics deviation from the forecasting model. Had the railway operator and insurer accepted the customized model terms as a valid trading tool, this calculation could allow the insurer to stipulate a compensation amount if the forecasted drop materialized. This mechanism would allow the devising of parametric business interruption policies that compensate the railway operator if certain transportation KPIs deviate from expectations.

This descriptive and predictive data analytic model based on historical data will identify the patterns and will generate a forecast in order to define KPIs and thresholds. Therefore, the resulting information will support decision making strategies and present insights for devising customized business interruption insurance products. In addition, it will define the baseline performance at the time of signing the policy intended for minimizing losses occurred during train freight transportation and will protect the rail freight transportation industry from unforeseen circumstances and calamities.

4. METHODOLOGY

With the exponential growth of data from businesses, data analytic methods have been considered by experts as one of the most efficient and effective solutions for managing information (Ji and Wang, 2017). Recently, this process has been optimized by the use of machine learning algorithms that have contributed to the management of large amounts of valuable information. The machine learning algorithms are implemented for searching through a set of possible predictive models and for identifying the model that best captures the relationship between the descriptive traits and the objective feature of a data set (Kelleher et al. 2015).

Moreover, the objective of this investigation is to examine all past and current information derived from an active freight transportation company by employing a descriptive and predictive analytical methodology. With the examination results, customized insurance products that consider identified patterns and predictive values that reflect the current and future freight transportation activity could be proposed. This methodology is based on the development of Python scripts that perform data extraction, cleansing, and descriptive and predictive data analyses through data analytic techniques. Subsequently, machine learning methods will be applied for predicting the evolution of the gathered indicators.

4.1 Data Wrangling

The methodology starts with gathering and processing a large amount of raw data from the active freight transportation company which is publicly available online in a PDF format.

This process, referred to as *data wrangling*, consists of cleansing, structuring, and enriching raw data into a desired format for effective and prompt decision making (McKinney, 2012).

The following tasks were performed for generating the final structured data: (*i*) data gathering from the web; (*ii*) correction of typographical errors and standardizing product titles (also referred to as *metrics*); (*iii*) deletion of empty and duplicate entries; and (*iv*) categorizing and structuring the pre-processed data according to the metrics, weeks, and years. Subsequent to the gathering of data, the methodology approach will address performing a descriptive analysis and performing forecasts. Figure 1 presents an example of the resulting structured data gathered from previous steps. Notice that the data is categorized by metric, year, and week. For the year 2020, the gathered structured data was collected only up to the 38th week of the year and does not reflect the entire year.

```
                          Metric  Year   Value  Week
0                          Grain  2013    2672     1
1             Grain Mill Products  2013    2082     1
2        Farm Products, Ex. Grain  2013     255     1
3                   Food Products  2013    1674     1
4                       Chemicals  2013   10087     1
...                           ...   ...     ...   ...
10045              Total Carloads  2020   64783    38
10046                    Trailers  2020    2109    38
10047                  Containers  2020   57904    38
10048            Total Intermodal  2020   60013    38
10049               Total Traffic  2020  124796    38

[10050 rows x 4 columns]
```

Figure 1 – Structured data example.

4.2 Descriptive Analysis

Once the data was structured as presented in Figure 1, the descriptive analysis was initiated.

The exploration of the data was performed with data visualization techniques such as pie charts, bar charts, histograms, and time series charts. For this purpose, the methodology approach filtered the data according to the desired analysis to be performed. For example, the data was filtered by specific year(s) and/or by a specific number of weeks. However, only the first 38 weeks of the year 2020 were filtered in order to provide and perform approximate comparisons with other years within the same time period.

Subsequently, a series of statistical data analyses that included graphs and metrics were performed. Such analyses were used for extracting information that reveals the following criteria for each year: (*i*) the histogram of the total transported carloads for each product in 2019; (*ii*) the volume percentage of the 10 most transported carloads in 2019; (*iii*) the time series of transported carloads by product from 2013 to 2020; (*iv*) the mean volume of transported products per season (winter, spring, summer, and autumn of 2013 to 2020).

4.3 Predictive Analysis

The structured data was composed of a sequence of values representing each type of transported products from 2013 to 2020. As a result of the data having been categorized into weeks and years for each metric, this categorization resulted in a sequence of values over time, i.e., a time series forecasting. Given this particularity for making projections about future performance on the basis of the gathered historical and current data, i.e., the forecast, a predictive model was proposed by applying the Holt-Winters forecasting model (Chatfield and Yar, 1988), also known as the *triple exponential smoothing* for time series forecasting.

Another reason which supports the use of the Holt-Winters forecast modeling method refers to the fact that this data reveals trend and seasonality over an entire year of (52 weeks). As a result, the introduction of an additional parameter to handle seasonality is required

(Kalekar, 2004). When the model is trained with the historical data, the model becomes a machine learning method that uses previously transported volume values that support the designing of customized business interruption insurance products based on identified patterns and predictive values that protect the train freight industry form unforeseen circumstances and calamities.

Figure 2 summarizes the methodology steps beginning from the raw data extraction to its analysis and prediction of future events.

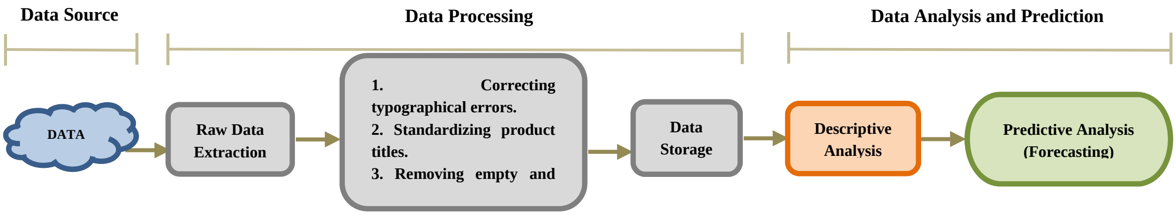


Figure 2 – Methodology Steps.

5. RESULTS AND DISCUSSION

This section provides a descriptive and predictive analysis of the train freight transportation data. In addition, a predictive model validation has been included. Moreover, this section will reveal the proposed customized insurance product functionality once all models are created. In accordance with the data structure, the following criteria was assessed for each year: (*i*) the total transported carloads for each product in 2019; (*ii*) the volume percentage of the 10 most transported carloads in 2019; (*iii*) the time series of transported carloads by product from 2013 to 2020; (*iv*) the mean volume of transported products per season (winter, spring, summer, and autumn) of 2013 to 2020; (*v*) the forecast for the year 2021, and (*vi*) the predictive model validation which included real data vs a forecast from 2019. Descriptive and predictive analytic methods were applied for completing this investigation. Furthermore, this analytical method involved monitoring data trends and patterns. The database representing the year 2019 was queried by employing a descriptive analytic method. The parsing process and descriptive analysis were developed using Python scripts.

5.1 Train Freight Transportation Descriptive Analytics

The descriptive analysis revealed the total transported carloads for each product in 2019 as depicted in Figure 3. According to the bar chart, the largest total volume carload was Coal with a total volume of 783,777 carloads. However, the least total volume carloads were Farm Products (excl. Grain) with a total volume of 9,514 carloads.

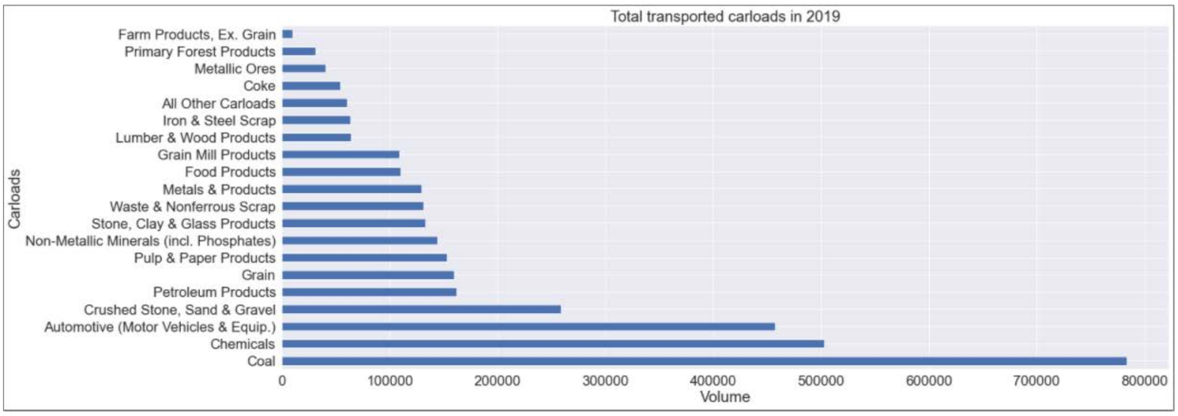


Figure 3 – Total transported carloads for each product in 2019.

Moreover, the 10 most transported carloads of 2019 are presented in Figure 4. Those carloads representing the most significant carloads were Coal with 27.1%, Chemicals with 17.4%, and Automotive (Motor Vehicles & Equipment) with 15.8%. The transport of Petroleum Products, Grain, Pulp & Paper Products, Non-metallic Minerals (Incl. Phosphates), Stone, Clay and Glass Products, and Waste and Nonferrous Scrap represented an approximate proportion of about 5% of the total.

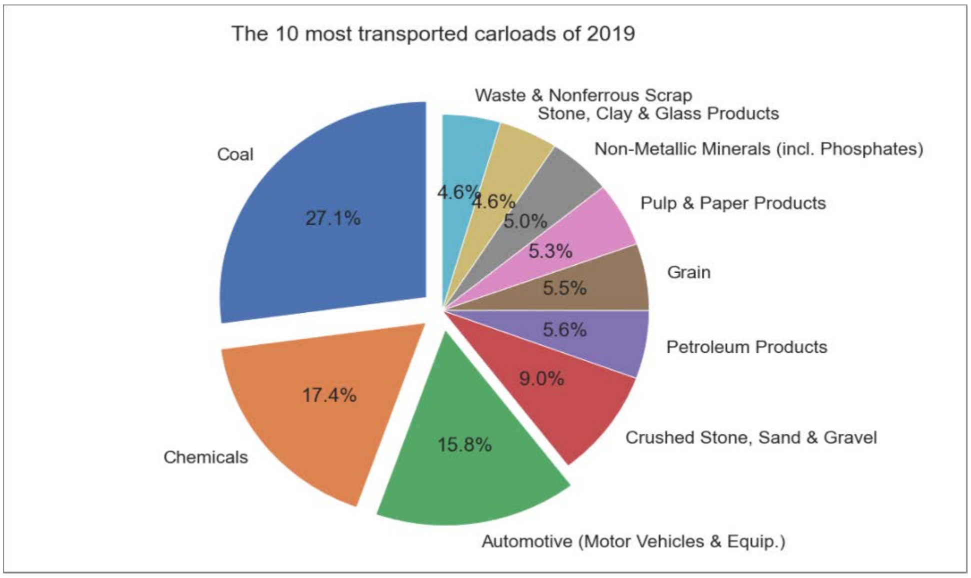


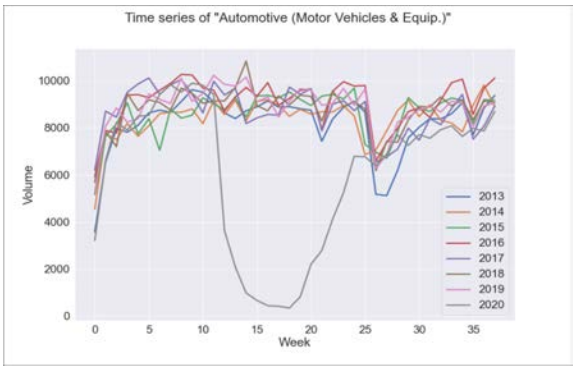
Figure 4 – Volume percentage of the 10 most transported carloads of 2019.

Figure 5 represents the weekly time series of four distinct transported carloads from 2013 to 2020: (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food

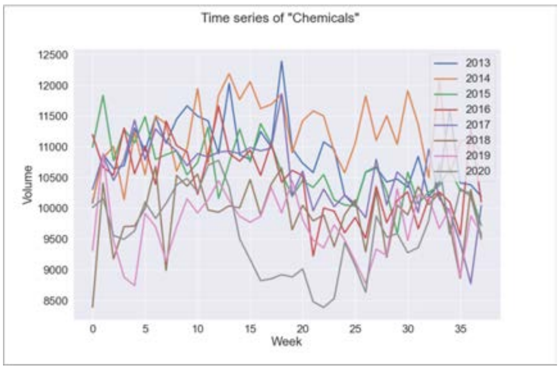
Products. The equivalent volumes of each carload per week provide a clear representation of the overall trend in the variability of each carload over the years. These graphs allow for a year-to-year behavior comparison for each week. For example, from 2013 to 2019, the Automotive (Motor Vehicles & Equipment) transported carloads maintained the same behavior week by week with approximately 2,000 units when compared to previous years. A similar trend can be observed for Food Products. Contrary to this, Coal volumes descended by almost 10,000 units in 2015. From then onward, volumes remained between 10,000 and 17,000 units until 2019. In the case of Chemicals, transported carload volumes had ascending and descending movements. During mid-2016, a decline in Chemical carloads became evident. Then in 2017, Chemical carloads began to ascend. However, during 2018 through the 38th week of 2020, Chemical carload volumes descended. Although the year 2019 collectively experienced the lowest Chemical carload activity when compared to other years, both 2017 and 2018 experienced the lowest Chemical carload points within a fractional period.

Moreover, the COVID-19 pandemic and its impact on carload volumes was also considered. The impact was more evident during week 10 of 2020. In particular, the Automotive (Motor Vehicles & Equipment), Chemicals, Coal and Food Products carloads were the most affected as a result of the COVID-19 preventive restrictions imposed by local governing authorities.

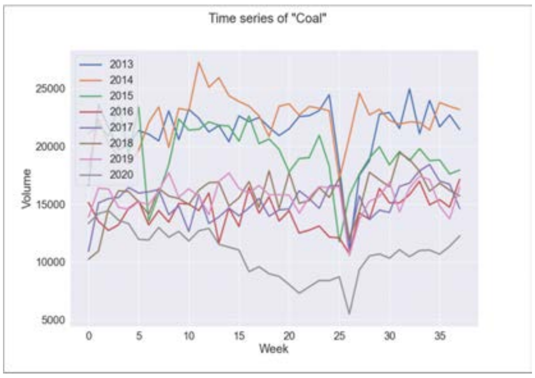
Despite the impact COVID-19 had on carload volumes, it can be observed that the need of Chemicals for producing sanitizers against COVID-19 resulted in a fast recovery for Chemicals' carload volumes. Furthermore, first necessity goods such Food Products carload volumes recovered faster than other transported goods.



(a) – Automotive (Motor Vehicles & Equip)



(b) – Chemicals



(c) – Coal

(d) – Food Products

Figure 5 – Time series of transported carloads from 2013 to 2020: (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food Products.

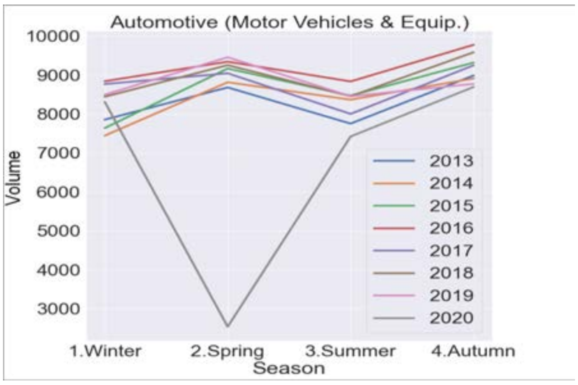
To complement the descriptive analysis, a seasonal analysis was completed. Figure 6 represents the volume of four distinct transported carloads per season (winter, spring, summer, and autumn) of 2013 to 2020 for (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food Products. The values for each season correspond to the "Mean" value of each carload. This compact structure generates a visualization of the year-by-year changes reflected in the columns. Figure 6 (a) illustrates a variability of 2,000 units between the 7,000 to 10,000 volume unit range for the Automotive (Motor Vehicles & Equipment) carload. This variability consists of comparable seasonal behavior where carload volumes increased during winter to spring and decreased during spring to summer.

The atypical behavior of transported carloads during spring of 2020 is exhibited in Figure 6 (*a*, *b*, *c*, and *d*). This atypical behavior resulted from the unexpected COVID-19 pandemic.

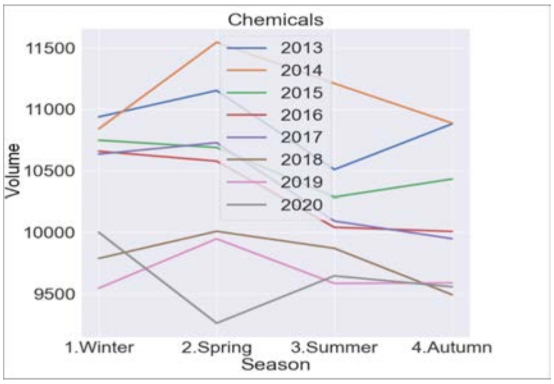
With the exception of 2020, spring was the season with the highest transported Food products carload volumes as illustrated in Figure 6 (*d*). Figure 6 (*a*, *b*, *c*, and *d*) illustrates the reactivation and recovery trend of the world economy following the COVID-19 pandemic. A similar carload volume recovery trend can be observed during autumn with the appearance of a second phase in some countries. The difference in volumes between the analyzed years remained stable since 2013 by approximately 350 units. On the other hand, Coal and Chemicals experienced greater carload volume variability from one year to the next as depicted in Figure 6 (*b*) and (*c*). Coal carload volumes for example remained at a high level from 2013 to 2015.

Although Coal carload volumes decreased between 2016 and 2017, carload volumes began ascending in 2018 and onward. This ascending behavior was particularly observed during spring of 2019 when Coal carload volumes reached its highest average volume throughout the analyzed years. Chemicals' carload volumes exhibited similar behavior in terms of year-to-year volume variability. Between 2015 and 2017,

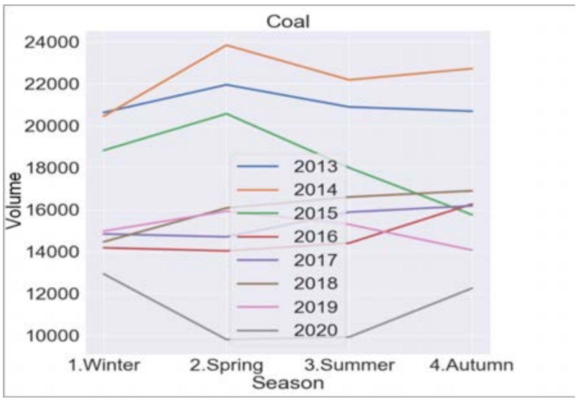
Chemicals' carload volumes followed a similar trend. A significant decrease in transported carload volumes was observed for the years 2018 and 2019. Figure 6 (*a*, *b*, *c*, and *d*) illustrates a significant decrease in transported volumes during the spring of 2020 due to the COVID-19 pandemic.



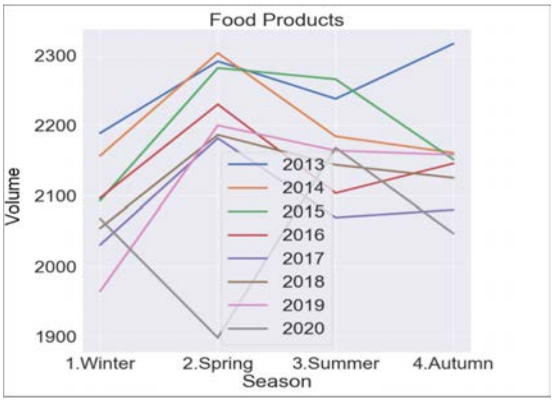
(a) – Automotive (Motor Vehicles & Equip)



(b) – Chemicals



(c) – Coal



(d) – Food Products

Figure 6 – Mean volume of transported carloads per season (winter, spring, summer, and autumn) of 2013 to 2020: (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food Products.

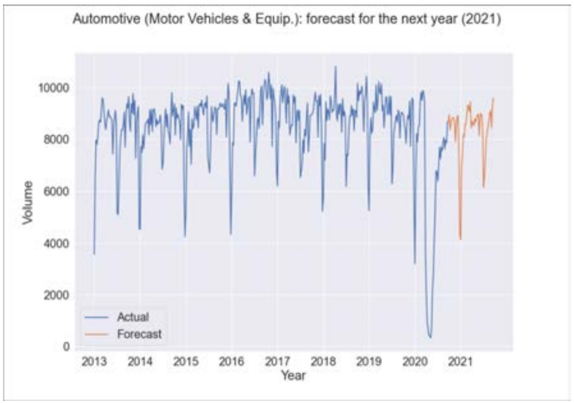
5.2 Train Freight Transportation Predictive Analytics

The Predictive analysis provided a transport carload volumes 2021 forecast for (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food Products. The forecast can be observed in Figure 7 (*a*, *b*, *c*, and *d*).

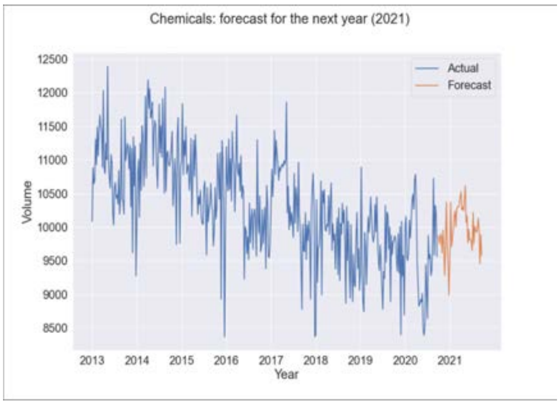
According to the one-year forecast, from week 38 of 2020 to week 38 of 2021, two significant decreases in transported carload volumes were anticipated in the Automotive (Motor Vehicles & Equipment) carloads. A decrease in transported carload volumes was expected towards the end of 2020. However, an increase in carload volumes was expected during the subsequent weeks. This increase of carload volumes is expected to maintain a stable flow until June 2021 when a decrease in carload volumes is anticipated. In the case of Chemicals, carload volumes were expected to remain stable during 2020. Then in 2021 onward, the carload volumes of Chemicals would begin an ascending trend. Chemicals' carload volumes similar to the previous year can be expected. In contrast, the transportation of Coal carload volumes descended since mid-2014. The forecast for Coal carload volumes anticipates a descending trend falling under carload volumes from the previous years.

In the case of Food Products, a comparable trend to Coal is anticipated, however, with less variability as has occurred during the previous years.

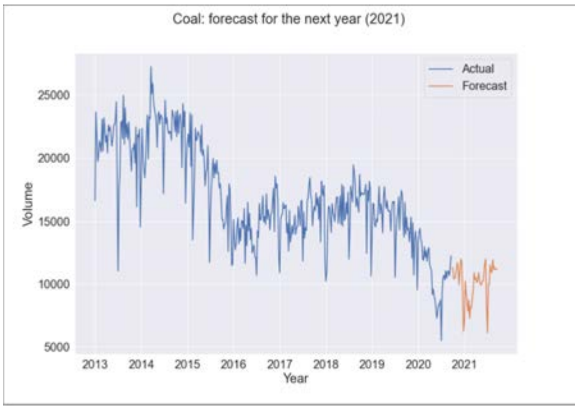
Moreover, a Predictive analysis could support decision-making by analyzing data patterns. As a result, business interruption insurance product thresholds can be set and defined with premiums established by the Insurer and the Insured in the event of exceeding thresholds.



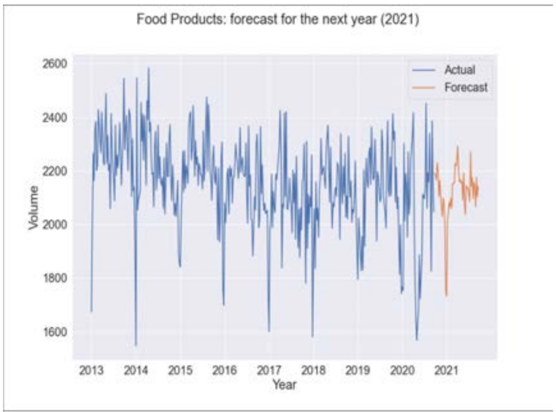
(a) – Automotive (Motor Vehicles & Equip)



(b) – Chemicals



(c) – Coal



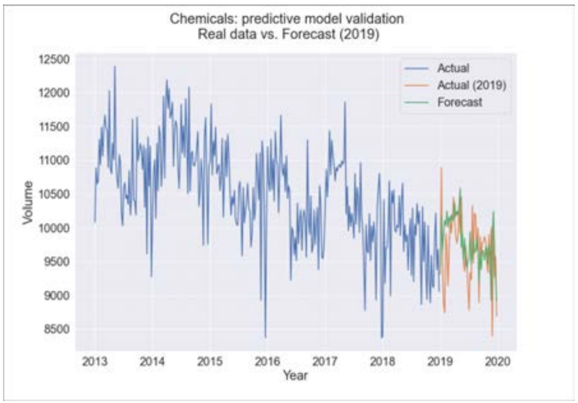
(d) – Food Products

Figure 7 – 2021 Forecast for (*a*) Automotive (Motor Vehicles & Equipment), (*b*) Chemicals, (*c*) Coal, and (*d*) Food Products.

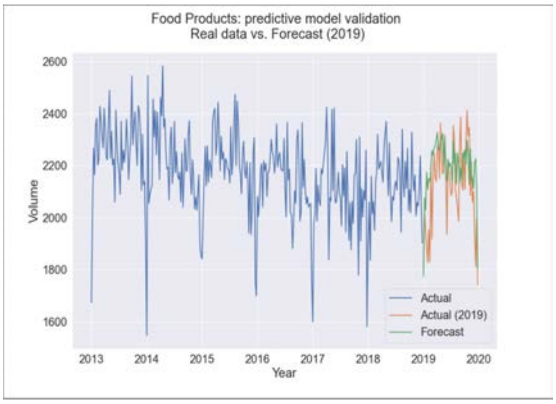
5.3 Predictive Analytics: Model Validation

The predictive model was validated with the cross-validation method which is a statistical method used for estimating the skills of machine learning models. The cross-validation method examined data from 2013 to 2019. The examined data was subsequently used as training data for this model. The validation data corresponds to the year 2019. Figure 8 (*a*) and (*b*) illustrates the predictive model validation for (*a*) Chemicals and (*b*) Food Products carloads, and compares Real Data with that of a 2019 Forecast. The comparison distinguishes actual 2019 data from predictive data that indicates what was expected to occur during 2019.

The predictive model graphs of both Chemicals and Food Products carloads exhibit the transported values for each period of the year. However, the predictive model graphs illustrate that during the first weeks of 2019, both Chemicals and Food Products carloads would have higher values than those actually obtained. Despite this difference, both the predictive model and the actual values indicate similar trends. In the second half of the year, the model values were closer to the actual values and accurately described the transported quantities of each product.



(a) – Chemicals



(b) – Food Products

Figure 8 – Predictive model validation: Real data vs. 2019 Forecast for (*a*) Chemicals and (*b*) Food Products.

Altogether, the values predicted by the model do not exactly match the actual values. In addition, as illustrated in Figure 8 (*a*) and (*b*), the model does not predict statistical data points or outliers which differ from the actual values such as volume increases and decreases.

Therefore, the validation revealed that predictive models based on the Holt-Winters forecasting method allow for predicting data behavior. Nevertheless, the model does not anticipate unexpected events. The model does however accurately predict behavior of values for each week.

5.4 Train Freight Transportation Customized Insurance Product

Once all models are created, the forecasting system will support the devising of customized insurance policies based on KPIs or metrics that trigger a compensation or payout upon satisfying the previously agreed conditions stipulated in the policies.

To understand how a customized insurance product works, the developments of the novel Coronavirus disease of 2019 or COVID-19 have been considered in this insurance policy "example". In December 2019, COVID-19 which is caused by the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) was detected. Nevertheless, it was not until March 2020 that COVID-19 was declared an official world pandemic. Assuming that prior to the COVID-19 outbreak, an insurance policy for the transportation of Automotive (Motor

Vehicle & Equip.) carloads stipulating coverage throughout the entire year of 2020 was devised and bound, and had been in effect noting the following condition:

- *Condition: The policy begins to pay once the transported carloads fall below a threshold of 7,000 carloads.*

Under this condition, will the railway operator receive a payout? As previously illustrated in Figure 5 (a), there was a significant decrease in the transport of Automotive (Motor Vehicle & Equip.) carloads in March 2020 when COVID-19 was officially declared a world pandemic and preventive measures were imposed. It is evident that throughout weeks 10 to 25, the carloads dropped below the 7,000 carloads threshold. In such an event, a payout would be triggered as it satisfies the condition. The insured or policyholder would receive the agreed compensation limit for business losses, approximated by the drop in cargo versus the expectations derived from the forecasting model. Such a policy mechanism, while applied to different cargo types, would offer the railway operator a statistical option for hedging potential business losses due to unexpected events. The fact that the forecasting model is fixed prior to the policy being devised and bound allows for both parties to agree on the algorithm as a feasible trading mechanism.

6. CONCLUSIONS AND FURTHER DEVELOPMENTS

As businesses emerge throughout the world, data has become an essential element in their operational development and their economic growth. In this study, a series of descriptive and predictive data analysis from an existing freight transportation company was performed for devising customized insurance products aimed at identifying existing data values and patterns, examining current data, and for predicting losses that could occur during freight transportation. In this regard, Python scripts for extracting and analyzing raw data were developed. In addition, machine learning strategies for predicting events that could result with losses were adopted.

The revealed information from the analyzed data was subsequently used for adopting resolutions and supporting decision making. Moreover, the data acquired from the 10 most transported carloads revealed informative discrepancies that could prevent businesses from reaching their operational and economical potential.

The employed analytical methods in this study facilitate the designing of customized business interruption insurance products for protecting businesses from losses resulting from unexpected events or disruptions such as the COVID-19 pandemic. For example, the data analysis performed for supporting this study revealed those carload volumes that decreased during transportation and those carload volumes that recovered during the developments of the COVID-19 pandemic. Furthermore, as world economies grow and business operations thrive, data analytics is emerging in a short period of time.

In an effort to protect businesses from sustaining financial losses as a result of unexpected events and disruptions, a daily data analysis rather than a weekly analysis could possibly improve the accuracy in predicting fluctuating data behavior. Data is knowledge, and with knowledge, businesses will be predisposed with the necessary criteria for predicting operational activities, making decisions, and for acquiring reliable insurance products.

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MONITORIZACIÓN Y ANÁLISIS DEL COMPORTAMIENTO DE APARATOS DE VÍA FRENTE A EVENTOS CLIMÁTICOS EXTREMOS

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RESUMEN

El cambio climático y el previsible aumento de los fenómenos climáticos extremos, tales como olas de calor o lluvias torrenciales, supone un gran desafío para la sociedad en su conjunto y para los medios de transporte en particular. El ferrocarril, cuya infraestructura se extiende por todo el territorio, debe afrontar dicho desafío y adaptarse a su entorno para mantener su sostenibilidad y fiabilidad en el futuro.

En este contexto, y como parte del proyecto de investigación MINFECLIMA (fruto de la colaboración entre AZVI, S.A.U. y SIER en el marco de una Convocatoria de Cooperación Internacional, con financiación del CDTI proveniente del Ministerio de Ciencia, Innovación y Universidades), se pretende monitorizar ciertos aparatos de vía especialmente críticos y vulnerables (como pueden ser desvíos o aparatos de dilatación) mediante sensores in situ, buscando un sistema sencillo que sea capaz de recopilar y transmitir datos regularmente. Entre otros, se pretende recoger información sobre temperaturas en carril y desplazamientos.

Posteriormente, estos datos se podrán analizar para evaluar el comportamiento de dichos puntos críticos de la infraestructura ferroviaria, y determinar su posible vulnerabilidad frente a fenómenos extremos que se prevén más adversos y habituales en el futuro. En última instancia, se pretende contribuir a lograr un ferrocarril más resiliente y fiable.

1. INTRODUCCIÓN

Durante las últimas décadas se ha venido observando cómo las infraestructuras de transporte se ven cada vez más afectadas por fenómenos meteorológicos extremos. Olas de calor, heladas o lluvias torrenciales pueden afectar seriamente a las redes de transporte, provocando graves daños e interrumpiendo servicios esenciales para el buen funcionamiento de nuestra sociedad. De acuerdo a las previsiones más recientes, estos fenómenos no harán sino agravarse en el futuro debido al cambio climático, por lo que se prevé necesaria una gran inversión para aumentar la resiliencia de todas las infraestructuras de transporte (IPCC, 2014).

Centrándonos en las redes ferroviarias, existen todavía ciertas carencias a la hora de cuantificar los efectos de los fenómenos climáticos extremos sobre la infraestructura y el servicio, debido en parte a las incertidumbres asociadas a la propia evolución del clima en las próximas décadas. No obstante, se han llevado a cabo algunos estudios en diferentes países para tratar de poner cifras al impacto del clima sobre las redes ferroviarias. Así, por ejemplo, Duinmeijer y Bouwknegt (2004) determinaron que los factores climáticos son responsables de entre un 5 y un 10% de los fallos en los ferrocarriles de los Países Bajos, cifra que Thornes y Davis (2002) elevan hasta el 20% en el caso del Reino Unido.

Son diversos los impactos que el clima puede tener sobre la infraestructura ferroviaria. Las olas de calor, por ejemplo, pueden provocar un fallo por pandeo, un fenómeno brusco de inestabilidad de carril que altera por completo la geometría de la vía y eleva el riesgo de descarrilo (Esveld, 2001). Según datos de la Agencia Europea del Ferrocarril (ERA), sólo en el año 2018 se produjeron más de 6000 episodios de pandeo en toda la red de la UE28, y esta cifra sigue una tendencia ascendente en la última década (Villalba et al., 2020). Según Dobney et al. (2009, 2010), el coste anual de los eventos de pandeo en la red ferroviaria del Reino Unido supera los 9 millones de libras, y Quinn et al. (2017) predice que esta cifra podría doblarse hacia el año 2080. Otros estudios como los de Baker et al. (2010), Palin et al. (2013) o Villalba et al. (2020) también predicen un aumento significativo de eventos de pandeo en el futuro. Respecto a los aparatos de vía, estos elementos son el componente principal de la infraestructura ferroviaria que afecta la disponibilidad del sistema (Morant et al., 2016), donde casi el 33% de los costes totales de mantenimiento es dedicado a los desvíos y cruces (Wang et al., 2017).

Otro impacto sobre la infraestructura ferroviaria digno de mención es la inestabilidad de taludes debidas a las lluvias torrenciales. Esta clase de fallo catastrófico depende en gran medida de la distribución espaciotemporal de las precipitaciones (Corominas et al., 2005), distribución que es de prever que se modifique notablemente en los próximos años a causa del cambio climático (Manning et al., 2008).

De ahí que diversos estudios sobre resiliencia de las infraestructuras ferroviarias (Quinn, 2017; UITP, 2016) destaquen la inestabilidad de taludes y los desprendimientos provocados por lluvias como uno de los principales fenómenos a tener en cuenta en el futuro.

En este contexto, es evidente que resulta imprescindible adaptar la infraestructura ferroviaria a las condiciones cambiantes del clima. Así, organismos internacionales tales como la UIC (Quinn, 2017), la UITP (2016) o la Agencia Europea del Medioambiente (EEA, 2014) ya han establecido recomendaciones generales de adaptación al cambio climático. También es de destacar en España el informe de necesidades de adaptación al cambio climático de la red troncal de infraestructuras de transporte elaborado por el CEDEX y el Ministerio de Fomento (2013). Sin embargo, a pesar de estos esfuerzos aún no existe, a día de hoy, un marco general o metodología unificada para afrontar estos problemas, y salvo algún caso aislado (siendo Network Rail en Reino Unido el más notable), ningún gestor de infraestructura ferroviaria ha adaptado todavía sus protocolos de monitorización y mantenimiento de acuerdo a las previsiones de cambio climático, o en todo caso no ha pasado de establecer algunas líneas o principios generales.

El proyecto MINFECLIMA nace precisamente con el objetivo de contribuir a un mejor mantenimiento de la infraestructura ferroviaria para adaptarla al cambio climático. Se trata de un proyecto de investigación desarrollado por AZVI S.A.U. y SIER en colaboración con la Universitat Politècnica de València en el marco de una Convocatoria de Cooperación Internacional con financiación del CDTI proveniente del Ministerio de Ciencia, Innovación y Universidades. Una de las principales tareas del proyecto se centra en monitorizar durante un largo período de tiempo ciertos elementos de la vía especialmente críticos y vulnerables, tales como desvíos o aparatos de dilatación.

Los trabajos presentados en esta ponencia se centran en la metodología de monitorización de un aparato de dilatación, detallando el montaje realizado, el tipo de datos a recopilar y una primera aproximación a la clase de análisis que se espera aplicar sobre los mismos.

2. METODOLOGÍA

En el marco del proyecto MINFECLIMA, antes explicado, se planea monitorizar durante un largo período de tiempo varios puntos críticos de la infraestructura ferroviaria, para poder recopilar un gran volumen de datos que permita determinar con mayor precisión los impactos provocados por los fenómenos climáticos extremos.

Este plan de monitorización incluye la instalación de sensores en un aparato de dilatación para determinar su comportamiento frente a los cambios de temperatura. En este apartado se exponen las principales características del equipo de monitorización a instalar.

2.1 Sección a monitorizar

El aparato de dilatación escogido (y su junta de dilatación asociada) se encuentran en el PK 62+000 de la vía del Corredor Mediterráneo (Figura 1). El principal motivo para escoger este aparato en concreto es que se trata de un diseño bastante representativo del tipo de aparatos de dilatación instalados en la red ferroviaria de Adif.

Fig. 1 – Aparato y junta de dilatación. Fuente: elaboración propia.

Concretamente se trata de un aparato con una carrera de 500 mm, situado a la entrada de un puente ferroviario, en un tramo entre las estaciones de L'Enova Manuel y Xàtiva, en la provincia de Valencia (España). Por esta línea circulan tanto trenes de pasajeros (incluyendo cercanías y media y larga distancia) como mercancías.

2.2 Equipo de medida

Para monitorizar el aparato de dilatación mostrado en la Figura 1 se ha optado por un sistema sencillo basado en sensores de fácil adquisición y un microordenador tipo Raspberry Pi 4. Mediante este equipo se pretenden monitorizar tres variables, tal y como se recoge en la Tabla 1.

Variable	Sensores
Temperatura en carril	2 sensores de temperatura en alma de carril
Separación entre estribo y tablero del puente	2 potenciómetros de desplazamiento en junta de dilatación
Desplazamiento en puntas del aparato de dilatación	2 sensores de ultrasonidos en las puntas del aparato

Tabla 1 – Variables a monitorizar en el aparato de dilatación

Como se aprecia en la Tabla 1, para medir la temperatura de carril se sitúan dos sensores de temperatura adheridos al alma mediante un adhesivo especial. Estos sensores son simples sondas de temperatura de 5 mm de tamaño con un rango de medición de -55ºC a 125ºC. Por otra parte, para medir la apertura de la junta de dilatación se emplean dos potenciómetros de desplazamiento lineal de 100 mm de carrera. Por último, para medir los desplazamientos de las puntas del aparato de dilatación se emplean dos sensores de ultrasonidos con un rango efectivo de medición de 25 a 450 cm. La Figura 2 muestra un croquis de la localización de estos sensores, mientras que sus principales características se recogen con mayor detalle en la Tabla 2.

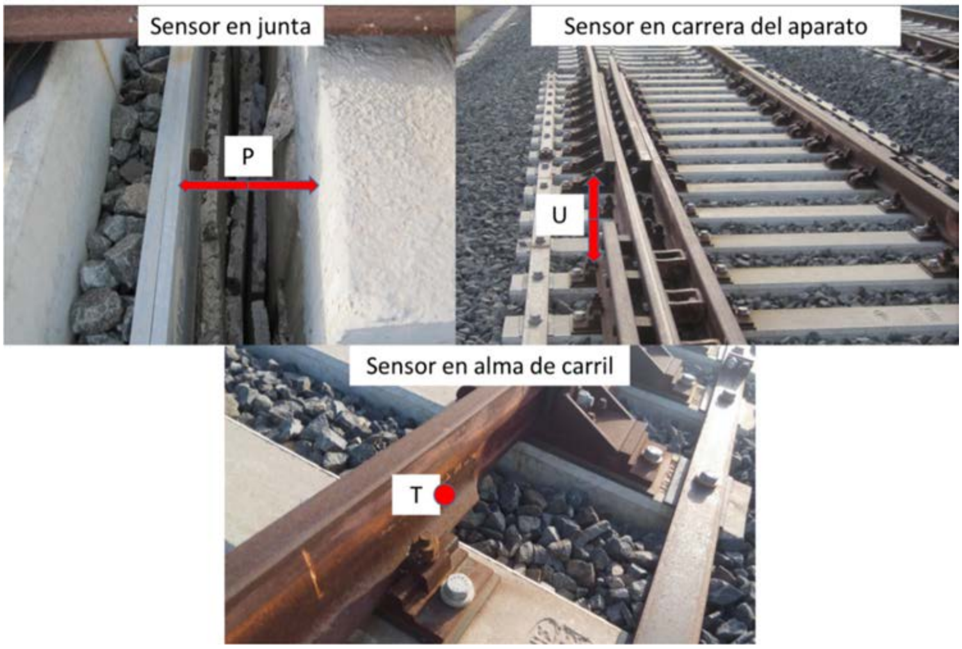

Fig. 2 – Localización de los sensores en el aparato y junta de dilatación.
P: Potenciómetro de Desplazamiento. U: Sensor de Ultrasonidos. T: Sensor de Temperatura. Fuente: elaboración propia.

Sensor de temperatura	
Rango de operación	-55ºC a 125ºC
Error (-30ºC a 100ºC)	± 1ºC
Tensión de alimentación	3-5,5 V
Dimensiones	4,95x4,95x3,94 mm
Potenciómetro de desplazamiento	
Carrera	100 mm
Linealidad	± 0,075%
Resistencia a vibraciones / impactos	15 g / 50 g
Temperatura de operación	-10ºC a 65ºC
Dimensiones	21x25x230 mm
Sensor de ultrasonidos	
Distancia de detección	25 a 450 cm
Ángulo del sensor	< 70º
Precisión	5 mm
Peso	54 g
Dimensiones	41x28,5 mm

Tabla 2 – Características de los sensores

Estos sensores se conectan a un microordenador Raspberry Pi 4 (Figura 3), que es el encargado de almacenar las señales de los sensores y enviarlas a un servidor mediante un módulo modem con antena GNSS.

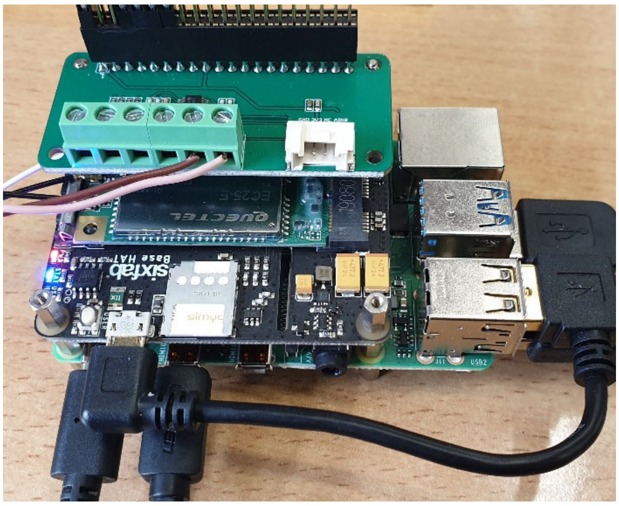

Fig. 3 – Microordenador para captación de datos

El conjunto del sistema se alimenta con una batería, que se recarga mediante paneles solares para garantizar su autonomía en campo.

2.3 Plan de monitorización

Una vez instalado el equipo, se procede a recopilar datos durante un período no inferior a 12 meses, si bien sería recomendable llegar a los 18 meses. La monitorización se realiza de forma automática de acuerdo al esquema mostrado en la Figura 4.

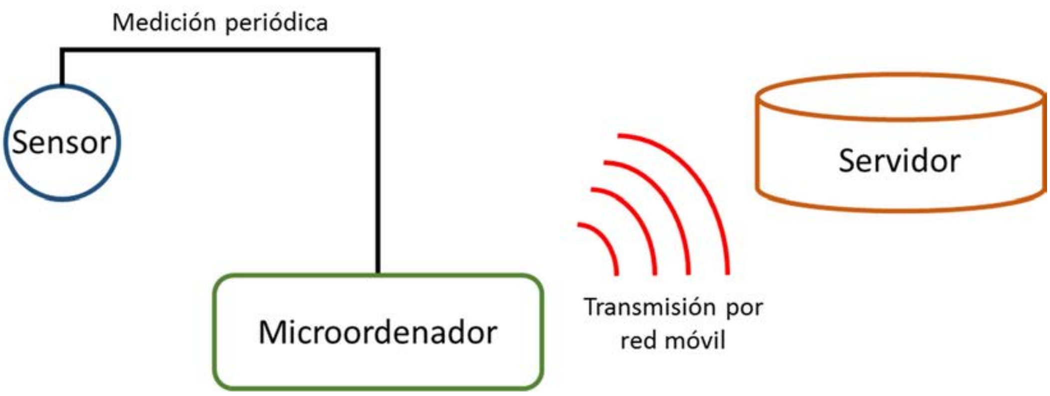

Fig. 4 – Esquema del proceso de medición. Fuente: elaboración propia.

Los sensores realizan una medición cada hora, registrando niveles de temperatura en carril, apertura de junta y desplazamiento de puntas. Estos datos se almacenan en el microordenador y se sincronizan regularmente con una base de datos habilitada a tal efecto mediante conexión 4G.

3.RESULTADOS

En este apartado se exponen los resultados que se esperan obtener a partir del montaje descrito en el apartado anterior. Cabe destacar que la labor de monitorización cubre un período extenso de un mínimo de 12 meses entre los años 2021 y 2022, por lo que se irán acumulando registros en la base de datos hasta alcanzar un volumen elevado que permita realizar un análisis exhaustivo del comportamiento del aparato de dilatación y la junta. En esta ponencia sólo se exponen, a título ilustrativo, la estructura de datos a obtener y el potencial que ofrece para futuros análisis.

3.1 Estructura de base de datos

Una vez instalado el equipo en vía, comenzará a tomar datos de forma regular siguiendo el esquema mostrado en la Figura 4. Los datos se almacenarán en una base de datos local en el propio microordenador, que se sincronizará a intervalos regulares con otra base de datos en la nube mediante la conexión 4G del sistema. Los datos se estructuran, en ambos casos, siguiendo el esquema mostrado en la Tabla 3.

Campo	Tipo de dato	Descripción
id	integer	Identificador del microordenador
tipo	string	Tipo de sensor (temperatura, distancia, etc.)
num_sens	integer	Número de sensor
dato	float	Valor de la medida
hora	float	Fecha y hora (expresada en tiempo UNIX)
synced	integer	Estado de sincronización.

Tabla 3 – Estructura de datos almacenados.

Así pues, cada registro tomado tendrá un identificador 'id' que indica desde qué microordenador se ha tomado (en el caso de que se realicen varios montajes en diversos puntos, tal y como está planificado en el proyecto MINFECLIMA), un indicador del tipo de sensor, una numeración de sensor (para distinguir entre varios sensores del mismo tipo), el valor de medición tomado, la fecha y hora en la que dicha medición se produjo (expresado en tiempo UNIX) y un indicador de sincronización con la base de datos en la nube (que tomará valores de 0 y 1 según la medición se haya o no sincronizado).

3.2 Volumen de datos y posibles análisis

Con una periodicidad de toma de datos de un registro por segundo, y asumiendo un período de toma de datos de dieciocho meses, se espera recopilar, para cada sensor instalado en vía, un total de 13150 registros. Evidentemente, este valor podría incrementarse notablemente si se aumenta la frecuencia de muestreo, cosa que se podría llevar a cabo si se estima oportuno para capturar fenómenos climáticos de evolución más rápida.

En todo caso, resulta claro que, gracias al montaje descrito en el apartado 2, será posible recopilar un extenso volumen de datos relativos al comportamiento del aparato de dilatación durante un período muy extenso, lo que permitirá plantear un análisis masivo de los mismos e identificar patrones, asociándolos a los diferentes fenómenos climáticos que se produzcan. Para analizar la información climática, se realizará una integración con los datos proporcionados por la Agencia Estatal de Meteorología (AEMET), principalmente de las estaciones climatológicas más cercanas a cada uno de los montajes de monitorización del proyecto.

Extendiendo este proceso a otros puntos singulares de la vía férrea, será posible llevar a cabo una labor concienzuda de recopilación de datos que permitirá estudiar nuevas opciones de mantenimiento que incluyan las variables climáticas y su evolución como factores fundamentales, contribuyendo así a un ferrocarril más sostenible y resiliente frente al cambio climático.

4. CONCLUSIONES

En el marco del proyecto MINFECLIMA, desarrollado por AZVI S.A.U. y SIER con la colaboración de la Universitat Politècnica de València, se pretende contribuir a mejorar la resiliencia y el mantenimiento de la infraestructura ferroviaria, aportando datos que permitan evaluar el comportamiento de puntos singulares de la vía frente a los fenómenos climáticos extremos.

En este contexto, la presente ponencia recoge un sistema sencillo y autónomo de adquisición de datos, diseñado para monitorizar temperaturas de carril y desplazamientos en un aparato y junta de dilatación. Se han expuesto las principales características del sistema, los sensores a emplear y su instalación en vía, y se ha detallado el plan de medición a aplicar, la estructura de datos que se va a generar y su sincronización automatizada con una base de datos en la nube

Está previsto que este montaje se aplique en breve y se inicie la recopilación de datos, que se extenderá durante un período de entre 12 y 18 meses entre los años 2021 y 2022. Conforme se vayan acumulando registros, será posible llevar a cabo un análisis exhaustivo de los mismos que permita identificar patrones novedosos y relacionarlos con los fenómenos climáticos extremos que se produzcan durante dicho período de medición.
En suma, la metodología descrita en esta ponencia es una de las herramientas mediante las que el proyecto MINFECLIMA aspira a aportar nuevos conocimientos y metodologías para un mantenimiento ferroviario adaptado a los desafíos del cambio climático.

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ENDURECIMIENTO CON EXPLOSIVOS DE CRUZAMIENTOS DE VÍA: PROCESO RIOMETAL DE MAXAM

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RESUMEN

Una de las piezas críticas de desgaste de la red ferroviaria es el corazón de los cruzamientos, un elemento sometido a mayores esfuerzos que las vías. Para su construcción suele emplearse acero Hadfield, con una dureza "de fábrica" en torno a 220 HBW.
MAXAM, líder europeo en la fabricación de material explosivo y sistemas de iniciación para uso civil (minería, túneles, canteras…), ha desarrollado un proceso de endurecimiento de estas piezas que permite aumentar su dureza por encima de 350-400 HBW, antes de su suministro e instalación, mediante el disparo de una carga explosiva especialmente diseñada denominada RIOMETAL.

Con esta dureza, el cruzamiento aumenta de manera notable su resistencia al desgaste, lo que implica una reducción aproximada de los costes de mantenimiento del 50%, una extensión de su vida útil de alrededor del 40% y una disminución del Coste del Ciclo de Vida (LCC) de un 20% aproximadamente, reduciéndose también el número y duración de las paradas para reparaciones, recargas de material y sustituciones.

Figura 1. Cruzamiento ferroviario

1. EL ACERO HADFIELD Y SU APLICACIÓN EN VÍAS FERROVIARIAS

Un desvío ferroviario es una construcción especial que permite a los trenes cambiar de una vía a otra para modificar su dirección. La parte fundamental de cada desvío es cruzamiento, a través del cual las vías se cruzan para luego separarse definitivamente en dos direcciones diferentes.

Dentro del cruzamiento, el elemento de mayor desgaste es el denominado corazón, donde se materializa la separación de ambas vías. El material más adecuado para la producción estos corazones es el acero austenítico al manganeso: acero Hadfield.

1.1 El acero Hadfield

El acero Hadfield es un acero austenítico al manganeso en el que la transformación martensítica de endurecimiento ha sido suprimida por una combinación de alto contenido en manganeso y carbono, y la precipitación de carburos por una alta velocidad de enfriamiento desde la temperatura de austenización.

El material es unifásico y presenta una estructura austenítica capaz de elevar su dureza desde 180 hasta 900 Brinell sin presentar transformación martensítica. Este material posee una incomparable capacidad de endurecimiento por deformación plástica y una alta resistencia a la tracción y a la compresión.

Por ello, es utilizado cuando se requiere resistencia al impacto y contra la abrasión, como en los campos del movimiento de tierra y minería (trituradoras, molinos, dientes de pala), la perforación de pozos, la siderurgia o la industria ferroviaria.
Sin embargo, es difícil de mecanizar, por lo que no son aptos para piezas que requieran alta precisión o que deban resistir la deformación plástica durante su servicio.

1.2 Cruzamientos ferroviarios

En los cruzamientos ferroviarios se emplea el acero Hadfield porque es capaz de endurecer su superficie de trabajo (es decir, aumentar su dureza superficial) bajo la presión y carga de choque que producen las ruedas de ferrocarril circulando sobre él.

Sin embargo, en los primeros ciclos de uso, puede sufrir un alto desgaste debido a que este proceso de endurecimiento no se ha producido aún.

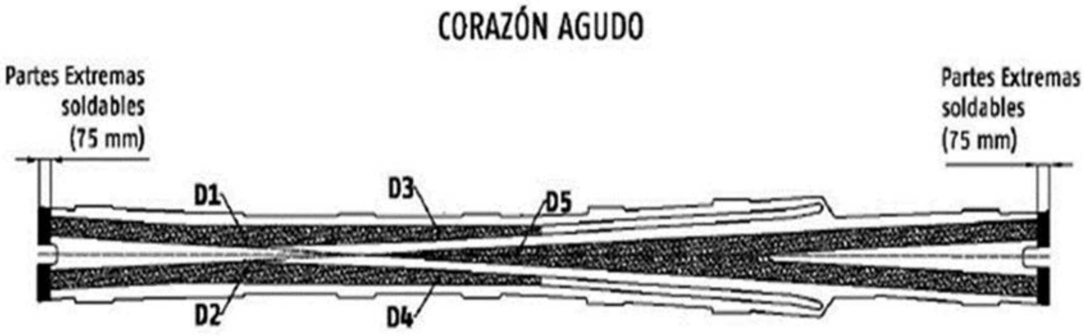

Figura 2. Ejemplo de un corazón de cruzamiento y zonas de pre-endurecimiento

Cuando los corazones de los cruzamientos se emplean sin endurecimiento previo pueden experimentar una deformación y un desgaste de unos 3 mm en las primeras semanas de servicio, hasta que logran alcanzar una dureza suficiente para minimizar este desgaste.

Este endurecimiento "natural" se produce por efecto de la deformación plástica que causan las propias cargas de operación (los trenes al pasar) sobre el acero austenítico al manganeso.

Para alargar la vida útil de los aparatos, reducir el coste de mantenimiento (recarga de material, sustitución) y optimizar su coste del ciclo de vida (LCC), los principales operadores ferroviarios especifican que, en sus vías férreas, los corazones de sus cruzamientos deben tener las bandas de rodadura endurecidas previamente a su instalación.

1.3 Pre-endurecimientos con explosivos

El proceso de endurecimiento previo a su colocación en la red ferroviaria más habitual es el endurecimiento con explosivos, patentado por primera vez en 1955.

Esta tecnología se fundamenta en la importante deformación plástica que sufre el acero al verse sometido a la onda de presión producida por la detonación del material explosivo, que aumenta drásticamente su dureza superficial.

El proceso de endurecimiento de aceros austeníticos con explosivos consiste en adherir una carga detonante a la zona de la pieza que se pretende endurecer (banda de rodadura) y hacerla detonar.

Con una sola detonación se pueden alcanzar valores de dureza Brinell superiores a 350 hasta una profundidad de unos 20 mm bajo la superficie de rodadura. Para alcanzar mayores durezas (>450 HBW), este proceso puede repetirse varias veces, normalmente hasta un máximo de 3.

Los principales operadores ferroviarios han establecido normas y criterios que incluyen los requisitos de dureza superficial y profundidad requeridos para los cruzamientos que han pasado por un proceso de pre-endurecimiento.

La Tabla 1 muestra, a modo de resumen, algunos ejemplos de requisitos exigidos en diferentes normas y regiones.

The validity of the standard	**Standard**	**Hardness after explosive hardening (HBW)**	**The explosive application depth Z (mm)**	**Length of hardening area L**	**Surface hardness test locations**
The European Union	EN 15689	321	10	100%	3, 4, 5
Switzerland	SBB 10-028-C3	321	14	100%	3, 4, 5
North America	AREMA 100-08	352	15,9	100%	1 to 7
Australia	ETA-03-03	350-415	20	100%	1 to 7

Tabla 1. Requisitos de dureza tras pre-endurecimiento según diversas normas

2. PROCESO RIOMETAL PARA PRE-ENDURECIMIENTO CON EXPLOSIVOS.

MAXAM ha desarrollado un proceso de endurecimiento de los corazones de los cruzamientos, utilizando para ello un explosivo específicamente patentado denominado RIOMETAL. Esta técnica se realiza en una instalación especialmente acondicionada en la planta de la Compañía en Páramo de Masa (Burgos).

Por este proceso han pasado, tan sólo en 2020, más de 1.100 corazones de cruzamientos producidos por los principales fabricantes europeos (Amurrio Ferrocarril y Equipos, JEZ sistemas ferroviarios, Mieres Rail, Vossloh Cogifer, Outreau Technologies…) que han sido instalados en líneas de alta velocidad, metros, ferrocarriles mineros y líneas convencionales y de mercancías de Europa, África y América.

Al tratarse de una aplicación de material explosivo, debe llevarse a cabo por personal autorizado y en un área acondicionada y autorizada para ello. En el caso de MAXAM, se realiza por artilleros de la propia compañía y bajo supervisión del departamento técnico, en el campo de tiro que hay dentro de sus instalaciones de Burgos.

2.1 Características técnicas de las láminas explosivas de RIOMETAL

Para el endurecimiento de la superficie de las piezas de acero, MAXAM emplea un explosivo laminado en bandas denominado RIOMETAL, formado por una base de pentrita muy fina embebida en una matriz plastificante.

El producto lleva una banda adhesiva que le permite adherirse a la superficie de la pieza que se quiera endurecer.

Este producto lo fabrica MAXAM para todo el mundo en su fábrica de Páramo de Masa (Burgos).

Figura 3. Láminas de RIOMETAL

Las características técnicas del RIOMETAL son las siguientes:

- Espesores de lámina: de 2 a 6 mm
- Ancho de lámina: Hasta 1.000 mm
- Longitud de banda: 10 m
- Velocidad de detonación: 6.500 m/s
- Clasificación UN: UN 0084, clase 1.1 D

Como todos los explosivos que comercializa MAXAM y en cumplimiento de la legislación vigente y del Reglamento de Explosivos, cada caja de RIOMETAL tiene su propio código de trazabilidad y, dentro de la caja, cada plantilla específica de su interior dispone de un código único de trazabilidad. Gracias a ello, podemos realizar el seguimiento de calidad en cada una de las piezas endurecidas.

2.2 Características del lugar de trabajo de los endurecimientos

Un factor fundamental para realizar este proceso es disponer de un lugar adecuado donde realizarlo, que deberá contar con su autorización correspondiente y, dado que se trata de hacer detonar explosivos al aire, deberá cumplir con los siguientes requisitos:

- Que el lugar esté alejado de zonas habitadas para evitar que la onda aérea cause molestias o daños.
- Que esté vallado y sin posibilidad de acceso de personas ajenas a la actividad
- Que cuente con un acceso adecuado para la entrada de los camiones de transporte de las piezas y los elementos de descarga (grúa)

- Que la superficie sobre la que se realiza el endurecimiento y su entorno esté limpio de cualquier elemento que pueda arder, como vegetación o embalajes, para evitar el riesgo de incendio, y contar con un sistema de extinción de incendios de seguridad.
- Deberá contar con plataformas para la colocación de las vías que permitan su perfecta nivelación y soporten el impacto de la detonación.

Figura 4. Vista general del campo de tiro de MAXAM en Páramo de Masa (Burgos)

2.3 Procedimiento operativo

Cada pieza que se pretende endurecer se identifica con un código y se diseña específicamente para ella la plantilla de explosivo que va a necesitar por medio de un programa de diseño gráfico.

A continuación, se recortan dichas plantillas a partir de los bloques de RIOMETAL que se almacenan en los depósitos de seguridad con los que cuenta MAXAM en sus instalaciones de Páramo de Masa y se les coloca la lámina adhesiva y el código de trazabilidad único y específico. Una vez está completo el lote, se embalan en cajas que, a su vez, se codifican para tener un control completo del producto explosivo que se va a utilizar en cada operación.

El día de disparo, se trasladan las cajas hasta el campo de tiro y se custodian por un vigilante de seguridad autorizado hasta que se produce su colocación y disparo.

Mientras, las piezas procedentes de la fundición son recepcionadas, identificadas, descargadas y posicionadas, prestando especial atención a su asentamiento en la cama de arena de la zona de disparo, para asegurar que la fuerza del impacto se trasmita de manera homogénea a la pieza.

Figura 5. Plantilla de RIOMETAL recortada y colocación en cruzamiento

Ya posicionadas, se revisan las piezas para detectar posibles anomalías y se limpian las superficies de contacto para proceder a la colocación del explosivo específico de cada pieza, que previamente fue recortado a medida. Esta labor la realizan artilleros especializados de MAXAM, bajo supervisión de su departamento técnico y cumpliendo con los protocolos establecidos.

Una vez finalizada la colocación de los explosivos y los sistemas de iniciación, se revisa la instalación, se asegura el perímetro de seguridad, se abandona la zona y comienza el procedimiento de disparo con la comprobación del circuito de voladura, la conexión del explosor en la caseta de disparo, la verificación final de que la zona está totalmente despejada y, si todo está bien, la detonación del explosivo en uno o más disparos secuenciados.

A continuación, los artilleros regresan al campo para comprobar que todo el explosivo ha detonado y que se puede retornar con seguridad. Cuando es así, se revisan de nuevo las piezas, se comprueban las durezas resultantes en los puntos de control de cada pieza con un durómetro portátil, se toman fotografías, que podrán formar parte del informe final de calidad, y se elabora el certificado de dureza específico.

Finalmente, se procede a la carga del material endurecido en el camión para enviarlo de vuelta a su fábrica de origen, donde será revisado de nuevo y rectificado si es necesario.

Figura 6. Secuencia de disparo

3. RESULTADOS DEL PROCESO

A lo largo de los años, MAXAM ha trabajado en el endurecimiento de más de 3.000 aparatos de ferrocarril para diferentes fabricantes internacionales.

A continuación, se recoge el estudio de los resultados obtenidos en las 1.398 piezas que endureció con el proceso RIOMETAL en sus cruzamientos de vías entre junio de 2015 y agosto de 2019.

Para ello, se recopilaron las durezas medidas y registradas en los informes de calidad en tres puntos de cada pieza: corazón, pata 1 y pata 2.

Durezas HBW	Punta	Pata 1	Pata 2	Pieza
Medio	367	361	363	**364**
Máximo	474	460	465	**474**
Mínimo	321	322	322	**321**
Percentil 10%	399	390	390	**394**
Percentil 99,5%	324	325	325	**325**

Tabla 2. Resumen resultados 1.398 piezas

La conclusión fue que, en las 1.398 piezas analizadas, se alcanzó un valor promedio de dureza de 364 HBW, con un 10% de las medidas superando, incluso los 394 HBW y el 99,5% de las medidas superando los 324 HBW.

Los resultados obtenidos se pueden ver resumidos en las siguiente tablas y gráficas que recogen los resultados obtenidos en las diferentes piezas:

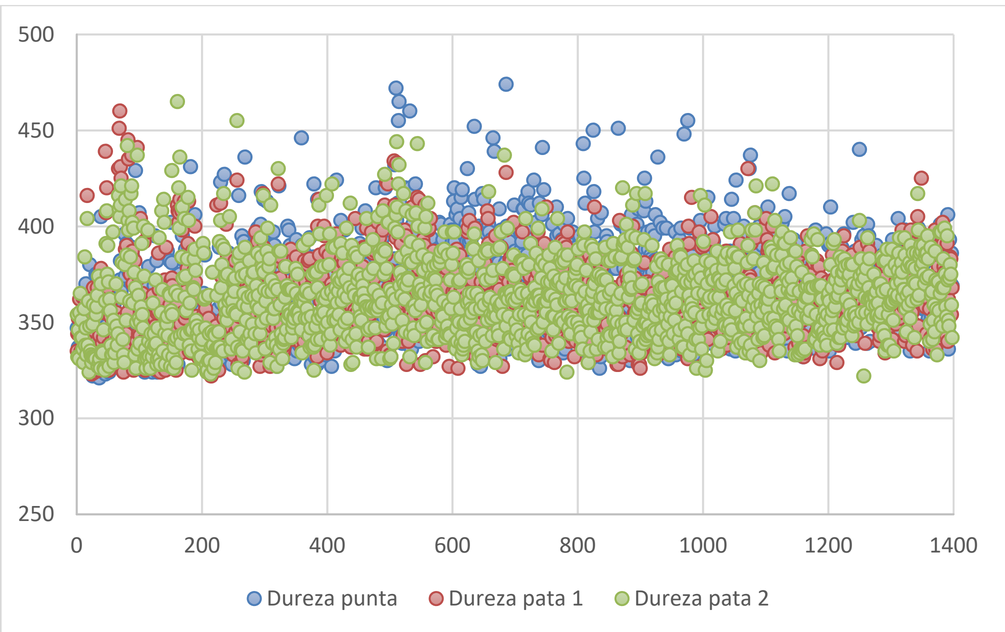

Figura 7. Resumen de resultados de dureza Brinell en punta y patas de cruzamientos

4. EJEMPLOS EXPERIMENTALES

Como ejemplos prácticos, incluimos en este artículo dos procesos de endurecimiento con una y con dos detonaciones llevados a cabo por MAXAM en 2020.

Los trabajos en campo fueron realizados por un equipo compuesto por un ingeniero, como Director Facultativo y responsable de la operación, y 2 artilleros, todos con una amplia experiencia en esta aplicación, que contaron con el apoyo externo del departamento técnico de MAXAM (TAP).

4.1 Caso 1: Endurecimiento con una detonación

Se trataba de 5 cruzamientos soldables de corazón agudo fabricados en acero Hadfield.

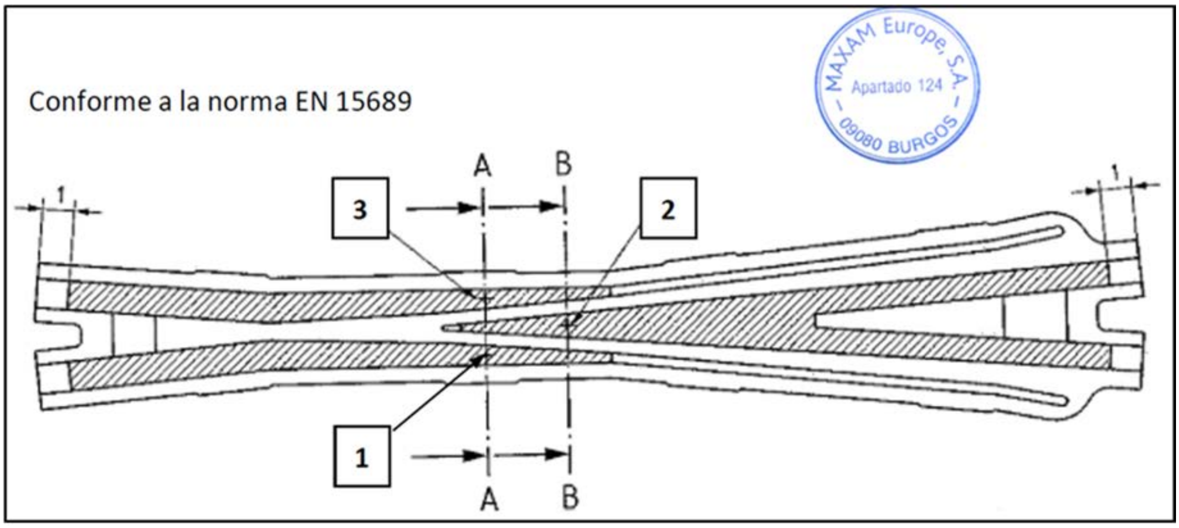

Figura 8. Esquema de cruzamiento, áreas de endurecimiento y puntos de control

En ellos se midieron la dureza inicial con un durómetro portátil calibrado modelo Equotip, de la empresa Proceq, con compensación automática, punta de carburo de tugsteno y un rango de medida de 150 a 950 HLD con una precisión de +/- 4 HLD, obteniéndose la siguiente tabla de valores:

	Pieza 1			Pieza 2			Pieza 3		
	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3
Medida 1 (HBW)	170,0	190	178	187	228	203	196	224	260
Medida 2 (HBW)	184,0	178	194	160	199	239	169	179	245
Medida 3 (HBW)	178,0	186	187	187	219	200	196	221	235
Valor promedio (HBW)	177,3	184,7	186,3	178,0	215,6	213,9	187,0	208,1	246,7
Valor promedio (HBW)	**182,8 HBW**			**202,5 HBW**			**213,9 HBW**		

	Pieza 4			Pieza 5			Media		
	Control 1	Control 2	Control 3	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3
Medida 1 (HBW)	193,8	209,0	213,6	205,4	219,5	220,0	190,4	214,2	214,9
Medida 2 (HBW)	226,3	165,5	203,7	278,4	144,0	213,9	203,5	173,2	219,1
Medida 3 (HBW)	190,5	195,3	220,7	186,7	218,7	244,9	187,7	208,0	217,5
Valor promedio (HBW)	203,5	189,9	212,7	223,5	194,1	226,3	193,9	198,5	217,2
Valor promedio (HBW)	**202,0 HBW**			**214,6 HBW**			**203,2 HBW**		

Tabla 3. Valores iniciales 1 detonación

El endurecimiento se llevó a cabo con un único disparo. El explosivo que se empleó fue una lámina de 4,5 mm de RIOMETAL, fabricado por MAXAM, y el proceso fue llevado a cabo en el campo de tiro de MAXAM en Páramo de Masa (Burgos).

Tras el endurecimiento, se volvieron a medir las durezas siguiendo el mismo procedimiento y con los mismos equipos de medida, obteniéndose los siguientes resultados.

	Pieza 1			Pieza 2			Pieza 3		
	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3
Medida 1 (HBW)	340,0	334	357	367,0	363	344	358,0	373	391
Medida 2 (HBW)	343,0	359	339	351,0	371	358	367,0	391	382
Medida 3 (HBW)	338,0	365	346	355,0	359	376	364,0	384	407
Valor promedio (HBW)	340,3	352,7	347,3	357,7	364,3	359,3	363,0	382,7	393,3
Valor promedio (HBW)	**346,8 HBW**			**360,4 HBW**			**379,7 HBW**		

	Pieza 4			Pieza 5			Media		
	Control 1	Control 2	Control 3	Control 1	Control 2	Conrtrol 3	Control 1	Control 2	Conrtrol 3
Medida 1 (HBW)	371,0	354	388	367,0	347	333	360,6	354,2	362,6
Medida 2 (HBW)	384,0	357	359	352,0	384	343	359,4	372,4	356,2
Medida 3 (HBW)	382,0	349	367	356,0	369	347	359,0	365,2	368,6
Valor promedio (HBW)	379,0	353,3	371,3	358,3	366,7	341,0	359,7	363,9	362,5
Valor promedio (HBW)	**367,9 HBW**			**355,3 HBW**			**362,0 HBW**		

Tabla 4. Valores finales tras 1 detonación

Como se puede observar, en todas las mediciones (45/45) los valores de dureza Brinell obtenidos son superiores a 334 HBW, con valores puntuales superiores a 390 HBW. El valor promedio fue de 362 HBW, que supone un incremento de la dureza media del 78%. La inspección final de las piezas no detectó ninguna grieta ni deformación fuera de rango.

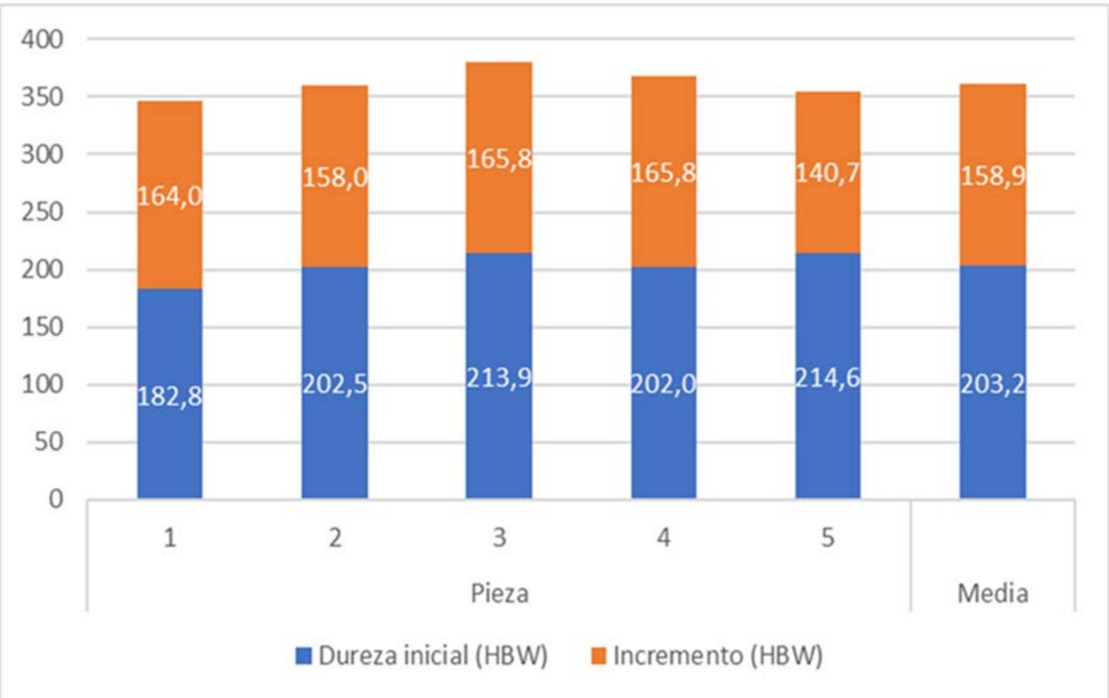

Figura 9. Incremento de dureza Brinell tras 1 detonación. Representación gráfica

4.2 Caso 2: Endurecimiento con dos detonaciones

En este caso, se trataba de endurecer una pieza con 11 puntos de control, cuyo esquema es el siguiente:

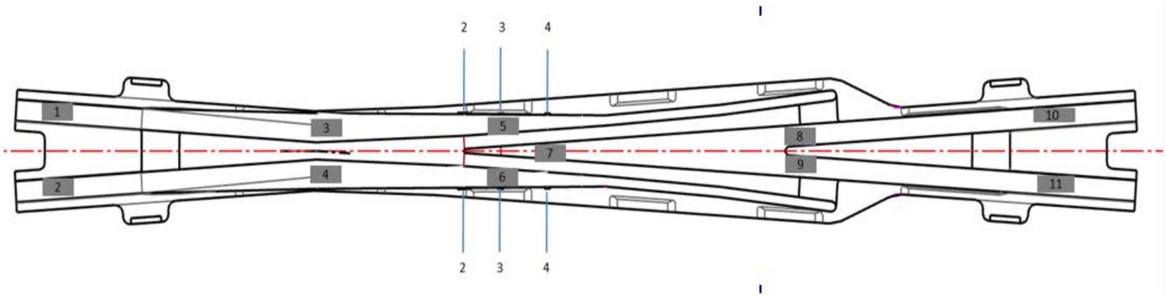

Figura 10. Esquema del cruzamiento

De cada uno de los puntos de control se tomaron 3 medidas de dureza antes y después de cada una de las detonaciones para un total de 99 valores de dureza HBW que se midieron con el mismo durómetro portátil calibrado modelo Equotip.

El endurecimiento se llevó a cabo con dos detonaciones. El explosivo que se empleó fue una lámina de 4,5 mm de RIOMETAL, fabricado por MAXAM, y el proceso fue llevado a cabo en el campo de tiro de MAXAM en Páramo de Masa (Burgos).

Los resultados que se obtuvieron fueron los siguientes:

Momento de la medida	Medidas de durezas (HBW)															
	Punto1			Valor medio	Punto2			Valor medio	Punto3			Valor medio	Punto4			Valor medio
Previo explosionado	226,0	222,0	218,0	222,0	192,0	201,0	204,0	199,0	213,0	193,0	200,0	202,0	185,0	197,0	200,0	194,0
Tras 1er explosionado	303,0	324,0	323,0	316,7	311,0	315,0	333,0	319,7	310,0	336,0	346,0	330,7	325,0	349,0	362,0	345,3
Tras 2º explosionado	350,0	352,0	351,0	351,0	356,0	351,0	354,0	353,7	355,0	351,0	352,0	352,7	**371,0**	**357,0**	**352,0**	**360,0**
	Punto5			Valor medio	Punto6			Valor medio	Punto7			Valor medio	Punto8			Valor medio
Previo explosionado	227,0	236,0	203,0	222,0	267,0	233,0	234,0	244,7	193,0	255,0	204,0	217,3	179,0	177,0	205,0	187,0
Tras 1er explosionado	321,0	372,0	340,0	344,3	323,0	333,0	331,0	329,0	319,0	318,0	343,0	326,7	345,0	323,0	345,0	337,7
Tras 2º explosionado	393,0	376,0	364,0	377,7	354,0	361,0	360,0	358,3	399,0	352,0	356,0	369,0	**354,0**	**359,0**	**354,0**	**355,7**
	Punto9			Valor medio	Punto10			Valor medio	Punto11			Valor medio	VALOR MEDIO			Valor medio
Previo explosionado	181,0	184,0	186,0	183,7	190,0	174,0	162,0	175,3	180,0	176,0	184,0	180,0	**203,0**	**204,4**	**200,0**	**202,5**
Tras 1er explosionado	338,0	330,0	341,0	336,3	333,0	339,0	345,0	339,0	335,0	343,0	349,0	342,3	**323,9**	**334,7**	**341,6**	**333,4**
Tras 2º explosionado	372,0	353,0	364,0	363,0	352,0	357,0	366,0	358,3	358,0	352,0	364,0	358,0	**364,9**	**356,5**	**357,9**	**359,8**

Tabla 5: Valores de dureza antes y tras cada detonación.

Mientras que los valores medios de dureza antes del disparo (pieza sin endurecer) variaban entre 175 y 245 HBW (media 202 HBW), la dureza superficial tras la primera detonación subía hasta 317 y 345 HBW (media 333 HBW), lo que supone un incremento de un +64,7% de la dureza superficial.

Tras la segunda detonación, la dureza media en capa punto de control osciló entre 351 y 378 HBW (media 360 HBW) lo que supone un aumento de un +7,9%.

5. CONCLUSIONES

El endurecimiento con explosivos de los corazones de los cruzamientos ferroviarios de acero Hadfield es una técnica ampliamente extendida que permite aumentar su resistencia al desgaste, lo que implica una reducción de su mantenimiento y una extensión de su vida útil.

Según los estudios realizados por los principales fabricantes de cruzamientos y operadores de líneas férreas, instalando un cruzamiento pre-endurecido se pueden conseguir las siguientes ventajas:

- **Reducción de los costes de mantenimiento** en un 50%, principalmente en los primeros meses después de su instalación.
- **Aumento de su vida útil** (carga soportada) en un 40%
- **Reducción del coste del ciclo de vida** en un 20%, considerando también el sobrecoste que supone el pre-endurecimiento del cruzamiento.

Adicionalmente, la reducción de mantenimiento y el alargamiento de su vida útil suponen una reducción del número y tiempo de paradas y estancias fuera de servicio. Todos ellos, aspectos fundamentales para los gestores de redes ferroviarias

En este documento se mostraron los requisitos exigidos para los cruzamientos pre-endurecidos con explosivos por los principales gestores de este tipo de instalaciones en diversas partes del mundo.

También se describió el proceso RIOMETAL, desarrollado por MAXAM específicamente para el endurecimiento de cruzamientos, y se mostraron los resultados experimentales obtenidos en cerca de 1.400 de los más de 4.000 endurecimientos llevados a cabo en sus instalaciones del Páramo de Masa (Burgos), donde también está su centro de producción del explosivo y el Centro de Innovación del Grupo MAXAM para todo el mundo.

Analizando tanto los datos históricos y como los últimos ejemplos, se puede afirmar que con el proceso RIOMETAL se alcanzan y sobrepasan las durezas requeridas tanto por las normas europeas como por las normas norteamericana y australiana, aún más exigentes, para la dureza superficial de los corazones de punta fija de cruzamientos ferroviarios.

Figura 11. Ilustración de ejemplo

NUEVOS DESARROLLOS PARA METROS LIGEROS

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RESUMEN

Metrotenerife es el operador del Metro Ligero de Tenerife desde su puesta en marcha en el año 2007. Asimismo, esta empresa pública perteneciente al Cabildo Insular de Tenerife lleva a cabo los estudios pertinentes para la implantación de nuevos corredores ferroviarios con el objeto de mejorar la sostenibilidad de la movilidad e incrementar la cuota de transporte público colectivo en la isla.

La experiencia que adquiere el operador de un sistema de transporte de metro ligero a lo largo de 14 años de servicio comercial le hace replantearse soluciones técnicas y tecnológicas que permitan mejorar las condiciones de seguridad de la circulación de convoyes y las acciones de mantenimiento. Metrotenerife ha desarrollado, entre otros, dos sistemas novedosos que le han permitido obtener dichas mejoras, y que están siendo además lanzados al mercado para permitir al resto de operadores poder beneficiarse de ellos. Se trata, por un lado, del SIMOVE (Sistema de Monitorización de Velocidad Embarcado), que permite supervisar de forma continua y a tiempo real la posición del vehículo y su velocidad, siendo capaz de activar de forma automática el freno de emergencia en caso de que se sobrepase el umbral de riesgo, y por otro lado la Chaqueta Aislante Extraíble para carril de garganta, un elemento de aislamiento eléctrico y acústico que por sus prestaciones permite sustituir dicho carril en tiempo reducido y sin necesidad de llevar a cabo obras de demolición y reposición de revestimientos de vía.

1. SIMOVE

1.1 Introducción

SIMOVE es un sistema de seguridad capaz de supervisar en tiempo real la velocidad del vehículo, alertar al conductor de las limitaciones de velocidad existentes en función del tramo por el que circula; y en caso de sobrepasarlas, aplicar el Frenado de Urgencia Automático del vehículo (FU en adelante).

SIMOVE está formado por dos partes: un sistema embarcado y el back office, que están comunicados vía Wi-Fi o tecnología 3G/4G. El primero es el encargado del control de velocidad, monitorización y registro de eventos. El back office recibe, gestiona y almacena la información de los equipos embarcados, además permite configurar y preparar la información para poder explotarla, en función de las necesidades del operador.

1.2 Funcionalidades de SIMOVE

Las funciones principales del equipo se han diferenciado e independizado dependiendo de la aplicación que se va a llevar a cabo, acordes a los requisitos RAMS (Reliability, Availability, Maintainability and Safety) exigidos, y para evitar que durante la fase de mantenimiento, la actualización de los parámetros de una de las funciones afecten al resto.

El sistema SIMOVE está basado en tecnología GPS para ubicar el vehículo en la línea y determinar su sentido; y en la lectura del odómetro embarcado para calcular la velocidad y distancia recorrida.

1.2.1 Control de la posición y velocidad del vehículo

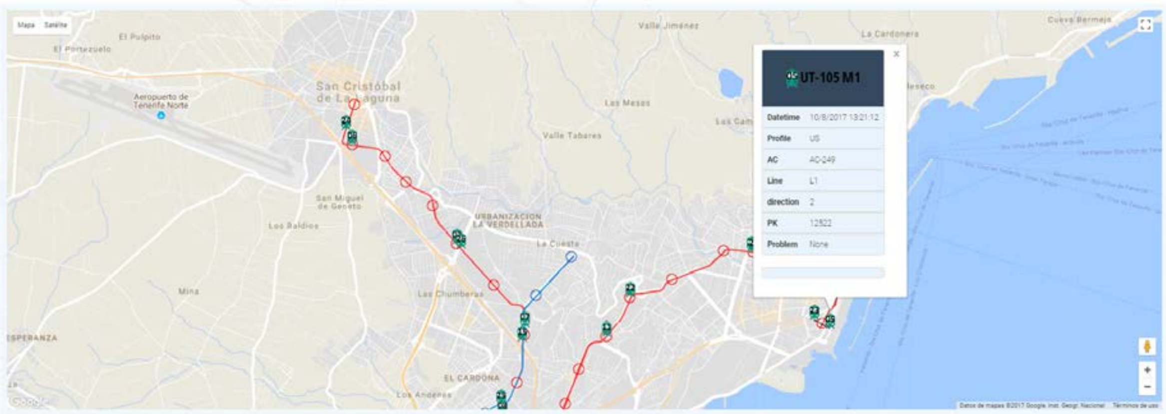

Fig. 1 - Posición de la flota operativa a tiempo real

- Seguimiento continuo de la posición del vehículo deduciendo línea y sentido de marcha.
- Seguimiento continuo de la velocidad del vehículo.
- Comparación de la velocidad del vehículo con las velocidades máximas de conducción impuestas en el tramo de la línea por el que circula y el tipo de vehículo.
- El sistema funciona en todo tipo de topologías (túneles, puentes, zonas entre edificios, etc.).

1.2.1.1 Localización del vehículo basada en tecnología GPS

La determinación de la línea y sentido del vehículo se realiza a través del GPS. Éste se activa al poner en marcha el vehículo desde la cabina de conducción, y no permite que el SIMOVE esté operativo hasta que localice un número mínimo de satélites con una potencia mínima establecidos.

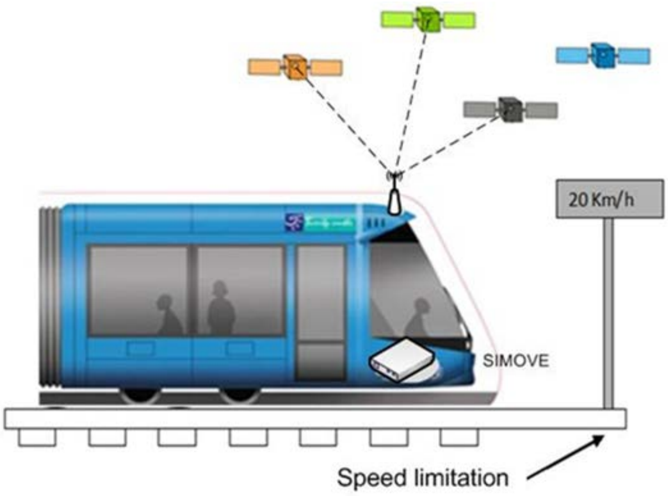

Fig. 2 - SIMOVE utiliza la constelación GPS para su localización

1.2.1.2 Localización del vehículo mediante lectura del odómetro

La conexión del SIMOVE con el odómetro embarcado permitirá el cálculo de la velocidad del vehículo, el desgaste de la rueda, la distancia recorrida desde la última posición de referencia y su ubicación sobre la línea.

1.2.1.3 Comparación con el perfil de velocidad del tramo.

Ubicado el vehículo en una línea y conociendo su sentido, el sistema compara la velocidad registrada por el odómetro, con el perfil de velocidad definido en dicho tramo. El sistema posiciona el vehículo en cada tramo con el objetivo de alertar al conductor del exceso de velocidad cuando supera el umbral de alarma, o frenando el vehículo cuando sobrepasa el umbral de emergencia.

1.2.1.4 Recreación de la posición y velocidad de la flota

SIMOVE permite efectuar una recreación de los viajes realizados por la flota completa, permitiendo al operador visualizar los desplazamientos de los vehículos en una franja temporal determinada, a modo de moviola. Esta funcionalidad permite analizar los siguientes puntos: gestión de la flota llevada a cabo por el PCC (Puesto Central de Control), gestión de incidencias por parte del PCC, análisis de eventos, etc.

1.2.2 Ratio de obtención de información.

El sistema embarcado obtiene información 3 veces por segundo. Es posible leer con frecuencias mayores. Las limitaciones son las de hardware y almacenamiento de datos

1.2.3 Aviso e información al conductor.

- El sistema embarcado está equipado con una pantalla situada en la cabina, que muestra al conductor la velocidad actual del vehículo y la velocidad máxima permitida en la sección en la que está circulando.
- Identificación del conductor mediante solicitud de usuario. El registro del conductor se realizará en ambas cabinas simultáneamente.

Fig. 3 - Registro del código de conductor

- Aviso si el conductor no se ha registrado en el sistema.
- Avisos sonoro (fichero de audio personalizable) y luminoso en la pantalla cuando la velocidad de *warning* ha sido sobrepasada. Si se alcanza el segundo umbral, denominado velocidad de emergencia, se aplicará un FU. Ambos umbrales de velocidad son parametrizables en cada una de las líneas, dirección y localización precisa.
- Aplicación de umbrales distintos dependiendo del tipo de vehículo, en adelante perfiles (por ejemplo, unidad simple, unidad doble, unidad de prueba, etc.

1.2.4 Actuación sobre el freno del tranvía.

- La orden de frenado FU se dará mediante la apertura del lazo de puertas provocado por el relé del SIMOVE.
- Tras la aplicación de un FU aparecerá en la pantalla un aviso de aplicación indicando la velocidad del tramo y la velocidad alcanzada. Posteriormente el conductor deberá reconocer el FU para poder continuar con la conducción.

Fig. 4 - Pantalla conductor en un FU

1.2.5 Aviso e información a terceras partes y/o aplicaciones.

- Los destinatarios de la información y avisos enviados por SIMOVE son completamente personalizables, así como el tipo de información que recibe cada uno de ellos.
- Publicación en un Servicio Web de los avisos de emergencia y FU en tiempo real, para poder ser explotados por terceras aplicaciones.
- Servicio Web que provee a tiempo real el posicionamiento del vehículo, el cual puede ser actualizado según parametrización para poder ser explotados por terceras aplicaciones.
- Generación de los ficheros KML conteniendo la velocidad y aceleración de cada viaje para su representación sobre interfaz GIS, aun cuando no hayan sido registrados eventos significativos.
- Envío de avisos por SMS o servicios de mensajería instantánea de las FU y otros eventos destacables a una selección de usuarios predefinida.

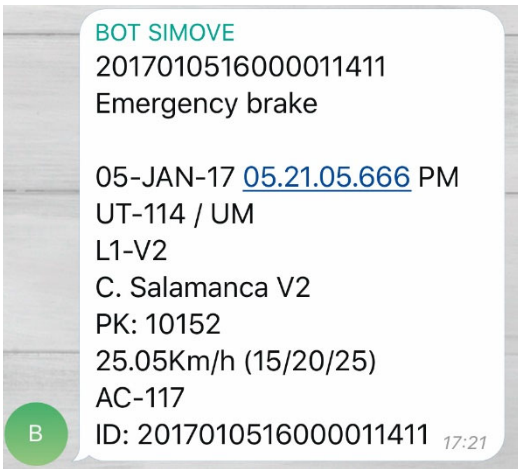

Fig. 5 - Mensaje de texto enviado a un destinario predeterminado ante un FU

1.2.6 Registro y almacenamiento.

- Registro de los datos significativos proporcionados por el sistema. Todos los datos registrables son parametrizables.
- Volcado de los mismos a un servidor central donde se almacenarán en una base de datos.
- Distintos medios de descarga de datos en el vehículo (USB, Ethernet y Wifi).
- Grabación del sonido ambiental de la cabina de conducción para verificar las alarmas acústicas en caso de exceso de velocidad.
- Informes operacionales disponibles para facilitar el análisis e investigación.
- Datos registrados:
  - Fecha/Hora.
  - Numero de vehículo y su cabina de conducción.
  - Línea y dirección de viaje.
  - Identificación del conductor.
  - Tipo de vehículo.
  - Posición GPS medida (coordenadas).
  - Posición Odómetro calculada.
  - Posición teórica (PK de la línea asociado).
  - Distancia de error entre GPS y PK asociado.
  - Velocidad GPS medida.
  - Velocidad Odómetro calculada.
  - Velocidad máxima del tramo.
  - Velocidad de alarma del primer aviso.
  - Velocidad de emergencia (2º aviso y aplicación del FU).
  - Activación de la alarma de precaución (aviso).
  - Activación del frenado automático en el vehículo.
  - Estado del conmutador de inhibición.
  - Precisión del cálculo de la posición, basada en los diferentes valores del GPS.
  - Incidencia detectada (código).
  - Número de satélites GPS encontrados.
  - Número de satélites GPS en uso.
  - Calidad de la señal GPS.
  - Activación del DGPS (corrección diferencial de GPS).
  - Relación r/n necesaria para cálculos con el odómetro (siendo r el radio de la rueda y n el número de dientes para un giro completo de la misma).
  - Distancia acumulada desde la última posición de referencia.
  - Control de las distintas versiones del software, configuración y parametrización.

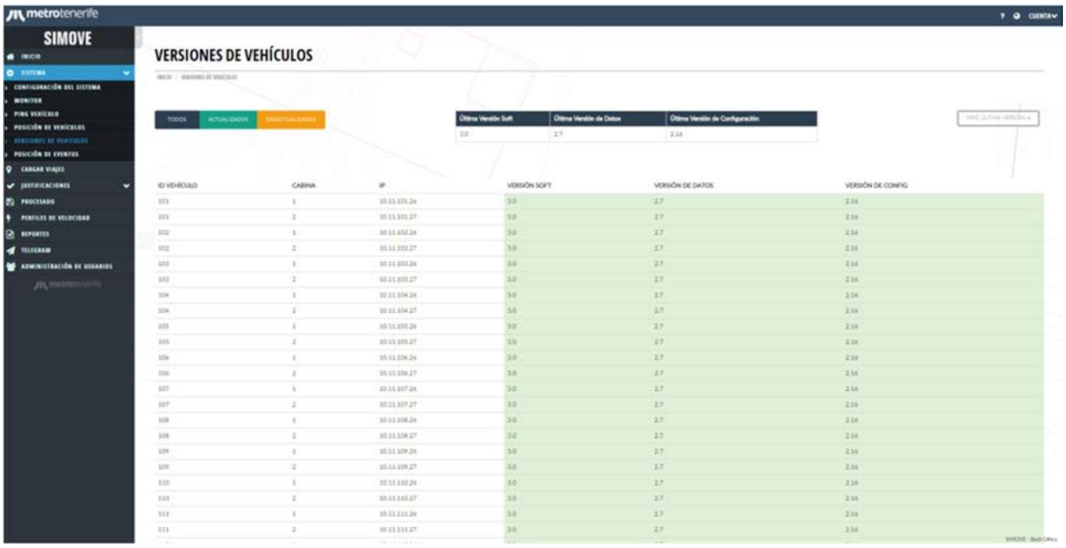

Fig. 6 - Versiones de vehículos en el back office de SIMOVE

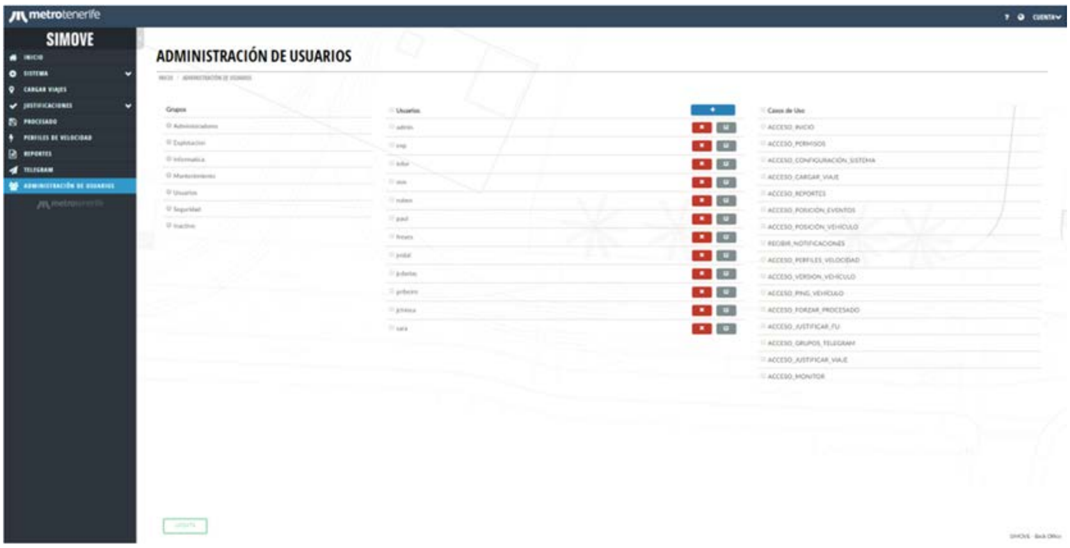

Fig. 7 - Administración de usuarios en el back office de SIMOVE

1.2.7 Mantenimiento y configuración.

- Recepción de ficheros desde el servidor central para su configuración.
- Menú de mantenimiento con código de acceso para:
    - Test de funcionamiento. Realización de pruebas periódicas que confirman el buen funcionamiento del equipo, tales como: conectividad, estado del GPS, números de pulsos, diámetro actual de rueda, etc.
    - Cambio de perfiles, unidad múltiple, unidad simple, líneas virtuales, etc.
    - Volcado de datos a memorias externas.
    - Versión de software, de datos, parametrización.
    - Identificación de unidad, cabina e IP.
    - Muestra si existen ficheros pendientes de cargar, tanto de datos como de audio.
    - Introducción del diámetro de la rueda después de su torneado o reemplazo.

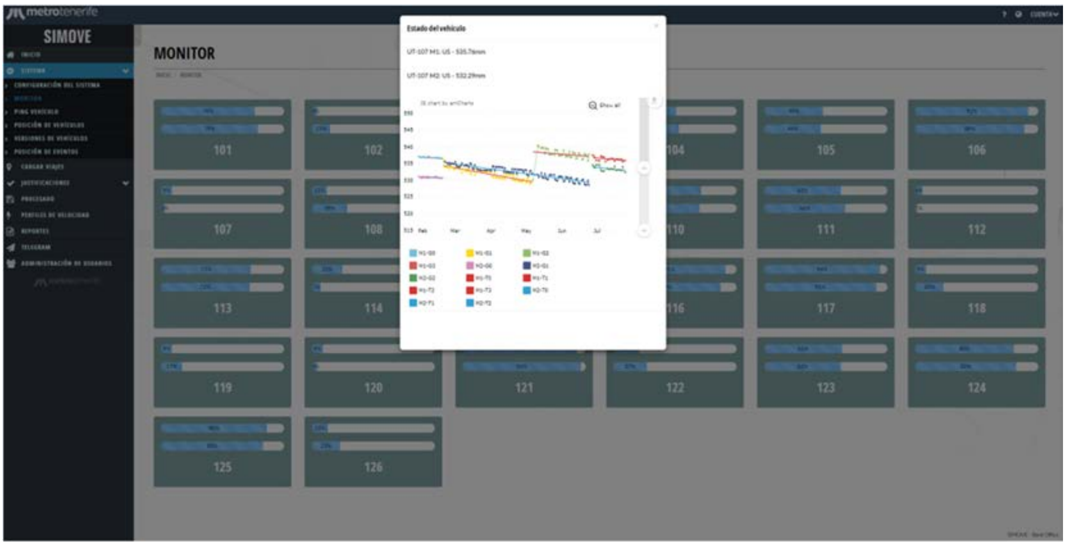

Fig. 8 - Información sobre el estado de la rueda en el back office de SIMOVE

- Actualización local o remota tanto del software como de los parámetros y tablas.
- Acceso mediante VNC al equipo embarcado desde el back office.

1.2.8 Inhibición del sistema embarcado.

- Inhibición automática del sistema en caso de que desconozca la línea/sentido y por tanto no pueda aplicar el perfil de velocidad correcto.
- Inhibición automática del sistema cuando el vehículo recorra una distancia establecida sin haber logrado reposicionarse por GPS.
- Posibilidad de inhibición manual por parte del conductor, sólo mediante autorización del operador, mediante el accionamiento del correspondiente conmutador, el cual se encuentra precintado para evitar la inhibición del dispositivo de forma no controlada.

1.2.9 Integración de la radiodifusión

El sistema puede ser integrado con la radiodifusión, de forma que controle la señal y volumen de la misma, evitando interferencias en las comunicaciones con el PCC y pasajeros. Además, si el SIMOVE emitiera avisos sonoros, estos prevalecerán sobre los sonidos de radiodifusión, que serían bloqueados durante el tiempo de duración de dichos avisos

2. CHAQUETA AISLANTE EXTRAÍBLE PARA LÍNEAS DE METRO LIGERO

2.1 Introducción

En líneas ferroviarias urbanas tipo LRT (L*ight Rail Transit*), con trazados en superficie, los carriles suelen implantarse en plataformas reservadas o compartidas, embebidos generalmente en revestimientos de pavimento rígido y en revestimientos verdes (césped natural o artificial); esto se debe a que en entornos urbanos existe en muchos casos la necesidad de transitar sobre la plataforma tranviaria (por ejemplo: cruces con calzadas de vehículos, calles peatonales…, etc.) y también por cuestiones de integración visual y paisajismo. La existencia de canalizaciones metálicas soterradas en entornos urbanos (canalizaciones de servicios) obliga a aislar los carriles debido a que éstos forman parte del circuito eléctrico de alimentación de los tranvías (circuito de retorno) y pueden afectar a las canalizaciones por el efecto de las corrientes vagabundas; por otro lado, es conveniente también aislar acústicamente el carril para disminuir la emisión de ruidos causados por la rodadura ferroviaria. Ambas circunstancias han llevado a la generalización del empleo de chaquetas aislantes que envuelven inferior y lateralmente al carril en este tipo de líneas.

En el marco de las operaciones de mantenimiento de una línea de metro ligero, la sustitución de carriles desgastados representa un quebradero de cabeza para los operadores de estos sistemas de transporte público. Con las soluciones actuales de aislamiento, la sustitución de carriles cuando llegan al final de su vida útil conlleva la demolición de los revestimientos, ya que tanto los carriles como sus sujeciones se encuentran embebidos en el revestimiento. En ese escenario, la sustitución de carriles conlleva un conjunto de inconvenientes que se citan a continuación:

- Coste para el operador por los trabajos de demolición y posterior reposición de pavimentos, operaciones éstas que no generan ningún valor añadido a la plataforma tranviaria, siendo por lo tanto una inversión sin rentabilidad
- Generación de residuos RCD (residuos de construcción y demolición), los cuales son generalmente trasladados a vertedero debido a su difícil reciclado.
- Plazo de ejecución de las operaciones de demolición y reposición, con interferencias para el servicio comercial de transporte
- Molestias al entorno urbano por ruidos, polvo, desvíos de tráfico, etc.

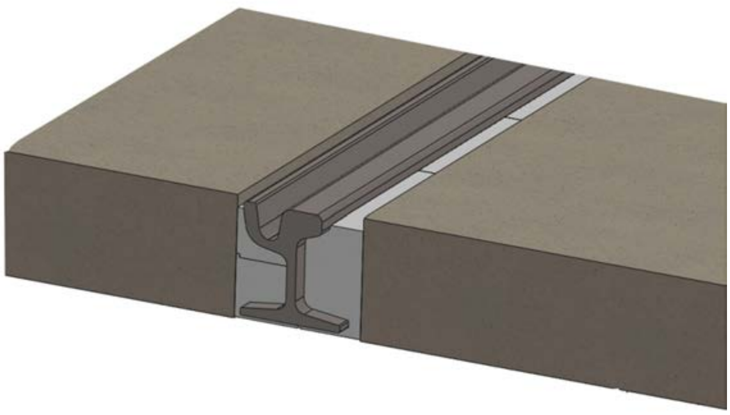

Fig. 9 - Solución habitual de chaqueta aislante de carril

2.2 Chaqueta Aislante Extraíble

Para solventar estos inconvenientes Metrotenerife ha desarrollado y obtenido la patente en España (OEPM) y en Europa (EPO) de un diseño de chaqueta aislante de carril que permite la sustitución de los carriles desgastados sin necesidad de afectar al revestimiento.

La Chaqueta Aislante Extraíble cumple con el cometido de aislamiento eléctrico y acústico que presentan el resto de soluciones del mercado, pero introduce la novedad de poderse retirar fácilmente para extraer el carril antiguo y volver a colocarse una vez reemplazado el carril nuevo, volviendo a cumplir con su tarea de aislamiento. La retirada de la chaqueta y su reposición no requieren de trabajos de obra civil tales como demolición o construcción, aportando por tanto un claro beneficio para el operador en los términos indicados anteriormente. Adicionalmente, este diseño concreto de chaqueta aporta otras ventajas en términos de fabricación respecto a otras soluciones constructivas, pues reduce el volumen de material empleado y además elimina la necesidad de uso de caperuzas de protección de la sujeción, hechas habitualmente en plástico, proporcionando por tanto beneficios medioambientales.

Metrotenerife comenzó con las pruebas de la nueva chaqueta en el año 2016, y desde entonces ha implantado esta solución constructiva en sus líneas durante las operaciones de sustitución de carril, obteniendo resultados satisfactorios hasta la fecha.

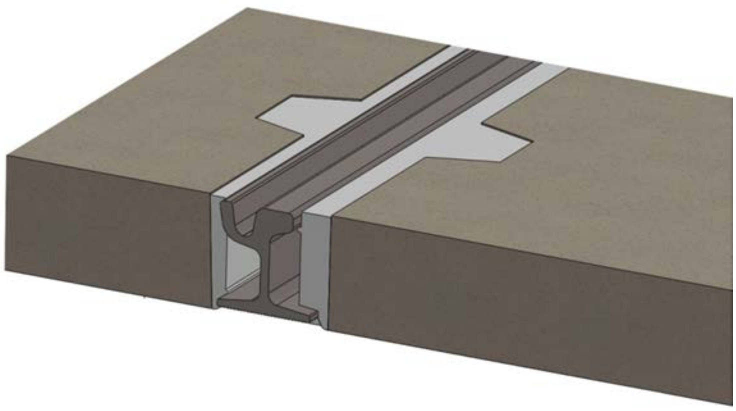

Fig. 10 - Solución chaqueta aislante extraíble de Metrotenerife

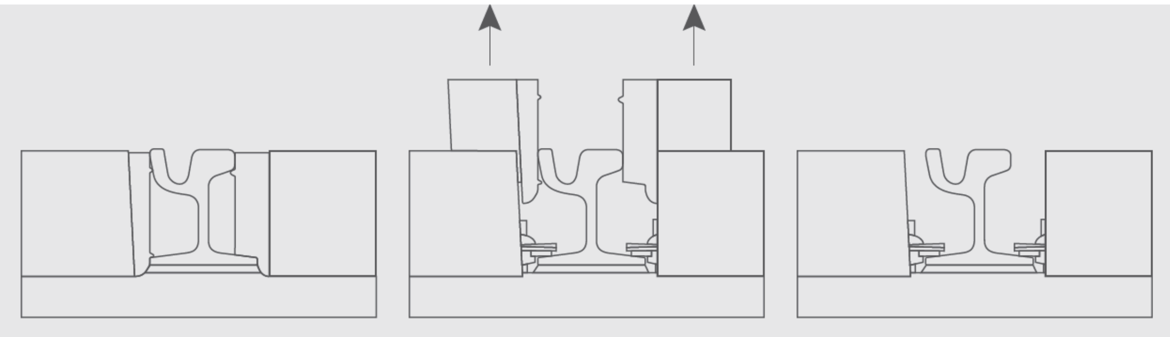

Fig. 11 - Extracción vertical y sustitución del enchaquetado sin necesidad de demoler el revestimiento

2.3 Solución polivalente

La solución de chaqueta aislante extraíble permite ser instalada en los diversos tipos de revestimientos empleados habitualmente en las líneas de metro ligero, tanto pavimentos rígidos como revestimiento verde (césped). Además, también permite ser instalada en cruces con calzadas de vehículos, en cuyo caso se añade un perfil metálico de protección de la interfaz entre chaqueta y revestimiento para evitar daño y erosión de ambos materiales, una solución empleada también en las soluciones constructivas habituales del mercado actual.

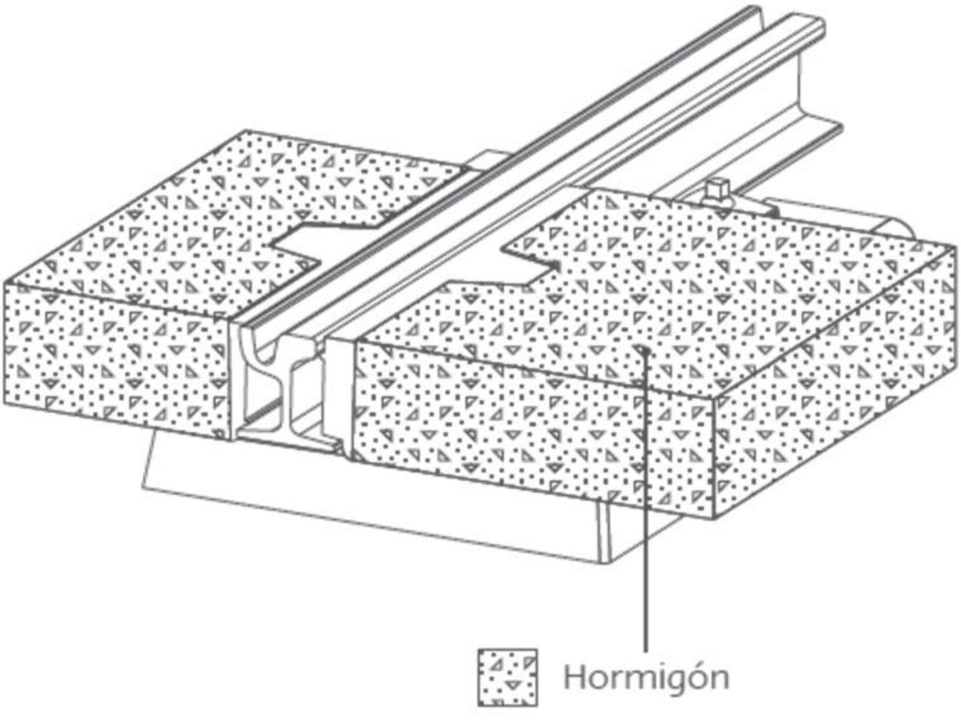

Fig. 12 - Instalación con revestimiento de hormigón, sin cruce con circulación rodada

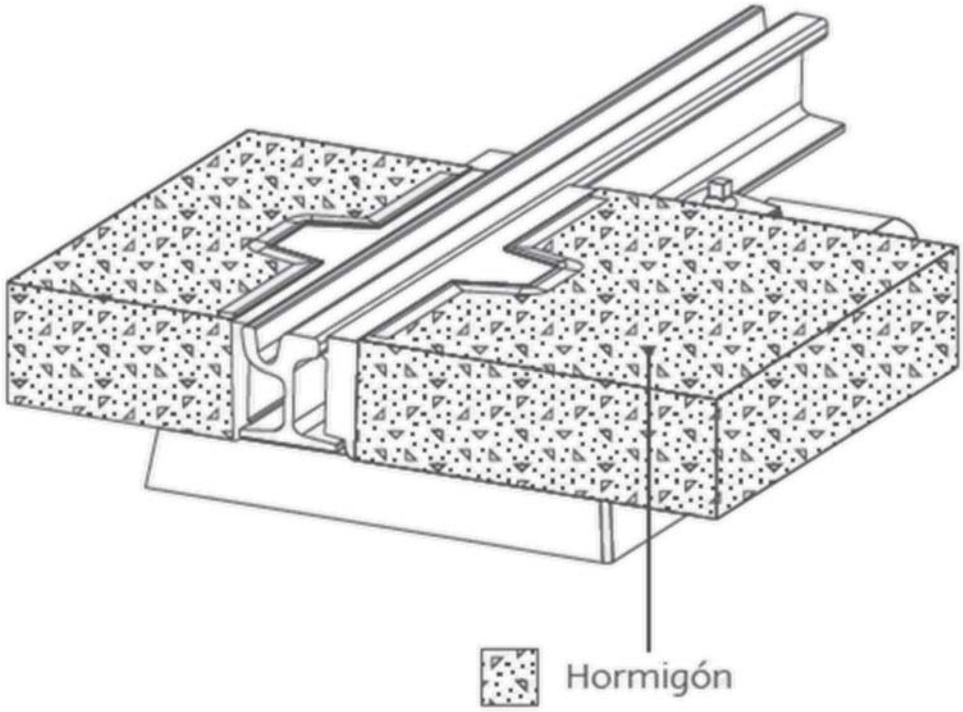

Fig. 13 - Instalación con revestimiento de hormigón, en cruce con circulación rodada (con perfil metálico de protección)

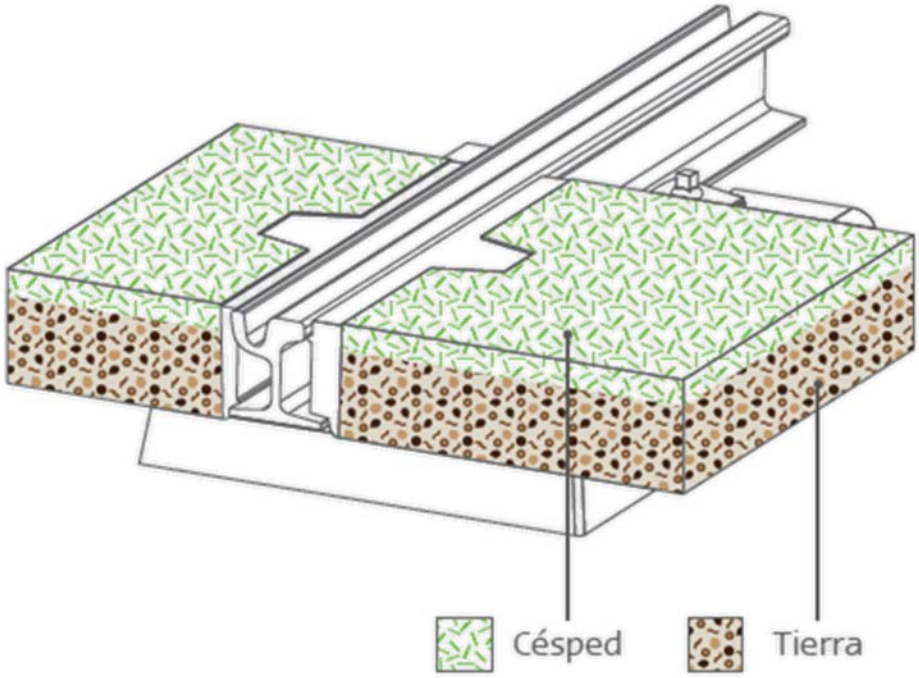

Fig. 14 - Instalación en revestimiento verde (césped)

		
Revestimiento de hormigón	Cruce con calzada	Revestimiento verde

Tabla 1 – Instalación con diversos revestimientos

2.4 Ventajas

Por tanto, la chaqueta aislante extraíble aporta las siguientes ventajas respecto a los modelos de chaqueta actuales del mercado:

- Menor coste de fabricación, al necesitar menor volumen de material
- Reducción del número de elementos a emplear en el conjunto de aislamiento, al eliminar la caperuza de protección de la sujeción, ya que la propia chaqueta cubre la sujeción
- Mejoras en afección medioambiental, al eliminar el uso de caperuzas plásticas
- Reducción de costes para el operador al eliminarse los trabajos de demolición y posterior reposición de pavimentos, operaciones éstas que no generan ningún valor añadido a la plataforma tranviaria
- Reducción de residuos RCD (Residuos de Construcción y Demolición) emitidos por las operaciones de sustitución de carril con soluciones estándar
- Reducción de los plazos de ejecución de las operaciones de demolición y reposición
- Reducción de las interferencias sobre el servicio comercial de transporte, al reducirse el plazo y eliminarse trabajos de obra civil en la plataforma ferroviaria
- Reducción de molestias al entorno urbano por ruidos, polvo, desvíos de tráfico provocados por la demolición y reposición en las soluciones estándar.

ESTUDIO EXPERIMENTAL DE LA PISADA DE PASAJEROS AL MOMENTO DE BAJAR AL ANDÉN DESDE UN TREN URBANO

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RESUMEN

El metro de Santiago de Chile es hoy en día uno de los medios de transporte más usado por los capitalinos, es por esto que muchos pasajeros con movilidad reducida (PMR) lo prefieren. Sin embargo, en las líneas del metro podemos encontrar distintas brechas verticales (BR) que se generan entre el tren y el andén. Estas BR dificultan los PMR para subir y bajar del tren generando un cambio en su pisada, afectando su estabilidad. Esta estabilidad se puede representar con distintas variables como la fuerza de rechazo y amortiguamiento, los rangos de recorrido de cada componente de pisada y el área generada por estos rangos de recorrido.

El objetivo de este artículo es estudiar, de forma experimental, el efecto de la BR en la pisada de PMR en el espacio tren-andén de estaciones de metro. Para esto, se llevó a cabo la construcción de experimentos a escala real que representan la transición tren-andén en el Laboratorio de Dinámica Humana de la Universidad de los Andes. Para obtener los datos, se ocupó una placa de fuerza Bertec y un software Bertec Acquire 4, el cual permite entre otras cosas obtener la fuerza en el eje z y los centros de presión en el eje x y eje y.

Los resultados muestran que a mayor BR, mayor es la inestabilidad en PMR. Además, también se observó como PMR cambian su estrategia de pisada al tener que enfrentar BR mayores a 11 cm, dado que cambiaron totalmente el ángulo de inclinación con el cual las personas posicionan su pie al bajar, de manera de poder hacer el proceso con mayor estabilidad. Se espera que en futuros experimentos se logre expandir el alcance de este tipo de estudios, al implementar más instrumentación y un mayor número de participantes.

1. INTRODUCCIÓN

Al igual que en otras ciudades del mundo, en Santiago de Chile, el transporte público más importante es el tren urbano o metro. Este sistema es el principal esqueleto que conecta todas las redes de la capital, cuenta con 7 líneas y conexiones a las otras redes de trasporte público, como buses suburbanos y Red Metropolitana de Movilidad (ex – Transantiago). Este a la vez presenta una característica esencial, que es tener accesibilidad universal, logrando que pasajeros con movilidad reducida (PMR) puedan usarlo sin problemas, sin ninguna restricción y de forma autónoma (Subsecretaría de Transportes, 2013; Ministerio de Vivienda y Urbanismo, 2010; 2016). La accesibilidad universal se debe entender como lo estipulado en la Ley de accesibilidad universal, contexto normativo en el cual se debe regir, inspirar y alcanzar:

> "Avanzar hacia un país inclusivo y moderno, que otorgue a todos iguales oportunidades de cumplir metas y aspiraciones personales: Un desafío a la arquitectura, urbanismo, programas y proyectos públicos a incorporar las condiciones necesarias para que nuestras ciudades, edificios, plazas y parques tengan posibilidades de acceso y uso para todos sus habitantes" (Ministerio de Vivienda y Urbanismo, 2010).

Esta cita explica a grandes rasgos, que en Chile se esta dando un importante impulso al diseño de ciudades para cumplir con todas las normativas vigentes. Por consiguiente, los diferentes sistemas de transporte público tienen el desafío de adaptarse a la accesibilidad universal para que los pasajeros puedan no solo acceder a este sino también utilizarlo (Tyler, 2002). La accesibilidad hoy es un término amplio y relativo, imprescindible tanto para conseguir una igualdad de oportunidades efectiva para todas las personas, como para optimizar el diseño de un entorno (Alonso, 2007). Sin embargo, hay dos tipos de diseños que son importantes de mencionar al hablar de accesibilidad en el transporte público: existen diseños de accesibilidad que están pensados para pasajeros con discapacidad y otros para PMR. Por ejemplo, los ascensores o rampas son una ayuda para pasajeros con discapacidad que requieren de una silla de ruedas como herramienta para poder moverse, sin embargo el uso de escaleras con pasamanos o escalones menos altos son soluciones que se buscan para dar accesibilidad a PMR. Por lo tanto, PMR son capaces de desenvolverse en entornos de transporte público sin accesibilidad universal, pero no por eso es menos importante buscar diseños que le mejoren la calidad de vida.

En trenes urbanos, los problemas de accesibilidad se concentran en la interfaz tren-andén, el cual presenta mayores riesgos de accidentes para PMR (Seriani y Fernández, 2015). En el caso del metro en Santiago, se ha utilizado un material de caucho como relleno para reducir la brecha horizontal entre el andén y tren (ver Fig. 1 - izquierda). Por otro lado, para reducir la brecha vertical (BR) algunas estaciones de metro han introducido andenes elevados.

A modo de ejemplo, la estación Green Park en el metro en Londres tiene un andén elevado que se extiende en una parte del andén y tiene una longitud total de 27 m (ver Fig. 1 - centro), por lo que este elemento cubre el segundo y tercer vagón y un total de cuatro puertas (dos dobles y dos individuales). A pesar de las diferentes medidas para mejorar la accesibilidad universal en dicha interfaz (Ministerio de Vivienda y Urbanismo, 2010; 2016), las soluciones se limitan a diferentes factores como el diseño del andén (por ejemplo, andenes curvos), puertas del tren (por ejemplo, número y ancho de puertas) y piso del tren (por ejemplo, material), y por lo tanto no pueden implementarse en todas las estaciones. Como consecuencia, algunas estaciones aún tendrán un BR, que es un valor fijo considerando el tipo de tren y el diseño de la interfaz en cada estación (ver Fig. 1 - derecha) (Oyanedel, 2020). Para ahondar en diseños de BR, estudios realizados por Fernández et al. (2010; 2015) buscó simular flujos unidireccionales en el que participantes suben y bajan de 3 BR distintas: 0 cm, 15 cm y 30 cm. Los resultados muestran un mejor diseño estaría dentro del rango de 0 cm a 15 cm. Esto abre un rango en el que este estudio busca trabajar y ver cómo se comporta el proceso de pisada para PMR.

Fig. 1 – BR en estaciones de metro: material de caucho (izquierda), andén elevado (centro), BR existente (derecha)

Para poder dar soluciones que mejoren la accesibilidad universal en la interfaz tren-andén, se necesita estudiar el efecto de la BR en la pisada de PMR. Mas específicamente, este articulo busca estudiar de forma interdisciplinaria como afecta la BR en la inestabilidad de PMR para un proceso de bajada desde el tren al andén, combinando conocimientos de transporte y kinesiología mediante instrumentación y métodos de estudio. Los objetivos específicos son los siguientes: (a) definir variables relevantes de estudio que afectan el proceso de pisada de PMR al enfrentar una BR, (b)definir un método para medir las variables relacionadas a la estabilidad de un proceso pisada, (c) simular en el Laboratorio de Dinámica Humana de la Universidad de los Andes (LDH en adelante) pasajeros que bajan una BR en un experimento a escala real, (d) analizar los datos obtenidos en el experimento para ver como varia la estabilidad de una PMR en distintas BR.

Este artículo está estructurado en cinco secciones, comenzando con la introducción. En la sección 2 se presentan los estudios existentes relacionados con la BR. En la sección 3, el método se explica en base a experimentos de laboratorio. En la sección 4, se presentan los resultados seguidos de la discusión y las conclusiones de la sección 5.

2. ESTUDIOS EXISTENTES SOBRE EL PROCESO DE PISADA

Podríamos decir que, en estaciones de metro, subir y bajar por diferentes BR es algo que pasajeros realizan a diario. Sin embargo, esta tarea locomotora tan cotidiana es bastante exigente para PMR, especialmente considerando sus restricciones de movilidad en sus extremidades inferiores. Enfrentar BR puede ser muy difícil, por lo que urge una manera, forma y solución que no demande tanto esfuerzo físico ya que sería una ayuda significativa en la calidad de vida de personas con impedimentos físicos. Además, recuperar la locomoción es un factor clave que ayuda a un paciente regresar a su casa después de una lesión (Startzell et al., 2000). Se puede identificar que la marcha al pasar una BR se pude separar en el ascenso y descenso de ésta, lo cual es significativamente una tarea compleja para PMR, que demanda un esfuerzo físico y también a su vez el uso de cierta capacidad motriz, siendo una potencial causa de pérdidas de equilibrio y caídas (Hashish et al., 2017).

El proceso de pisada es un proceso o secuencia de movimientos del pie por el cual una persona se mueve hacia adelante, se puede dividir en dos fases principales: (a) amortiguamiento, el cual corresponde cuando el pie hace contacto con el suelo, tomando toda la carga del cuerpo en el tobillo de este pie, (b) rechazo, el cual se define como el abandono de este pie del suelo, instancia en que la última parte en perder contacto corresponde a los dedos. Para estudiar dicho proceso, se debe analizar el desplazamiento del centro de masa (COM) que representa el grado de balanceo del cuerpo en diferentes direcciones. También es importante el centro de presión (COP), el cual se refiere al desplazamiento, calculado por los cambios de posición del punto de fuerzas de reacción del suelo, representando la estrategia de marcha y la estabilidad del cuerpo. En este sentido se puede calcular la estabilidad dinámica (DGS) como un parámetro que tiene en cuenta simultáneamente el COM y su velocidad instantánea, por lo que es una buena forma de medir pérdidas de equilibrio y caídas. Además, el ángulo de inclinación del pie existente en dos planos, el antero posterior y plano medio lateral, es un parámetro difícil de medir e tiempo real, pero esta directamente relacionado con la inestabilidad. Por su parte, la placa de fuerza es un instrumento para medir las fuerzas de reacción del suelo generadas por un cuerpo que pasa o esta sobre este. Generalmente son usadas para cuantificar el equilibrio, la marcha y otros parámetros de la biomecánica. Dicha placa se complementa con cameras VICON, las cuales son utilizadas como instrumento para registrar los movimientos de las personas tridimensionalmente mediante el uso de pines de metal reflectantes, generalmente con aplicaciones médicas y deportivas (Bhatt et al., 2011).

A partir de las definiciones anteriores, un estudio realizado por Song et al. (2020) analizó cómo las personas descienden por un escalón. Los resultados arrojaron que a mayor complejidad de la tarea cognitiva o manual que se realiza al bajar la escalera menor es la velocidad de la pisada, pero no afectó DGS ni tampoco el ángulo de inclinación. Lo anterior dado que se creía que la marcha ocurre inconscientemente y no involucra funciones cerebrales superiores. Los resultados dicen que las tareas cognitivas y manuales en paralelo requieren recursos adicionales, demostrando el peligro que es hacer tareas en paralelo mientras se descienden escalones. También es importantes destacar cómo afecta llevar cargas externas a la hora de descender o ascender por un escalón. Un pie soporta el peso de todo el cuerpo, el otro pie avanza al siguiente escalón generando una desigualdad en la carga y por consiguiente un aumento en la velocidad medio lateral del COP (Anker et al., 2008), y también mayor desplazamiento de este durante el inicio de la pisada (Vieira et al., 2016).

Por otra parte, un estudio realizado por Wang y Gillette (2020) buscó investigar el efecto de carga simétrica y carga asimétrica externa en las extremidades inferiores durante el proceso de descenso y acenso de escalones. Los resultados indicaron que llevar carga de manera asimétrica es lo que más daña la estabilidad seguido por la carga simétrica. En ambos casos este parámetro se vio más perjudicado a la hora del descenso y manteniéndose relativamente normal en el acenso.

En base a los estudios anteriores, poder medir la estabilidad es una de las características más importantes que ayudan a las personas a intuir caídas, además de poder completar acciones secundarias mientras esta está en desplazamiento. Dadas todas las formas de establecer qué es la estabilidad, una forma empírica, práctica y con bastante literatura de respaldo para medir, es mediante desplazamiento del COP (Huang y Brown, 2013). La obtención del COP se logra médiate el uso de una placa de fuerza, la cual entrega un punto en milímetros de donde se sitúa el COP en dicha placa, situando un eje cartesiano imaginario donde el punto 0,0 está justo en el centro de ésta. El uso de la placa es una técnica relacionada con la cuantificación del balanceo postural o movimiento plano medio lateral de una persona de pie. Ayuda a medir el balanceo real de cada pie o el balanceo de todo el cuerpo. Los desplazamientos del COP es una de las medidas más comunes de balanceo corporal (Lafond et al., 2004). La interpretación empírica más extendida de las medidas típicas del balanceo de la postura plano medio lateral es que un mayor balanceo significa mayor inestabilidad, lo que se considera una indicación de un sistema de control postural deteriorado. Este razonamiento se basa en muchos experimentos sobre el envejecimiento y las condiciones patológicas que, de hecho, han observado una mayor influencia en esas condiciones. Sin embargo, se debe tener en cuenta que puede que no siempre sea así (Lafond, et al., 2004).

El valor del desplazamiento COP depende, de dónde pisa la persona en la placa de fuerza. Un procedimiento típico en el análisis del COP es eliminar el valor medio de los datos ya que este es generalmente por el largo del pie, generando la presencia de una tendencia.

Si bien se podría argumentar que la tendencia en sí misma podría brindar información valiosa sobre la señal (Zatsiorsky y Duarte, 2000), el problema es que la mayoría de las medidas que se usan deben asumir que la señal es estacionaria. Una señal es estacionaria si sus propiedades estadísticas (como la media y la varianza) no cambian a lo largo del tiempo. Por lo tanto, para eliminar la tendencia de los datos puede ser necesario en ciertos casos aplicar un filtro de paso alto a los datos con una frecuencia de corte relacionada con el período de adquisición de datos (Witt et al., 1998).

Por otro lado, la velocidad media expresa la velocidad promedio del desplazamiento del COP, calculada simplemente como la variable de trayectoria total (el desplazamiento total) dividida por el período total. Esta variable generalmente se conoce como velocidad, pero como es un escalar, debería llamarse velocidad propiamente tal. La velocidad media resultante es la velocidad calculada en forma vectorial considerando cada dirección, es decir, la raíz cuadrada de la suma de la velocidad al cuadrado de la dirección antero posterior y la dirección plano medio lateral. Otra forma de medir el balanceo postural es calcular el área que abarca los datos del COP en el plano antero posterior y el plano medio lateral usando una curva en un plano (por ejemplo, un círculo o elipse) o un polígono (por ejemplo, un rectángulo). Un método común para ello es calcular una elipse de predicción, que se encuentra ajustando una elipse a los datos utilizando conceptos del procedimiento estadístico conocido como análisis de componentes principales. Una elipse de predicción del 95% es un intervalo de predicción para los datos de COP de modo que existe un 95% de probabilidad de que una nueva observación se encuentre dentro de la elipse. De la interpretación del COP se puede decir que, a mayor área de desplazamiento durante un determinado tiempo, mayor será la inestabilidad y también el balanceo (movimiento plano medio lateral) de la línea dejada por el desplazamiento del COP de una persona avanzando rectamente. Entre menos recta sea esta línea, mayor será su inestabilidad.

En conclusión, la información bibliográfica indica que, dada la literatura expuesta y a pesar de los avances encontrados hasta la fecha sobre el proceso de pisada y sus variables asociadas, se requiere un estudio sobre el comportamiento de la estabilidad para distintas BR en la interfaz tren-andén. Se debe estudiar en conciso cómo afecta la variación de BR en la estabilidad dinámica de PMR que tiene que descender por ésta desde un tren urbano, lo cual será el objetivo principal de este artículo.

3. MÉTODO EXPERIMENTAL

3.1 Diseño experimental en laboratorio

Para el diseño experimental se realizaron mediciones de las 7 líneas de la red de metro en Santiago, eligiendo 3 estaciones por cada línea, dando una muestra de 21 estaciones (correspondientes al 15% de la red). En terreno se recolectó datos de cada estación en ambos sentidos durante la semana del 4 de diciembre de 2019.

En la Tabla 1 se muestran las BR observadas por este estudio, se agrupa las estaciones por su línea correspondiente, y cada estación se divide en dirección 1 y 2, correspondiente a cada andén, respectivamente. Las BR están en un rango de valores entre 0 y 12,5 cm. En el caso de BR = 0 cm corresponde a las nuevas líneas 3 y 6, donde los trenes nuevos tecnología de puertas en andenes y el tren se dirige sin conductor (de forma automatizada). El caso de 12,5 cm corresponde a la línea 2, donde se utilizan trenes más antiguos.

Para medir las BR en cada estación, se utilizó elementos de medición directa (por ejemplo, una huincha de medir) al momento que el tren se detenía próximo al andén. Se seleccionó la puerta más crítica de un tren, entendida como la puerta que está próxima a la salida o entrada del andén, y por ende la que probablemente utilizan PMR, ya que este tipo de pasajeros tienden a fatigarse al desplazarse en trayectos largos (Tyler, 2002).

Línea	Nombre Estación	Dirección 1	Dirección 2
		BR [cm]	BR [cm]
Línea 1 (L1)	Estación Central	1,5	1,7
	Pedro de Valdivia	0,0	1,3
	Los Dominicos	1,5	1,7
Línea 2 (L2)	Vespucio Norte	12,5	1,8
	Parque O'Higgins	10,5	1,7
	La Cisterna	1,7	1,7
Línea 3 (L3)	Puente Cal y Canto	6,0	6,0
	Irarrázaval	5,5	5,3
	Plaza Egaña	4,5	5,5
Línea 4 (L4)	Tobalaba	6,3	4,2
	Quilín	2,7	3,0
		4,0	5,0
	Hospital Sótero del Río	2,2	4,7
Línea 4A (L4A)	La Cisterna	6,5	4,0
	Santa Rosa	4,7	4,0
	Vicuña Mackenna	1,7	1,7
Línea 5 (L5)	Blanqueado	11,0	9,0
	Ñuble	6,6	8,0
	Vicente Valdés	6,0	1,6
Línea 6 (L6)	Lo Valledor	5,3	5,0
	Franklin	5,5	5,5
	Los Leones	5,0	5,0

Tabla 1 – Dimensiones brecha vertical (BR) observadas en las estaciones de metro en Santiago

Para realizar el experimento se tuvo que construir un piloto a escala real en el Laboratorio de Dinámica Humana (LDH) de la Universidad de los Andes, basado en los datos de BR que se mencionan en la Tabla 1. El piloto consta de 6 cajones de maderas independientes entre sí, cinco de estos serían “el tren” y el otro restante correspondería al “andén”. Es importante mencionar que el cajón del andén es de suma importancia, ya que en él está la placa de fuerza, por lo que su diseño debió ser especial, meticuloso y más complejo. La decisión de construir los cajones de forma independiente se tomó, principalmente, porque de esta manera se resolvería el problema de que estos no fueran a quedar perfectamente apoyados al piso, generando movimientos indeseados mientras los participantes estuviesen caminando sobre ellos en el experimento. Además de esto, transportar y almacenar el piloto en el LDH sería mucho más cómodo. Una vez montado el piloto, fue sujetado con 4 ligas entre sí como muestra la Fig. 2, generando una sola estructura rígida con los 5 cajones correspondientes al “tren”. De esta manera se podía trasladar la placa a cada nivel distinto de BR de una manera fácil y rápida. Cabe destacar que el diseño del cajón correspondiente al andén era el más importante en este estudio, ya que cualquier falla generaría ruidos en los datos. Esto debido a la sensibilidad de la placa de fuerza durante las mediciones. Se hizo una base solida y pesada de planchas de madera para la placa de fuerza, de esta manera el peso ayudaría a que no se generasen vibraciones y así trabaría por separado al cajón.

Fig. 2 – Piloto para la experimentación en el LDH: pasajero pisando la placa de fuerza (izquierda), movimiento de cajón “andén” para diferentes BR (derecha)

Los escenarios para simular la bajada de pasajeros desde el tren al andén se muestran en la Tabla 2, cuyos valores están en el rango de observaciones de estaciones del metro de Santiago reportadas en Tabla 1.

Escenario	Cajón “Tren”			
	Ancho (m)	Largo (m)	Alto (cm)	Brecha vertical (cm)
1	0,80	1,50	13,00	0,00
2	0,80	1,50	16,75	3,75
3	0,80	1,50	20,50	7,50
4	0,80	1,50	24,25	11,25
5	0,80	1,50	28,00	15,00
	Cajón “Andén”			
	Ancho (m)	Largo (m)	Alto (cm)	Nivel (cm)
Todos	0,80	1,50	13,00	0,00

Tabla 2 – Escenarios que representan BR en el LDH

Por motivos de la pandemia (COVID 19), no fue posible reclutar PMR para el experimento.

Lo anterior porque las pruebas se llevaron en los meses que la ciudad de Santiago se encontraba con medidas de cuarentena y con un número alto de casos activos. Por lo mismo, se optó por buscar personas sanas y simular mediante casos una reducción en su movilidad.

Los participantes del experimento fueron 5 hombres jóvenes de 26 años, entre ellos un rango de altura de 172,4 ± 7,7 cm, con masa corporal de 70,4 ± 9,7 kg. Los criterios de exclusión de participantes (no podían participar) fueron la incapacidad de seguir las instrucciones, afecciones de inestabilidad cardíacas, reemplazo de articulaciones de miembros inferiores, artritis, diabetes, problemas de visión o cualquier otro problema neuromuscular que pueda evitar que los participantes puedan ejecutar el ensayo forma segura y efectiva. Los participantes no podían estar bajo prescripción de un medicamento en los últimos siete días y además no debían tener experiencia de anomalías al caminar en los últimos tres años.

Todos los participantes reportaron tener el pie derecho dominante, y lo definen como la pierna preferida para patear una pelota de fútbol. Con esto último podemos lograr reducir errores en los resultados, asegurando que la persona usó su pie más diestro para bajar desde el tren al andén (Gribble et al., 2007).

Respecto a los escenarios, se consideraron 4 casos de estudio (ver Fig. 3) para casa situación de BR definida en la Tabla 2. En cada caso se buscó simular algún tipo de características de PMR en los participantes añadiendo cierto factor de movilidad reducida. En cada caso se afrontó el proceso de amortiguamiento, es decir la bajada del tren al andén. Para dar mayor validez a los datos se efectuaron 3 repeticiones por cada proceso de pisada. En resumen, se consideró cinco participantes en 4 casos, con 5 BR diferentes, en la modalidad de bajada considerando 3 repeticiones por caso. Esto dio un total de 300 archivos .csv los cuales almacenaron en un proceso de pisada completo de principio a fin.

Fig. 3 – Casos a considerar en los experimentos de laboratorio: bota ortopédica (superior izquierda), carga simétrica (superior derecha), carga asimétrica (inferior).

En resumen, se consideraron los siguientes casos:

- Caso 1: En el primer caso cada participante hizo el experimento sin factores que afecten su movilidad. Esto para tener una medición base de sus perfiles y ver cómo se comporta su centro de presión en la normalidad. Esto fue tomado más adelante como la estabilidad "normal" para después poder comparar estos valores con los valores obtenidos por los otros casos.
- Caso 2: Cada integrante utilizó una bota ortopédica en el pie derecho, lo cual le dio menor movilidad en sus articulaciones, tratando de simular a una persona con problemas o lesiones en sus extremidades inferiores.
- Caso 3: Cada integrante cargó con el 20% de su masa corporal distribuida de manera simétrica en su mano derecha e izquierda, para simular un pasajero con dos bolsos de compras (siguiendo el estudio de Wang y Gillette, 2020).
- Caso 4: Cada integrante cargó con el 20% de su masa corporal distribuida de manera asimétrica en su mano derecha, buscando simular un pasajero con un solo bolso de compras de mayor carga (siguiendo el estudio de Wang y Gillette, 2020).

3.2 Medición de variables

La forma en que la placa de fuerza entrega los datos es a través del software Bertec. Una vez ya instalada la placa en el piloto y listo el participante para el experimento llega el momento de elegir qué datos se desea grabar.

El software en sí es sencillo y amigable para poder trabajar con la placa de fuerza. Éste permite, entre otras cosas, poner el nombre al archivo, ver gráficos en tiempo real de la pisada, su tipo de extensión (.CVS), para luego poder trabajar con estos en Python. Para el nivel de detalle que se necesita se usó 100 hz para no crear archivos extremadamente grandes. Una de las cualidades más importantes del programa es que tiene un filtro de auto-zero digital, lo que permitió eliminar todo tipo de ruidos adicionales que se produjeron por vibraciones del ambiente. El valor que se ocupó como filtro fue 4 kgf o 39,2 N en el eje z el cual es el recomendado por el desarrollador y viene listo de fábrica. Este valor de magnitud no tiene relación con el COP, pero al usarlo como filtro, se eliminaron todos los puntos de COP asociados a los valores menores a 4 Kgf en el eje z. Lo anterior afecta directamente al área y la velocidad, ya que los registros que se filtraron creaban puntos extra que no correspondían al proceso de pisada propiamente tal y “ensuciaban” los resultados.

Mediante distintas librerías Python, se generó un código para obtener valores por cada proceso de pisada. Para esto el código se ubicó en la misma carpeta que todos los otros archivos. Este automáticamente leyó cada valor de pisada y generó matrices asociadas al nombre de cada archivo. Estas matrices fueron de dimensiones (3, n), siendo n el largo del archivo, donde la primera columna es la fuerza en el eje z (Fx Z), mientras que la segunda columna es el COP-antero posterior y la tercera columna es el COP-plano medio lateral.

Un ejemplo de los datos de salida del código usado en Python se muestra en la Fig. 4. Los valores obtenidos por cada archivo fueron:

- Área elipse 95 % confianza (cm^2)
- Largo de movimiento antero posterior (cm)
- Largo de movimiento plano medio lateral (cm)
- Velocidad movimiento antero posterior (cm/s)
- Velocidad movimiento plano medio lateral (cm/s)
- Suma de ambas velocidades al cuadrado (cm/s)

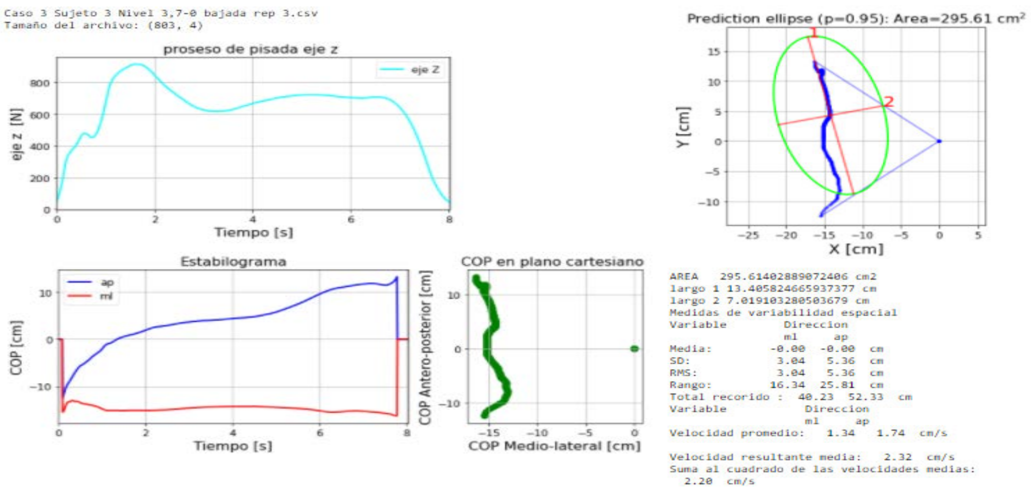


Fig. 4 – Ejemplo de datos de salida del código en Python con filtro a 4 kgf

Una vez ya leídos todos los archivos por el código, se traspasaron los valores obtenidos de cada uno a una planilla de Excel donde se promediaron las 3 repeticiones hechas en cada BR y caso para los 5 participantes. Una vez completada la planilla, se exportaron sus datos en Power-BI, la cual es una plataforma que permite hacer operaciones y visualizarlos de forma adecuada. De esta manera, estudiar como varía la estabilidad de los participantes en cada caso del experimento al cambia las BR. Estos valores obtenidos fueron combinados entre si mediante la obtención de las siguientes variables de comparación por caso (de ahora en adelante VC). Se da este carácter de comparación debido a que ni una variable por si sola puede darnos mucha información, pero al ver como varían entre ellas podemos dar con información útil.

La VC1 (ver ecuación 1) es de gran ayuda para estudiar el comportamiento del área formada por la elipse de 95% confianza. A mayor largo del pie mayor será su recorrido antero posterior, y por ende mayor el área de la elipse. Haciendo esta división se logra llegar a un valor donde las características físicas del pie del participante no afectan los datos.

$$VC1 = \frac{Área\ elipse\ (cm^2)}{Largo\ de\ pie\ (cm)} \quad (1)$$

El rango medio lateral representa la estabilidad. A mayor rango medio lateral menor estabilidad durante el proceso de pisada. Al comparar BR distintas el rango de movimiento antero posterior va a variar, y por ende es necesario compararlo con el medio lateral en una razón expresada en ecuación 2.

$$VC2 = \frac{Medio\ lateral\ (cm)}{Antero\ posterior\ (cm)} \quad (2)$$

La división en ecuación 3 relaciona que tan grande fue la velocidad de la pisada en el plano antero posterior, en comparación al rango de movimiento antero posterior. Si este valor aumenta, se debe a que la estabilidad disminuye. A menor rango antero posterior se le atribuye un menor ángulo de inclinación en el plano antero posterior. Este ángulo es con el que se entra y sale del proceso de pisada. Al sentir inestabilidad ante una BR, el participante busca entrar con un ángulo de inclinación más cercano a los 90 grados. Por ello, no se tiene un rango de movimiento antero posterior menor. Además, si a esto se le agrega que este rango antero posterior se lleva a cabo a una velocidad igual o mayor es porque la persona busca salir rápido de la situación para lograr estabilidad rápidamente antes de caerse, comúnmente visto en personas que se tropiezan al bajar escaleras o que no puede controlar su velocidad en este proceso.

$$VC3 = \frac{Vel.\ antero\ posterior\ (cm/s)}{Antero\ posterio\ (cm)} \quad (3)$$

En la ecuación 4 se repite la lógica anterior de VC 3, sin embargo en este caso se ve la relación del vector de velocidad que se compone por velocidad del plano antero posterior del plano medio lateral, por lo que se hace una comparación con el área de la elipse.

$$VC4 = \frac{\sqrt{vel.AP^2 + vel.ML^2}\,(\frac{cm}{s})}{Área\ elipse\ (cm^2)} \quad (4)$$

Las variables de comparación VC 2, VC 3 y VC 4, son divisiones de variables con unidades distintas. Estos VC no se exponen por su unidad resultante ya que no tienen un sentido físico.

Más bien se exponen como divisiones ya que lo que se busca es ver como estas se comportan entre si y si su relación aumenta o disminuye al variar las BR. Las VC se comparan utilizando gráficos de cajas, los cuales se usan para grupos de puntuaciones en escala. De esta manera, permite estudiar las características de distribución de un grupo de puntuaciones, así como el nivel de las puntuaciones. Las puntuaciones se ordenan de menor a mayor, y se forman cuatro grupos de igual tamaño a partir de las puntuaciones ordenadas. Es decir, el 25% de todas las puntuaciones se colocan en cada grupo. Las líneas que dividen los grupos se denominan cuartiles y los grupos se denominan grupos de cuartiles. Por lo general, se etiqueta estos grupos del 1 al 4 comenzando por la parte inferior. En los resultados además se añadió un punto circular que da el promedio de los datos, así también poder ver una tendencia de este lo que agrega una mayor comprensión de estos. Cada punto le corresponde al promedio de las 3 repeticiones hecha por cada participante.

4. RESULTADOS

4.1 Caso 1 (base)

Los resultados de este caso son de gran importancia, ya que son los que sentarán las bases para el resto de los casos. En la Fig. 5 se observa que el VC 1 (razón entre el área de la elipse y el largo del pie) presenta una leve pero constante disminución a medida que aumenta la BR. Se esperaba ver un aumento del área de la elipse, ya que al aumentar la BR los participantes debiesen haber presentado un cambio negativo en su estabilidad. De hecho, esto si sucedió, sin embargo 4 de los 5 participantes cambiaron su estrategia de pisada al afrontar BR más grandes. Para cambiar la estrategia se debe disminuir el ángulo de inclinación en el plano antero posterior. Es decir, que el pie derecho buscó estar en una posición más cercana a los 90 grados al llegar al andén. Si bien en este estudio no se pudo medir el ángulo de inclinación, podemos deducir si esta variable disminuyo o aumento relacionando las demás VC del caso base.

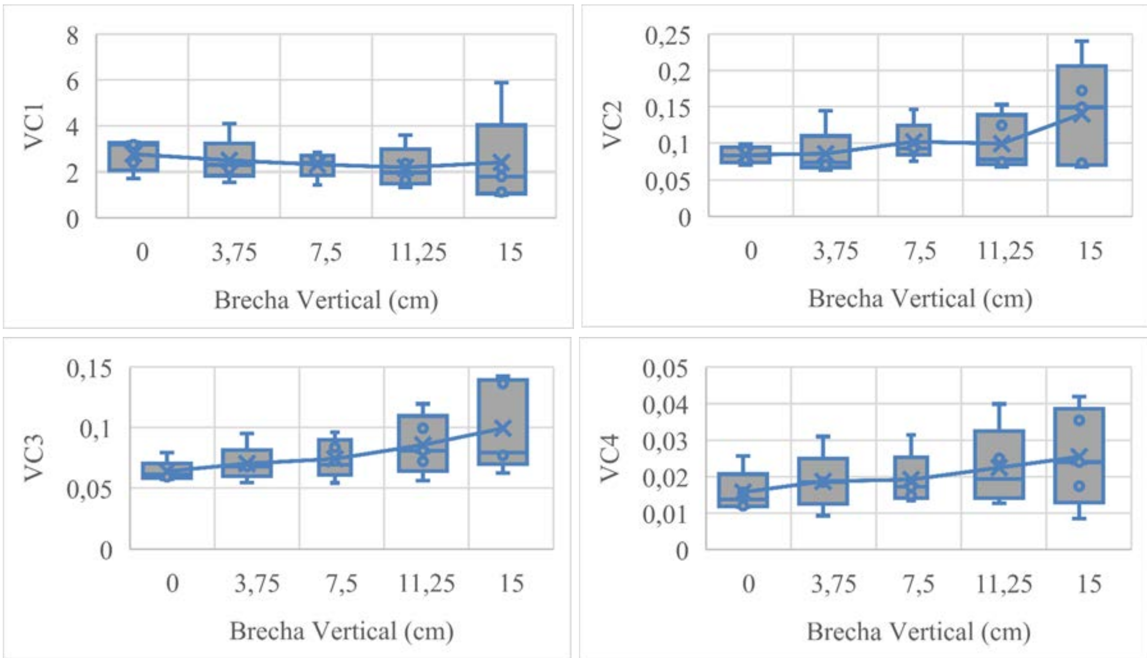


Fig. 5 – VC para cada BR en el Caso 1 (base)

Respecto a VC2 (razón entre el medio lateral y antero posterior) la Fig. 5 muestra un constante pero pequeño aumento de inestabilidad. Esto quiere decir que la estabilidad plano medio lateral se vio afectada de manera negativa al aumentar la BR. El mayor salto se puede ver entre la BR 11,25 cm y BR 15 cm. En el caso de VC 3 (razón entre la velocidad del movimiento antero posterior y antero posterior) y VC4 (razón entre la velocidad del movimiento antero posterior, velocidad del movimiento medio lateral y área de elipse), la Fig. 5 muestra una clara tendencia al aumento de la inestabilidad. Esto comprueba que el ángulo de inclinación del plano antero posterior disminuyó constantemente al aumentar la BR. Como se explico anteriormente esto se debe a que los participantes cambiaron su estrategia de pisada.

Los gráficos obtenidos para el caso 1 fueron utilizados como la base de comparación en los siguientes casos. Se hace hincapié en mencionar que todas las VC se comportaron como se esperaba, a excepción de la VC1. En esta se esperaba ver un crecimiento en vez de una disminución, sin embargo, al analizarla y ver como se comportó el resto podemos entender que la razón está en el cambio de estrategia de pisada. Se puede dar como conclusión del Caso 1 que, a mayor BR, mayor fue la inestabilidad, en donde BR = 15 cm fue la más perjudicial para los participantes.

4.2 Comparación de casos

En el Caso 2 (bota ortopédica), los resultados de la Fig. 6 no muestran una tendencia tan clara como en el Caso 1 (base). Los valores en promedio se mantuvieron sin variaciones extremas. Es decir, algo en la bota ortopedia aportó cierta ayuda a los participantes.

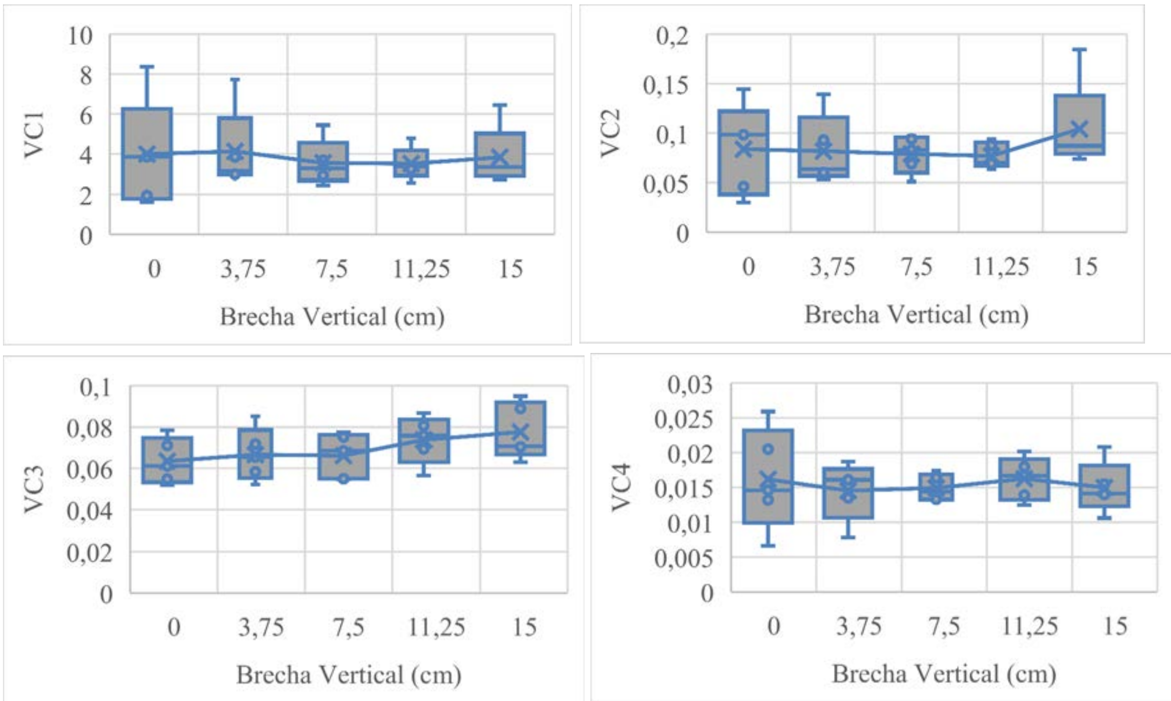


Fig. 6 – VC para cada BR en el Caso 2 (bota ortopédica)

Las botas ortopedias son usadas en caso de lesiones o roturas producidas en las extremidades inferiores y a diferencia de los yesos clínicos estas pueden ser removidas, para ayudar al paciente. Su construcción es mayormente de plástico de alta densidad y tela acolchadas para no producir heridas en la piel de quien la usa. Estas botas restringen toda la movilidad en la pantorrilla, tobillo y dedos del pie, generando una dificultad al caminar. Una posible razón de está poca variación en los valores obtenidos para cada VC se debe a que la suela de la bota es curva, lo cual afecta el plano antero posterior y plano medio lateral. Esta curvatura lo que genera es que el COP tienda a centrarse durante todo el proceso de pisada, disminuyendo sus rangos antero posterior y medio lateral, y por ende las VC no mostraron una tendencia clara de mayor inestabilidad al aumentar las BR. Esto no significa que esta mayor inestabilidad no sucedió, sino que el método empleado basado en el COP no logró medir bien las pisadas con este tipo de suela con curvatura.

En la Fig. 7 se observa que el Caso 3 (carga simétrica) es una versión más inestable comparada al Caso 1. Esto debido al peso extra añadido a los participantes el cual correspondió al 20% de su peso. Esta inestabilidad se hizo notorio en las últimas BR, lo cual tiene una explicación clara, pues a mayor BR el peso que llevaba cada participante genera una aceleración, y por ende los participantes tuvieron que hacer un esfuerzo mayor para mantenerse estables (reflejado en las VC2 y VC3).

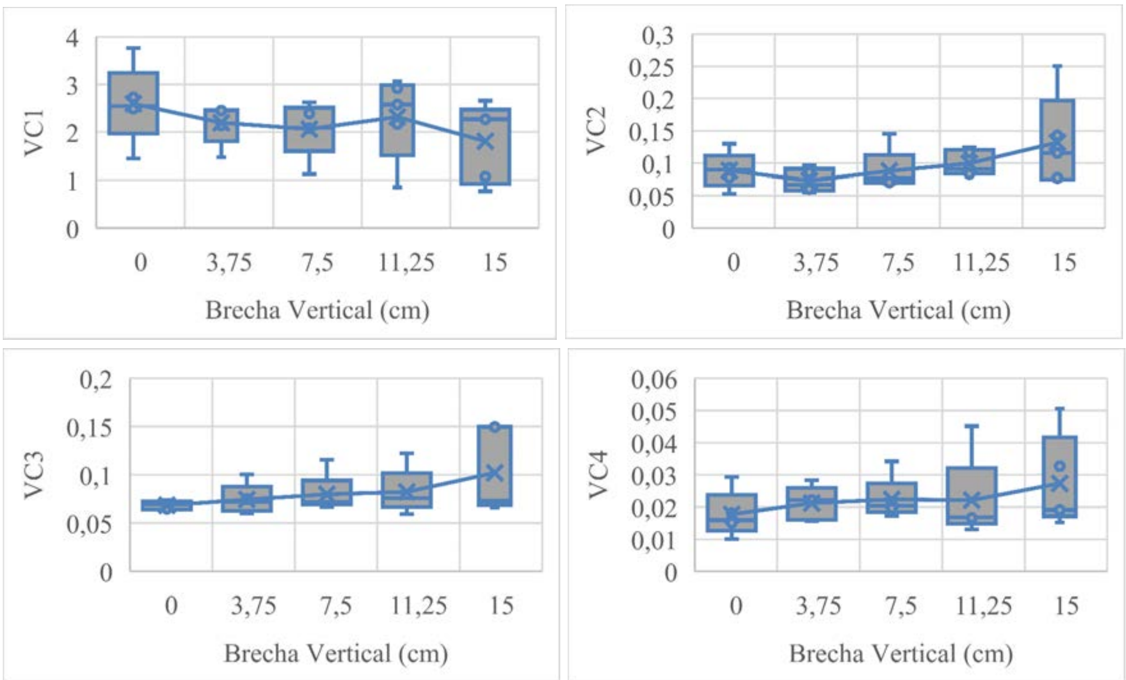
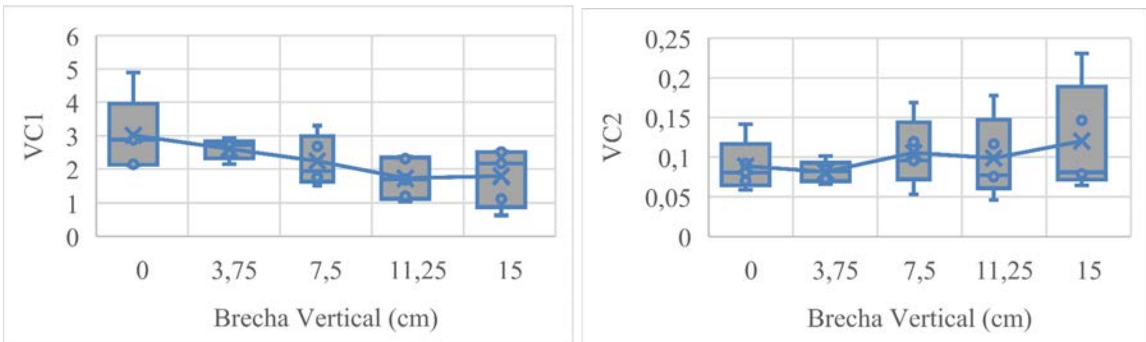


Fig. 7 – VC para cada BR en el Caso 3 (carga simétrica)

En el Caso 4 (carga asimétrica) la Fig. 8 muestra tendencias similares al Caso 3. La VC2 marca un aumento similar al Caso 3, lo que implica que la estabilidad plano medio lateral se vio afectada de manera negativa al aumentar las BR. Sorprende que la variación fue menor a las del Caso 1 y al Caso 3. Sin embargo, un nuevo fenómeno se observó (y también en el Caso 3) durante la inspección visual de los gráficos de pisada. Este fenómeno se mostró en desplazamientos del COP erráticos y anormales en un 3,5% de archivos correspondientes a BR = 15 cm. También este fenómeno se observó para BR = 11,25 cm. Los participantes presentaron desplazamiento como se observa en la Fig. 9 donde se aprecia que, en vez de hacer un desplazamiento lineal, se genera un desplazamiento en forma de "V". La inestabilidad generada fue tan alta que la amortiguación se hizo primero con los dedos del pie. Este fenómeno se considera común en un proceso de salto, pero no de pisada. Luego, el peso pasó a los talones para después continuar con un proceso "normal" de pisada.



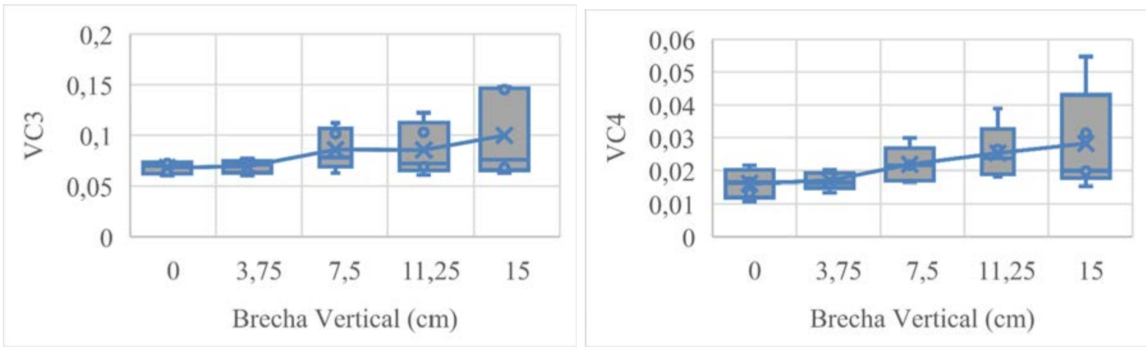


Fig. 8 – VC para cada BR en el Caso 4 (carga asimétrica)

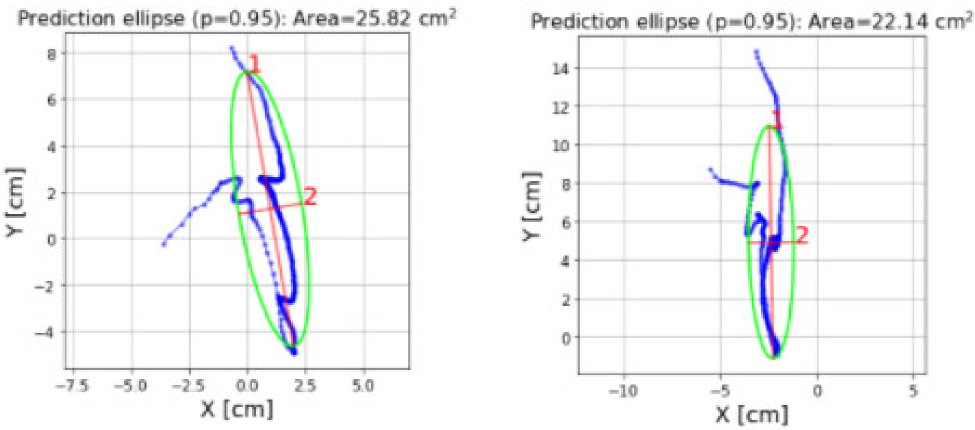


Fig. 9 – Desplazamiento del COP en forma de "V": Caso 4 (izquierda) y Caso 3 (derecha)

5. CONCLUSIONES

Este artículo se centró en estudiar las variables que afectan la estabilidad de PMR al enfrentar distintas BR, para luego construir un piloto experimental que pudiera determinar una forma eficaz de medir las variables asociadas a la pisada en el proceso de bajada desde un tren urbano a un andén. La metodología expuesta se basó en el diseño del piloto a escala real que permitió simular y medir este proceso de pisada. Una vez obtenidos los datos necesarios para poder ver el movimiento COP y el área de la elipse de 95% de confianza, se obtuvieron los valores suficientes para llegar a las 4 variables comparadas (VC), y así observar como varían en 4 casos diferentes para 5 escenarios de BR (realizando 3 repeticiones de pisada).

Los 4 casos distintos de estudio, permitieron dar una muestra de datos para estudiar el impacto de BR en la inestabilidad de PMR. El Caso 1 (base), entregó más información, dado que los resultados fueron los puntos de comparación para el resto de los casos. De los resultados se puede desprender que el área de la elipse no es la mejor manera de medir inestabilidad, puesto que los participantes del experimento tomaron cambios de estrategia para distintas BR, lo cual generó un cambio en el ángulo de inclinación del plano antero posterior de su pisada.

En el Caso 2 la suela curva de la bota ortopédica no permitió que se pudiera medir correctamente el desplazamiento del COP. Esto hace sentido ya que una suela curva genera que la persona tenga menos posibilidad de caer o resbalarse y así contrarrestar el efecto negativo de esta bota en su movilidad

Los Casos 3 y 4, dieron un fenómeno nuevo. Entregaron datos de inestabilidad mayores al Caso 1, y además mostraron desplazamientos erráticos para BR = 11,25 y BR = 15 cm. Esto demuestra que BR mayores a 15 cm no son aptos para PMR.

Una de las áreas que este estudio no pudo profundizar y puede ser fuente de inspiración para investigaciones en el futuro es hacer mediciones de COP y COM simultaneas en los participantes. De esta manera se puede lograr la obtención del ángulo de inclinación en el plano antero posterior y medio lateral, logrando tener datos empíricos de sus valores durante un proceso de pisada. Para esto debería usarse un sistema más complejo de medición, lo que añadiría una cantidad de tiempo necesaria para llevar a cabo el experimento. Sin embargo, se recomienda este camino ya que este artículo es más bien exploratorio y parte desde las bases, por lo que un estudio que expanda la experimentación realizada sería un excelente complemento para esta línea de estudio.

Por otra parte, la mayor limitación que se tuvo en este estudio, y es además la razón principal de porque los datos no mostraron tendencias claras en algunos casos como se esperaba. El número reducido de participantes que se pudo congregar para ser parte del experimento en el LDH fue un punto complejo de solucionar. Esto debido al marco de la pandemia del COVID19 que está atravesando el país y el mundo en este momento.

Se concluye que los resultados entregados para determinar el cambio de estabilidad en PMR en distintas BR, dan evidencia que a mayor BR se genera de manera directa y indirecta una mayor inestabilidad. Si bien no se logró dar con un diseño final o entregar valores absolutos de BR, los resultados permiten comparar escenarios y casos, los cuales dejan entre ver que nos es posible tener rangos de BR mayores a 15 cm en personas sanas (Caso 1) y rangos de BR mayores a 11,25 cm en PMR, puesto que causaría una alta inestabilidad en el proceso de pisada al bajar desde un tren urbano al andén.

AGRADECIMIENTOS

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METHODOLOGY FOR THE DEVELOPMENT OF RAILWAY OPERATING PLANS

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ABSTRACT

The main objective of this paper is to determine the methodology to be followed for the optimization of railway transport services supply in a railway line selected as scope of the study.

To carry out this optimization, it is vitally important to have a high-quality database, which includes consolidated technical information. This database will be made up of different items, which will refer to aspects related to the infrastructure (equipment, alignments, slopes, speeds, etc.) and to its traffic type (passengers, freights or mixed).

Furthermore, a geographic database must be considered, in order to the railway line will be digitized from a satellite image, and on which all the items included in the database that are relevant for the development of the operating plan will be spatially captured.

Once the data is collected, gear simulations are carried out with commercial times and the calculation of energy consumption for each rolling stock. This allows us to know the commercial times that would be registered on the line with different trains and consumption, in order to determine the optimal material that would be of interest for commercial exploitation.

Through the elaboration of traffic meshes, the economic balance of the operator is calculated for different service offers, until the one that the operator considers optimal is obtained. Likewise, it provides production results and operating costs.

This methodology focuses on the maximization of the railway transport capacity to attract potential passengers from other modes that could be more environmentally aggressive. For this reason, the reduction of the energy consumption by taking advantage of braking energy is a key issue.

The main objective of carrying out a railway operating plan is to promote the use of rail transport by improving the service, both quantitatively and in terms of quality, by reducing travel and waiting times, increasing supply and reducing operating costs.

Therefore, to carry out said optimization of existing or newly created passenger services, an analysis of the current situation of both services and infrastructure must be carried out, an estimate of the demand that would involve the incorporation or elimination services, and finally an economic analysis.

1. ANALYSIS OF CURRENT AND FUTURE SITUATIONS

To perform a good optimization of services, it is vitally important to have a quality database, which includes revised and consolidated technical information. To do this, an analysis of the infrastructure to be exploited and the railway material available or the new material that will be available in the service must be carried out.

This base will be made up of numerous indicators, which will refer to aspects related to infrastructure (equipment, alignments, slopes, speeds, etc.) and to the traffic that develops on it (travelers, goods or mixed).

There must also be the existence of a reference cartographic base, where the layout will be digitized from a satellite image, and on which all the aspects contained in the database that are relevant for the elaboration of the data will be spatially captured.

This allows to create relevant tools so that the operator can optimize and manage the strategy for the operation of the line

2. TRAVEL TIME CALCULATION

Once the type of material destined for railway operations has been analyzed and defined, the commercial times are calculated.

To do this, minimum speed simulations have to be carried out, obtaining the minimum times and energy consumption that each service would have. Once these minimum times have been obtained, the commercial progress must be calculated taking into account the commercial and recovery margin defined in the UIC 541-1.

To obtain these times and consumptions, the simulation model will be based on an integration model. These types of models are basically based on three different approaches to estimate train movement: (i) a function of time, (ii) a function of distance, and (iii) an event-based model.

The best method used is based on the second option (function of distance) for estimating motion as well as energy. For this, it can be stated that energy consumption is the applied force necessary to move the vehicle a certain length:

$$E = \int F(s) \cdot ds \quad (1)$$

From the above formula it can be highlighted that:

- In each process of acceleration of the train there is a consumption of energy, because the positive acceleration implies a tractive force.
- In each deceleration process a certain amount of energy is generated in the brake, because negative acceleration implies a retarding force, which depending on its type can be dissipated in the form of heat or transformed into electrical energy and returned to network.

The way that is chosen to model the movement of a train is to calculate all the forces that act on the vehicle point to point. In this case, it corresponds to each meter, that is, in each meter of a defined line (Origin-Destination) the forces to which it is subjected are determined and / or the forces exerted on it are estimated.

The forces acting on the motion of a vehicle are:

a) Drag (R*av*).

$$R_{av} = A + B \times V + C \times V^2 \quad (2)$$

Where: *V* is the trains speed (km/h). A, B and C are the mechanical, air intake and aerodynamic coefficients that depend on the physical characteristics of the train *(daN, daN/(km/h) and daN/(km/h)^2).*

b) Resistance due to the curve (R*c*).

$$R_c = M_{car} \times \frac{600}{R} \rightarrow R_c = M_{car} \times \frac{800}{R} \quad (3)$$

Where: M_{car} is the mass of the loaded trains *(tons)* and R is the curves radius measured in metres *(m).*

c) Resistance due to slopes (R*p*).

$$R_p = M \times g \times i \quad (4)$$

Where: M mass of the train *(tons)*, g is gravity *(m/s^2)*, i is the slope *(mm/m)*

d) Traction or brake force (F*t*/F*d*).

The traction curve and the brake curve are in function of the speed (effort-speed curve) and depend on the train power and the adherence. Both curves are parameters provided by the manufacturer.

Next, it is showed an actual example of the effort-speed curve.

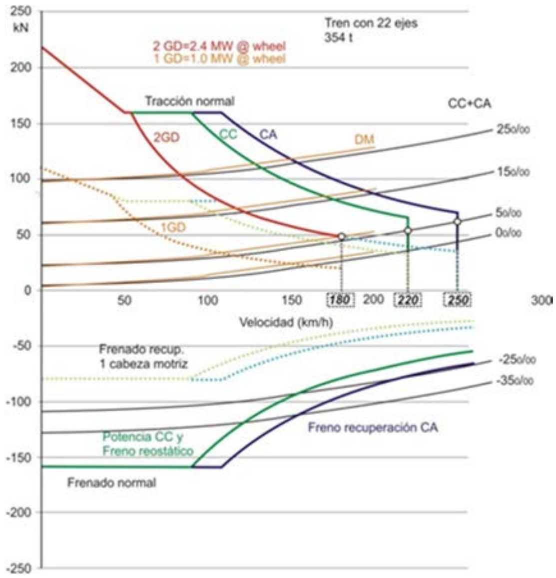

Figure 1. Example of the effort-speed curve

Knowing the forces exerted by the vehicle, both traction and braking, the energy consumption and the energy dissipated in the brake, essentially, are estimated with the following equations:

$$E_c = \int F_t(s) \cdot ds \;\; o \;\; E_R = \int F_d(s) \cdot ds \qquad (5)$$

Where: Ec is the energy consumed by the train (kWh), Er is the energy dissipated in the brake (kWh), Ft Tractive force (daN), Fd is the force exerted by the brake (daN), and ds is the differential of length.
The resultant of all the forces exerted and / or applied on the vehicle is the force used to estimate the acceleration (or deceleration)

$$F_{tot} = R_{av} + R_c + R_p + F_t + F_t = M_{tot} * \frac{dv}{dt} \qquad (6)$$

The M_{tot} parameter corresponds to the total mass of the vehicle considering the rotating masses.

Knowing the total force at a point, the acceleration, the speed, and the travel time are calculated using the equations of uniformly accelerated rectilinear motion.

This allows us to know the commercial times that would be recorded on the line with different trains and their consumption, in order to determine the optimal material that would be of interest for commercial exploitation.

3. DEMAND

Once the new travel times and the services to be implemented are known, it is essential to have a demand study for the different means of transport that currently serve this corridor, and to know the induced demand that will be captured from them. thanks to the improvements and possible changes proposed.

In order to carry out this demand study and find out the number of travelers they will have on the new services implemented, the current demand for the different media, their travel times and their frequencies is first analyzed.

In passenger transport there is a differential factor of the utmost importance, since, to move from one place to another, the traveler must not only pay the price of the ticket, but must also "contribute" their own time. People perceive that their time has value, and they implicitly "monetize" it or convert it into the equivalent of money. This total cost is what is called generalized cost, and it is what allows us to determine which means of transport each traveler will use.

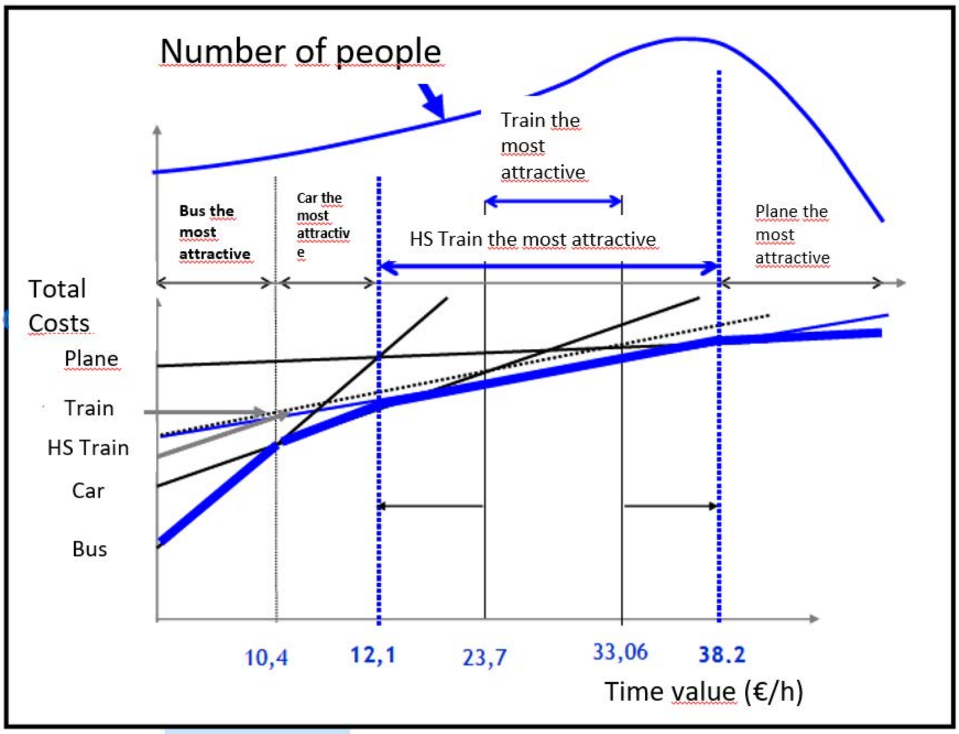

Figure 2. Generalized cost in various modes of transport as a function of the value of time. Effect on the competitiveness of the train of an increase in its speed.

To verify the demand data obtained, a study of generalized costs has been carried out, which is detailed below.

The parameters to take into account for the calculation of said generalized cost are:

a) Frequency
b) Time

To make the trip, in addition to the travel times of each means of transport, the waiting times, information and ticket purchase, travel and terminal times are taken into account.

$$Tt = Tb + Tdt + Te + Tv \quad (7)$$

Where:

Ticket time (Tb): It is the time used to get informed, get the tickets ...).
Travel time and terminal (Tdt): It is the time used to arrive and leave the terminal and to travel through it. The centrality of the stations and their limited dimensions will be taken into account.
Waiting time (Te): It is the time taken to wait for a transport offer. On average, the wait time is the inverse of the frequency.
Travel time (TV): The bus and car travel times will include the possibility of traffic jams, considering an average of 5 minutes throughout the journey.

c) Perceived Time

In each of the phases of the trip, time has a different value for each person, which coincides with personal experience. For example, the time is longer when the user has a bad time or is uncomfortable.

In this way, a modulation coefficient of perceived time is applied to the times, which introduce comfort, ergonomics, the perception of safety, etc. into the model.
The formula for the total perceived time would then be:

$$Tptot = \beta \times Tb + \delta \times Tdt + \Phi \times Te + \upsilon \times Tv \quad (8)$$

These coefficients depend on physical, utility or psychological factors:

- Physical factors: If the user is uncomfortable, without air conditioning, with noise.
- Useful factors: If you can take advantage of the time during the trip.
- Psychological factors: fear, uncertainty, insecurity.

The coefficients will have a value greater or less than 1 to homogenize the duration of time.

The higher these coefficients, the time "gets longer"

The cost of the time spent on the trip is calculated by multiplying the total time by the Value of time, VT (€ / hour).

$$Ct(€) = Tptot \times VT \qquad (9)$$

The total cost of the trip is the sum of the monetary costs and the cost of the time used, so the total general cost will be:

$$Ci = (Cmd + Cmo) + Ct \qquad (10)$$

Cmd: Direct monetary cost (€).
Cmo: Cost related to the station. They are considered transports from the origin and to the destination.
Ci: Generalized cost

Next, the modal split is calculated according to each mode of transport and its generalized cost:

$$Pi = e\ (-\gamma * Ci)\ \in e\ (-\gamma * Ci) \qquad (11)$$

Pi: Probability of choosing the medium "i"
Ci: Generalized cost of the trip in the medium "i"
n: Number of means of transport
γ: Model calibration parameter

Once the number of travelers per year is known, it is necessary to make a daily distribution, taking into account the usual oscillations such as weekends, times of greater load, oscillations between roundtrip directions, etc., in order to be able to size the fleet for the biggest daily commuter tip.

4. ESTABLISHMENT OF SERVICES

When preparing the best services according to the expected demand, it is necessary to define the analysis scenarios, calendars, service periods and patterns-types of schedules.

- Calendars: the "service calendars" of seasons of the year (for example, vacation, non-vacation) will be defined, indicating the number of weeks per year for each; as well as the peak, valley and flat periods defined for each season for standard days:

a) Monday to Friday; b) Saturdays, and c) Sundays and holidays. In the case of tips, it will indicate which is the dominant traffic direction at the tip.

- Hourly periods: Four time periods can be defined according to the classification of the hours: a) peak (with distinction of the two senses); b) flat; c) valley; and d) super-reduced.
- <u>Service patterns</u>: Various patterns (origins-destinations of trains and stops) to be associated with each of the time periods will be defined by technical assistance. These patterns will be defined for one hour and one direction, considering in principle that the schedules are cadenced and symmetrical. The most suitable minute of symmetry will be analyzed to optimize the rotations in all the headers.
- <u>Types of services:</u>
    - Stops service: This type of service is characterized, as its name indicates, by making stops at all stations on the line.
    - Semi-direct Service: It is characterized by making stops only at certain stations on the line. These stations have been determined based on the demand of each one of them, in order to support the dependencies that have the greatest demand.
    - Direct service: Direct services are those that are performed only between the main stations

In addition to the type of services mentioned above, it is also necessary to analyze whether it is convenient to establish optional stops

These stops are characterized by making it only in those dependencies in which passengers are going to get on or off.

With this type of service, which was in force at Renfe in the 1980s, it is intended to guarantee the reliability of the line's services by eliminating the stoppage of the train in those dependencies in which, in that specific service, there were no passengers who were to get on or off the train. In this case, the drivers, through the controller, will know those optional stops in which it is necessary to stop the train to allow passengers to get off. As for the ascent, it will be the driver, as the stations pass, who will make the stop depending on the presence of travelers on the platform.

- Thanks to this type of service you get:
- - The survival of those stops whose number of passengers is small or even null, which have the possibility of disappearing.
- - Reduction of travel times that can translate into margins for economical driving.
- - Fuel savings that may be due both to economical driving, as well as to the reduction of braking and acceleration due to the reduction in the number of stops, in case of switching from a service with stops to a service with optional stops.

- - Reduction of CO_2 emissions, which is given by the reduction of energy consumption.
- - Savings in maintenance of both the rolling stock and the track, due to less wear and tear due to reduced braking and acceleration.

It should be noted that each time a service is modified, the demand analysis must be carried out again, since each small change can cause an increase or decrease in the number of travelers on the operation.

5. SCHEDULE COORDINATION

Schedule design is a method by which energy consumption can be reduced at no additional cost. This makes this measure one of the best methods to reduce energy consumption.

It should be clarified that, in order to achieve these energy savings, in addition to applying the compatibility of schedules, the use of the regenerative brake is a crucial condition for any energy reduction in terms of schedules.

There are three aspects to be taken into account to reduce energy consumption. The first of them is related to (i) time frames and their compatibility with eco-driving previously explained; while the second and third are related to the (ii) coincidence between the departures, or between (iii) the departures and arrivals of the trains at a station respectively.

These aspects are described below.

- Time frames used to perform eco-driving:

Carrying out efficient and economical driving consists of exploiting advantages offered by the existing time frames in the schedules, in order to reduce energy consumption.

On the other hand, train schedules need "regularity margins" to be more robust and reliable.

That margin is often longer than the time required to perform eco-driving, therefore, it is possible to allow a small amount of time to do an eco-driving in the sections where there are no time requirements, and distribute the rest of the time between the points of the sections that require punctuality. Another possibility is to reduce the times in the stops in order to add these times to the margins necessary to carry out economical conductions.

- Avoid simultaneous departures:

The different tracks of the same station are normally fed by the same substation, even in some cases several stations are fed by the same substation. Therefore, if there is a simultaneous output of different trains, there is an increase in the peak power required in the substation, as shown in the following figure.

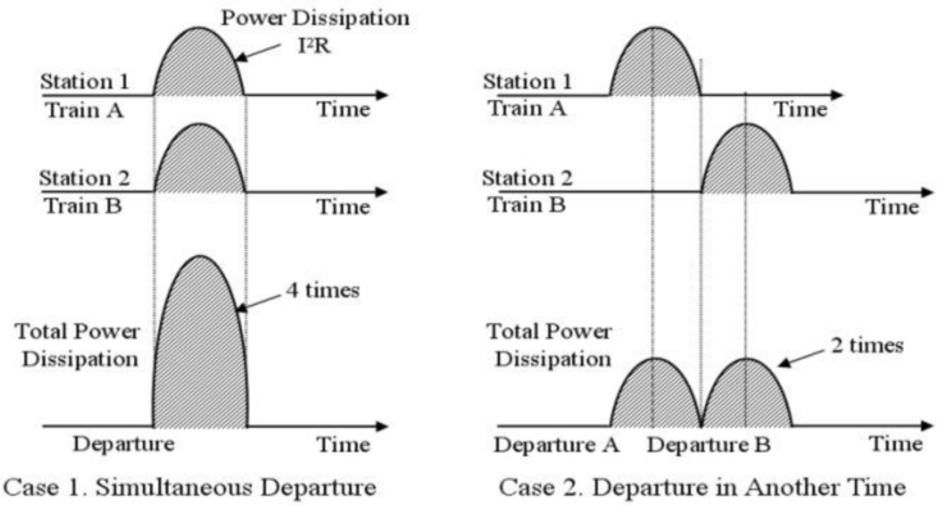

Figure 3. Power peaks due to train departures. Source: K.M. Kim et al. (2010).

This also implies an increase in ohmic losses, and therefore an increase in the energy required. In addition, the installation of a higher capacity substation is required, which translates into an increase in investment costs.

- Simultaneous arrivals and departures at the same station:

On a line with frequent stops and trains with regenerative braking, if trains depart and arrive at the same time at the same station, greater energy savings would be achieved, since the energy regenerated by the brake of the incoming train at the station can be used by the trains leaving said station in their acceleration process, as shown in the following figure.

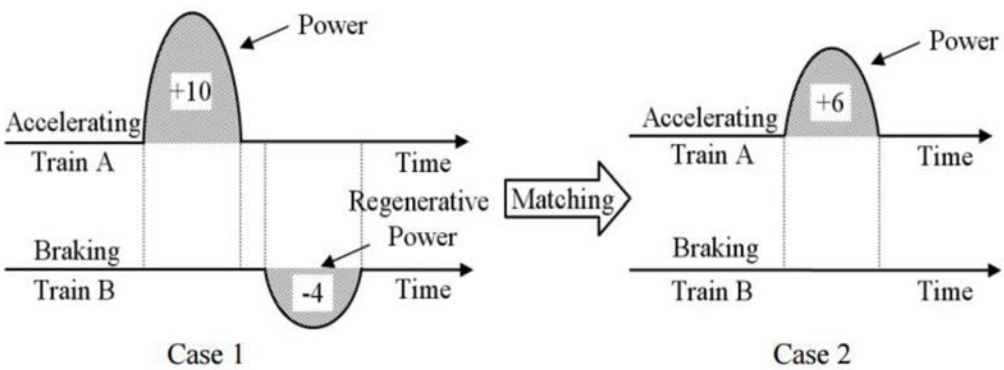

Figure 4. Power peaks in substations due to departures and arrivals. Source: K.M. Kim et al. (2010).

Timetable compatibility can help reduce energy consumption and costs, both energy and facilities, with similar travel time and almost no investment.

6. MESH CREATION

Once the services have been created and the demand known, multiple different supply scenarios configured with different type patterns (calendars, time periods, service patterns, schedules, symmetry minutes) will be carried out in order to obtain a range of possible solutions to achieve an optimal exploitation plan.

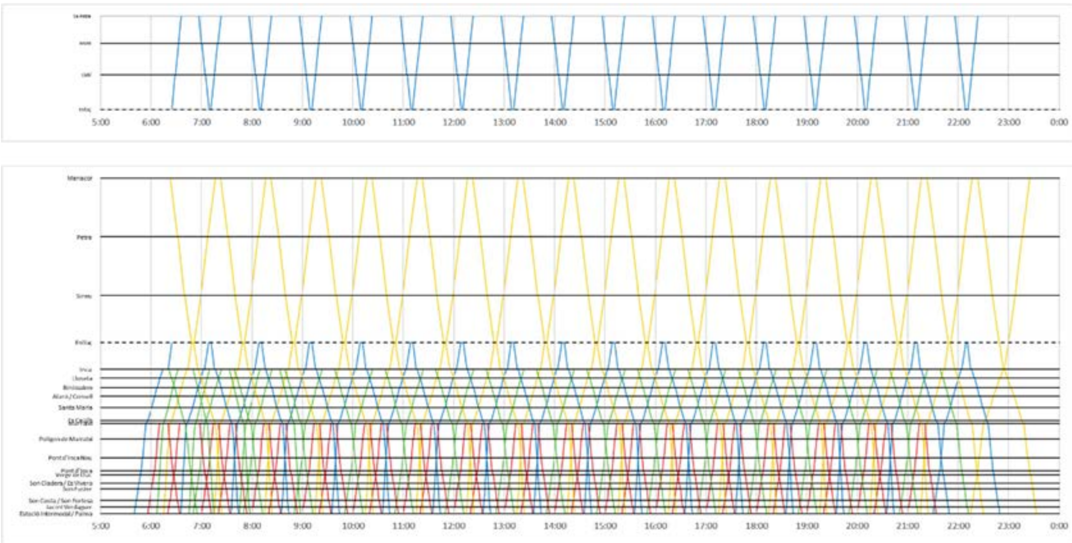

Figure 5. Daily mesh of an exploitation plan

Finally, with the N different scenarios, having a range of solutions (different meshes), a comparison will be made between them, in such a way that the advantages obtained with each one are revealed, keeping the mesh whose offer in squares meets with the planned mobility.

Through the elaboration of circulation meshes, the economic balance of the operator is calculated for different service offers until the one that the operator considers optimal is obtained. Similarly, it provides production results and operating costs.
In addition, apart from seeking a maximization of transport capacity to attract travelers in other more aggressive ways with the natural environment, other objectives are prioritized such as reducing energy consumption by taking advantage of braking energy.

The (annual) results to be obtained for each scenario are as follows:

- Production data: trains, trains.km, cars kilometer, seats, seats.km. Minutes of driver driving and minutes of accompanying personnel.
- Matrix of seats offered for each relationship

7. ECONOMIC ANALYSIS

Each calculated scenario assumes costs and monetary income that will be influenced by the following parameters:

- Energy cost: It is the cost of the energy that would be needed to carry out all the services. For this, the characteristics of the train and the reference prices for the cost of energy are taken into account.
- Maintenance: It will be taken into account whether it has its own workshop or not, and the cost of fixed and variable maintenance of the trains, the latter influenced by the number of kilometers carried out annually.
- Personnel costs: It is a cost closely related to the increase or decrease in services, since if there is a facility with many frequencies, it will be necessary to incorporate more personnel on the staff.
- Other costs: These are those related to financial expenses, possible contingencies and compensation, cleaning costs and all those costs related to the operation.
- Fare income: are those obtained from the sale of tickets either at the box office, agencies or on the internet portal.
- Special income: These are those related to advertising on the internet portal, on tickets and on the trains themselves.

With these parameters obtained and knowledge of all the previously known variables, the final income statement will be made, obtaining a balance between Expenses and Income for each of them.

COSTS		
Fixed costs	**Total**	**%**
Train Maintenance	240.197,13 €	50%
Energy	94.089,60 €	20%
Rolling Stock Amortization	4.429.571,99 €	919%
Financial expenses	2.214.786,01 €	460%
Variable costs	**Total**	**%**
Variable Maintenance Trains	481.889,70 €	100%
Energy	1.720.579,07 €	357%
Personnel cost	732.390,53 €	152%
Selling Costs	385.240,89 €	80%
Other Costs	308.962,35 €	64%
TOTAL COSTS	**10.607.707,27 €**	

INCOME		
Income	**Total**	**%**
Fare income	12.646.444,50	97%
Special income	194.918,35	3%
TOTAL REVENUE	**12.841.362,85 €**	

Earnings Before Interest and Taxes (EBIT)	**2.233.655,58 €**

Figure 6. Example of an income statement

Therefore, the optimal scenario to implement will be the one in which the Benefit for the operator is the highest possible, that is, the one in which the income is greater than the expenses.

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REFLEXIONES FRENTE A LA LIBERALIZACIÓN DEL TRANSPORTE DE VIAJEROS EN LAS LÍNEAS DE ALTA VELOCIDAD EN ESPAÑA. CORREDOR MADRID-LEVANTE.

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RESUMEN

El proceso de liberalización del transporte ferroviario de viajeros impulsado por la Unión Europea y su consiguiente incorporación al ordenamiento español ha permitido que desde el 14 de diciembre de 2020 se materialice la incorporación de nuevas empresas ferroviarias a la operación de servicios de alta velocidad y larga distancia. Aunque a fecha de hoy en España solo está operando la empresa RIELSFERA, cuyo accionista al 100% es el operador SNCF, en el corredor Madrid-Barcelona existe otra, ILSA (INTERMODALIDAD DEL LEVANTE, S.A.), que es un consorcio formado por los accionistas de la aerolínea española Air Nostrum (franquicia de Iberia) y la compañía ferroviaria Trenitalia, que tiene previsto operar a corto plazo en el corredor Madrid-Levante.

Esta liberalización supone, naturalmente, un aumento de circulaciones en los tramos citados, siendo de esperar que este aumento se extienda también a los tramos que en un futuro se abran a la competencia. En principio, el total de nuevos servicios añadidos a los que ya realizaba RENFE OPERADORA, al menos a corto y medio plazo, no parece suponer un problema para la operación, ya que la capacidad de las líneas está diseñada para soportar un mayor número de composiciones. Sin embargo, el problema se plantea en el resto de las infraestructuras, como son las estaciones de viajeros, tanto a nivel de circulaciones como de viajeros, pues éstas están diseñadas con un número de vías y con unas longitudes de andenes no tan generosas. Por ello, la nueva situación está obligando al administrador de infraestructuras a realizar una serie de modificaciones e incluso nuevas instalaciones que puedan facilitar el movimiento de los viajeros que se incorporan a los nuevos servicios, así como a la operatoria del mayor número de trenes involucrados, sobre todo en lo que concierne a su operación en estacionamientos.

Pues bien, en el nuevo escenario de la liberalización, el paquete de capacidad marco propuesto a los candidatos ofrece la posibilidad de competir con la variable “frecuencias” para atraer a clientes a este proceso, pero, en nuestra opinión, adolece de importantes incertidumbres a sumar a las propias del incremento del tráfico ferroviario.

A las dificultades indicadas hay que añadir que, para desarrollar una tarea tan compleja, las empresas deben demostrar la solvencia técnica y económica suficiente, realizando las correspondientes demostraciones de capacidad para desarrollar un proyecto empresarial de esta magnitud, sobre todo cuando los grupos candidatos, además, pueden ser de nueva creación.

Por supuesto, también cobra especial importancia estudiar en profundidad el nivel de los cánones a aplicar a las nuevas empresas que entren en el mercado español en función de la cuota de mercado abarcado pues, de alguna manera se tiene que abordar el sostenimiento económico de los servicios comerciales por líneas convencionales que en la actualidad son sostenidos por los ingresos procedentes de la explotación comercial del que ha sido, hasta ahora, el operador único de las líneas de Alta Velocidad.

1. ESTUDIO DEL NUEVO ESCENARIO

Ante la liberalización efectiva de los servicios comerciales, de acuerdo con las directrices de la Unión Europea y la Comisión Nacional de los Mercados y la Competencia, el administrador de infraestructuras español debe asegurar una gestión eficiente del tráfico ferroviario y garantizar un acceso no discriminatorio a las mismas.

Esta obligación se extiende no sólo a las vías, sino también a todos los espacios en las estaciones dedicados a las actividades de los operadores de transporte.

Para ello, ADIF Alta Velocidad elaboró una oferta de capacidad marco para el corredor Madrid - Levante (Valencia y Alicante), vinculando la capacidad de la línea con el estacionamiento en las estaciones de viajeros. Esta capacidad marco queda agrupada en 3 paquetes con las características siguientes:

Paquete A	1 tren/hora Madrid- Valencia 1 tren/hora Madrid- Alicante
Paquete B	1 tren/2 horas Madrid- Valencia 1 tren/2 horas Madrid- Alicante
Paquete C	4 trenes/día Madrid-Alicante/Valencia

Tabla 1. Capacidad marco. Fuente Adif AV.

Los paquetes son asignados a la empresa ferroviaria u otro candidato que se comprometa a una mayor utilización en un periodo de 10 años.

Centrándonos en el tramo Madrid-Valencia del corredor la variación de capacidad queda ofertada según las siguientes tablas:

Surcos/día (ambos sentidos)	Capacidad líneas	Servicios actuales	Capacidad marco	Incremento
Madrid-Valencia	184	36	52	+ 44%

Tabla 2. Variación en la capacidad actual y ofertada. Fuente Adif AV.

Surcos/día (ambos sentidos)	Servicios actuales	Paquetes propuestos				
		A	B		C	
		Surcos	Surcos	%	Surcos	%
Madrid-Valencia	36	32	16	31%	4	8%

Tabla 3. Configuración de la capacidad marco propuesta. Fuente Adif AV.

2. EXPLOTACIÓN EN LA ACTUAL INFRAESTRUCTURA. VALOR DE LA INFRAESTRUCTURA.

2.1. Algunos conceptos a tener en cuenta

La diferente caracterización y funcionalidad de la red plantea un problema ante la capacidad de absorber el aumento de circulaciones adjudicadas y futuras, que es el *"valor de la infraestructura"*, valor que aumentará cuanto mayor sea la posibilidad de transporte que ofrezca y cuanto más atractivas y menos costosas sean las condiciones de acceso a este transporte.

Para los operadores, el valor potencial generado por la operación está compuesto, básicamente, por el producto de dos factores:

- El valor de cada surco, valor dependiente del número de viajeros que puede transportar un tren que utiliza el surco y del margen económico que esos viajeros pueden aportar al operador del servicio. Cuando estos viajeros estén dispuestos a pagar una cantidad mayor por su billete y cuanto el transporte resulte menos costoso para el operador del servicio, más valor tendrá el surco, y por ello más valor potencial tiene la infraestructura.
- El número de surcos en un periodo de tiempo queda definido como la capacidad de circulación de la línea.

La maximización del valor de la infraestructura puede venir por la combinación más adecuada de los factores anteriores pudiéndose obtener con un menor número de surcos con mayor valor unitario, o con un mayor número de surcos pero de menor valor cada uno.

El aumento del valor de la infraestructura puede venir, tanto del aumento de la capacidad (número de surcos por periodo), como de la capacidad de cada tren, apoyándose en parámetros y condiciones de la infraestructura, o mejorando las condiciones económicas para el operador.

El valor del surco depende del número de plazas por cada tren, del ingreso que potencialmente puede aportar cada viajero y del coste que supone. El número de plazas por tren y los ingresos o costes unitarios deben referirse a los aspectos en que vienen condicionados por la infraestructura, por sus parámetros y por su explotación.

El valor de un surco se inscribe en el ámbito de la operación del servicio, donde existen puntos sobre los que actuar para que cambie el valor del tren, pero la propia infraestructura condiciona el valor del tren. Así, y por lo que se refiere al número de plazas ofertadas por tren, si se aceptan trenes más anchos, más altos o largos por así permitirlo ADIF, con un mismo tren podrán transportarse muchos más viajeros. ADIF, al fijar estas condiciones de admisión de los trenes, aumenta el valor de cada surco permitiendo al operador que aumente la capacidad del tren que lo utiliza.

La potencialidad en términos de valor que ofrece la infraestructura puede ser aprovechada o no por el operador de servicios en función de su estrategia y su diseño operativo (por ejemplo, puede no estar interesado en aumentar la capacidad de cada tren para así ofrecer más frecuencia en una relación origen-destino en la que la demanda sea muy sensible a este factor), pero si el administrador no hace posible el aumento de la capacidad de cada tren (por no permitirlo los parámetros de la línea) se está privando al operador de la posibilidad de explotar este tipo de trenes y, por ello, limitando potencialmente su competitividad frente a otros modos de transporte.

Pero la capacidad no sólo se limita a las composiciones que pueden circular por una línea o tramo. La capacidad está también relacionada con el resto de las infraestructuras como son las estaciones, vías de apartado, centros de mantenimiento, etc. En el caso de los centros de mantenimiento, en la actualidad existen centros de mantenimiento que corresponden a Renfe Operadora, en los cuales se realizan las tareas correspondientes a la puesta a punto de trenes y las reparaciones necesarias para el cumplimiento de la normativa correspondiente, con el fin de realizar el transporte de viajeros de forma segura y confortable. Cabe resaltar también que estos centros de mantenimiento deben estar homologados y su personal debe estar en posesión de la correspondiente habilitación que le permita realizar este tipo de trabajos por lo que las nuevas empresas ferroviarias, en caso de utilizar centros propios para este mantenimiento, deberán estar en condiciones de poseer dichas habilitaciones.

2.2. Aplicación a algunos casos prácticos

Como ilustración de lo comentado anteriormente se trae a colación aquí algunos ejemplos sencillos que pueden servir de referencia para entender el tipo de cambios a los que nos referimos, que se deben analizar e introducir en las infraestructuras ferroviarias existentes.

Se trata de los casos de las estaciones de transporte de viajeros de Valencia Joaquín Sorolla y Madrid Puerta de Atocha. Aquí, de una forma esquemática se presentan dos problemáticas de distinta naturaleza, que ocurren en la actualidad y que merecen la pena su consideración por las ventajas que se derivarían de su tratamiento:

Estación Madrid-Puerta de Atocha

La estación es el origen de las líneas de alta velocidad con destino a Barcelona - frontera francesa, Levante y Andalucía. Las vías de circulación de entrada y salida (2 vías) de la estación desde Andalucía y Levante, a fecha de hoy, son las mismas desde la bifurcación de Torrejón de Velasco, que está situada en el p.k. 28,8, siendo su origen la estación de Madrid-Puerta de Atocha.

La existencia de limitaciones permanentes de velocidad a la salida de la estación tiene mucha influencia en la capacidad de la línea, todo ello sin tener en cuenta las incidencias que puedan producirse, además, como consecuencia de situaciones degradadas.

Otro punto a considerar es la disposición de las vías en la estación. Según el esquema siguiente encontramos una diagonal que "cizalla" las 4 vías de entrada y salida y que da acceso a la base de mantenimiento y vías de apartado de Cerro Negro produciéndose paradas técnicas que repercuten en retrasos, tanto a las circulaciones de entrada como a las de salida. En el gráfico siguiente se observa la disposición de las vías así como el ejemplo del recorrido que realiza una composición desde una vía de estacionamiento (vía 6 A) hasta la aguja de entrada de la citada base.

La distancia existente entre la vía de estacionamiento y las agujas de entrada a la base es de 2,441 kilómetros y la limitación de velocidad máxima existente en el trayecto oscila entre los 30 y 50 km/h. El tiempo invertido que pueden emplear las composiciones, teniendo en cuenta la actuación del diferímetro, es el siguiente:

- Establecimiento del itinerario: 3 minutos.
- Recorrido de la composición: 2 minutos.
- Liberación del itinerario : 3 minutos.

Esto, claramente penaliza la duración del viaje con un tiempo de espera que puede llegar a 8 minutos debido a la citada maniobra, que se debe realizar en espacios de tiempo donde la afección a la circulación sea mínima.

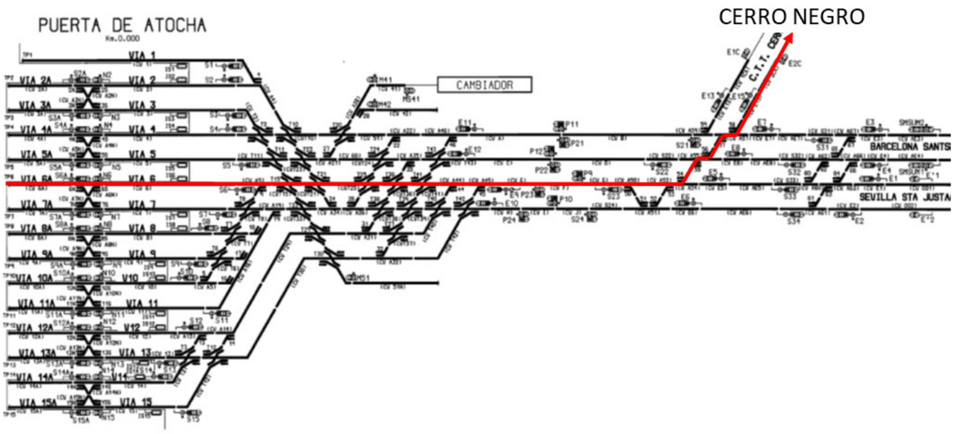

Figura 1. Interferencia en las circulaciones Madrid-Puerta de Atocha. Fuente: ADIF.

Estación Valencia Joaquín Sorolla

En el caso de esta estación (estación provisional, con el "peligro" que tiene la expresión de provisionalidad) se plantea el problema de estacionamiento tanto para circulaciones en doble composición como para el estacionamiento de una circulación en composición simple en vía ocupada. La estación cuenta con 9 vías de estacionamiento, 6 vías de ancho estándar (1.435 mm.) y 3 vías de ancho ibérico (1.668 mm). En la tabla siguiente se muestra la longitud de los andenes de la estación:

Ancho vía	Vía	Longitud andenes
Estándar	1	227 m.
	2	
	3	409 m.
	4	
	5	227 m.
	6	
Ibérico	7	185 m.
	8	374 m.
	9	400 m.

Tabla 4. Longitud de andenes de la estación Joaquín Sorolla. Fuente: ADIF.

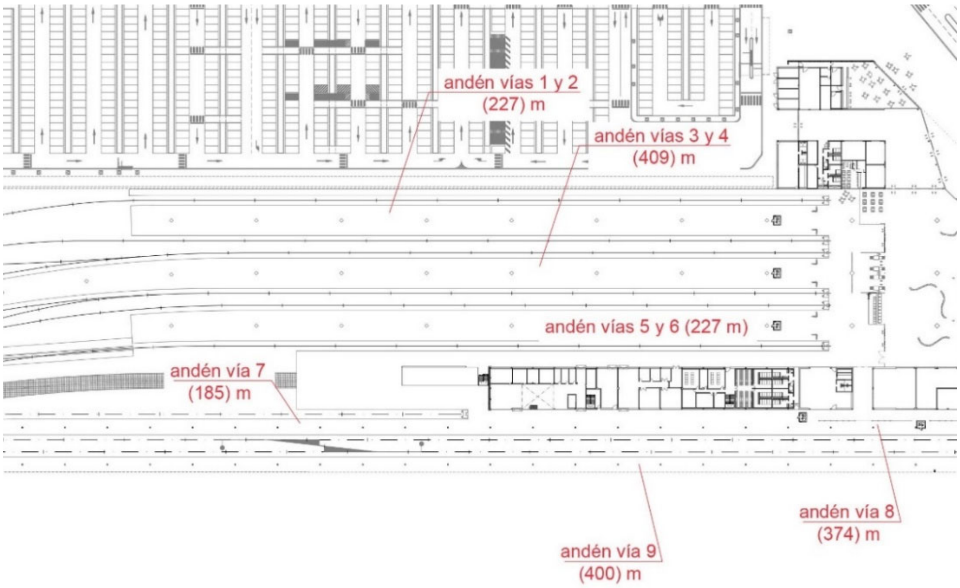

Figura 2. Disposición de vías de estacionamiento en la estación de Joaquín Sorolla. Fuente: ADIF.

Según las dimensiones de los andenes, sólo se pueden estacionar trenes que circulen en doble composición en las vías 3 y 4 y no pudiendo estacionar ningún tren sobre vía ocupada por otro. En la actualidad la estación utiliza las vías de estacionamiento como vías de apartado par material rodante fuera de servicio, lo que reduce la capacidad de las vías.

3. FINANCIACIÓN DE SERVICIOS COMERCIALES EN LÍNEAS CONVENCIONALES.

Otro tema que, aunque sea brevemente conviene que sea tratado, por su relevancia, es el de la financiación de los servicios comerciales operados por Renfe Operadora en las líneas convencionales. En estos momentos el resultado positivo de los servicios prestados por la empresa en Alta Velocidad, después de la liquidación de los correspondientes cánones, compensa los resultados negativos de todos los demás negocios de viajeros y de mercancías.

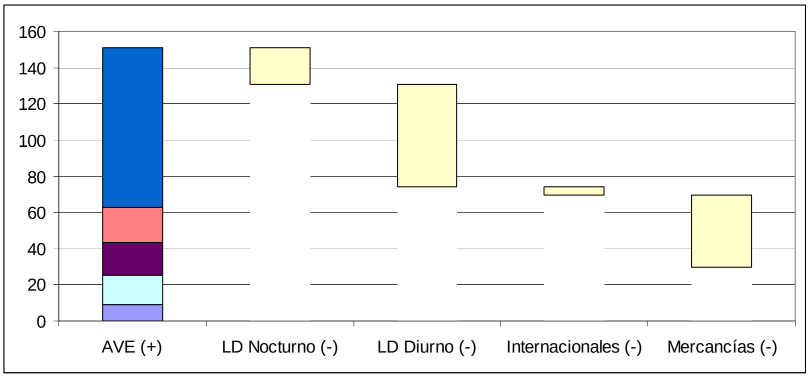

Figura 3. Contribución del AVE a la financiación de servicios comerciales de Renfe. Fuente: García, 2019.

4. CONCLUSIONES

El aumento de circulaciones, sumadas a las efectuadas por el operador actual, no presenta problemas por el aumento de surcos concedidos ya que la capacidad de la línea está calculada para soportar un mayor número de composiciones. El problema se plantea más bien en el resto de las infraestructuras, como son las estaciones de viajeros, diseñadas con un número de vías y con unas longitudes de andenes que obligan al administrador de infraestructuras a realizar una serie de modificaciones en sus instalaciones e incluso la construcción de nuevas que puedan soportar el aumento de viajeros y el aumento de trenes estacionados.

Con la liberalización el paquete de capacidad marco ofrece la posibilidad de competir con la variable “frecuencias” para atraer a clientes, pero este proceso nace con importantes incertidumbres añadidas al del propio negocio por incremento del tráfico ferroviario. Un aumento de frecuencias requiere, además de realizar las correspondientes solicitudes de capacidad técnica y económica, desarrollar un proyecto empresarial por parte de los grupos candidatos, el cual debe ser analizado con especial atención si, además, se trata de grupos de nueva creación.

La posible demanda de viajeros, bien inducida o nueva ante los nuevos operadores, puede ocasionar un descenso de clientes en el actual operador, lo que obligaría a realizar una política económica de búsqueda de captación de clientes, como puede ser lanzamientos de ofertas, bajadas de precios, etc. Frente a este descenso de los ingresos se debe estudiar a fondo la manera de sostener los servicios comerciales en las líneas convencionales y que no están soportadas por Obligaciones de Servicio Público. Se debería estudiar minuciosamente el nivel de los cánones a aplicar a las nuevas empresas que entren en el mercado español, en función de la cuota de mercado abarcado para, manteniendo la competitividad de los mismos, ver si resulta posible colaborar en el sostenimiento de los servicios convencionales, tal como se estaba haciendo hasta la entrada de los competidores.

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FORMACIÓN E INNOVACIÓN EN EL TRANSPORTE
TRAINING AND INNOVATION IN TRANSPORT

ANÁLISIS DE LAS ENSEÑANZAS EN VEHÍCULOS Y TRANSPORTES EN LAS TITULACIONES DE INGENIERÍA INDUSTRIAL Y AFINES

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RESUMEN

La presencia de asignaturas relacionadas con el Transporte y los Vehículos en las diferentes Escuelas de Ingeniería de España es muy dispar, aunque existen líneas bastante comunes.
El presente estudio, promovido desde el Foro de Ingeniería del Transporte (FIT) pretende mostrar la enseñanza en vehículos terrestres y transportes en general en el ámbito de las titulaciones de Ingeniería Industrial y afines con el fin de establecer un punto de partida que promueva el diálogo entre profesores, determinar puntos comunes y dispares entre Universidades, y así establecer contenidos prioritarios en cada caso, así como promover la creación de nuevos materiales de estudio.

Debe tenerse en cuenta que la Orden CIN/351/2009, de 9 de febrero, por la que se establecen los requisitos para la verificación de los títulos universitarios oficiales que habiliten para el ejercicio de la profesión de Ingeniero Técnico Industrial, no fija ningún conocimiento obligatorio relativo a transportes o vehículos. Sin embargo, la Orden CIN/311/2009, de 9 de febrero, por la que se establecen los requisitos para la profesión de Ingeniero Industrial, establece que es obligatorio que los alumnos alcancen "Conocimientos sobre métodos y técnicas del transporte y manutención industrial".

Según el requisito anterior, no existen directrices de obligado cumplimiento en relación con estas materias en las titulaciones de Grado y sólo se plantean exigencias en el Máster en Ingeniería Industrial.

Por otra parte, en muchos casos, las fronteras entre Ingenierías resultan difusas por lo que el presente estudio puede recoger algunas titulaciones con sesgos más o menos centrados en la Ingeniería Industrial, pero con contribuciones de otras ramas de la ingeniería. En total, se han analizado 52 Universidades, 92 titulaciones de Grado y 88 titulaciones de Máster para mostrar un escenario, dinámico por otra parte, de este tipo de enseñanzas.

1. INTRODUCCIÓN

La presencia de asignaturas relacionadas con el Transporte y los Vehículos en las diferentes Escuelas de Ingeniería de España es muy dispar, aunque existen líneas bastante comunes.
Desde el Foro de Ingeniería del Transporte (FIT) se lanzó la iniciativa de analizar esta situación, tanto en el ámbito de la ingeniería Civil como Industrial. Este artículo comprende estas últimas y se pretende mostrar la enseñanza en vehículos terrestres y transportes en general en el ámbito de las titulaciones de Ingeniería Industrial y afines con el fin de establecer un punto de partida que promueva el diálogo entre profesores, determinar puntos comunes y dispares entre Universidades, y así establecer contenidos prioritarios en cada caso, así como promover la creación de nuevos materiales de estudio.

Las enseñanzas de transportes en Ingeniería Industrial vienen condicionadas, al menos en parte y para las titulaciones de Máster en Ingeniería Industrial, por la Orden CIN/311/2009, de 9 de febrero, por la que se establecen los requisitos para la profesión de Ingeniero Industrial, establece que es obligatorio que los alumnos alcancen "Conocimientos sobre métodos y técnicas del transporte y manutención industrial". Sin embargo, la Orden CIN/351/2009, de 9 de febrero, por la que se establecen los requisitos para la verificación de los títulos universitarios oficiales que habiliten para el ejercicio de la profesión de Ingeniero Técnico Industrial, no fija ningún conocimiento obligatorio relativo a transportes o vehículos. Según los requisitos anteriores, no existen directrices de obligado cumplimiento en relación con estas materias en las titulaciones de Grado y sólo se plantean exigencias en el Máster en Ingeniería Industrial.

Sobre ese marco, se ha procedido al estudio de la presencia de materias sobre vehículos y transporte terrestre en las titulaciones de Grado en Ingeniería de Tecnologías Industriales y Máster en Ingeniería Industrial. Por otra parte, dado que, tradicionalmente, los ámbitos del transporte y los vehículos han estado vinculados a áreas de Ingeniería Mecánica (además de Ingeniería del Transporte), el estudio se ha extendido a las titulaciones de Grado y Máster en Ingeniería Mecánica. Sin embargo, la importancia de otros ámbitos con vinculación a la Ingeniería Industrial, tanto tecnológicos (electrónica, control, eléctrico, etc.) como de gestión, logística o fabricación, hace que otras titulaciones también incluyan materias vinculadas a vehículos o sus componentes y sistemas. Este hecho ha sido tenido en cuenta, aunque asignaturas transversales como, por ejemplo, medios de fabricación, solo se han considerado si se orientan específicamente a vehículos terrestres. De igual forma, aspectos como asignaturas sobre motores de combustión han sido excluidas al haber recaído en áreas de conocimiento específicas. Sin embargo, sí se han incluido tecnologías de vehículos eléctricos y sistemas electrónicos al tener una fuerte vinculación con el ámbito vehicular. Adicionalmente, se han analizado titulaciones específicas de vehículos y transportes.

Por último, debe recalcarse que, en muchos casos, las fronteras entre Ingenierías resultan difusas por lo que el presente estudio puede recoger algunas titulaciones con sesgos más o menos centrados en la Ingeniería Industrial, pero con contribuciones de otras ramas de la ingeniería. Así, en total, se han analizado 52 Universidades, 92 titulaciones de Grado y 88 titulaciones de Máster para mostrar un escenario, dinámico por otra parte, de este tipo de enseñanzas.

2. TITULACIONES GENERALISTAS DE INGENIERÍA INDUSTRIAL

2.1 Grado en Ingeniería en Tecnologías Industriales GITI

Se han analizado 31 titulaciones de GITI, de las cuales solo 11 incluyen en sus planes de estudios alguna asignatura sobre vehículos o transportes (Tabla 1). De hecho, resulta relevante mencionar que, de esas 11, en 6 solo hay una asignatura mientras que en 1 hay 2 y en 4 hay 3 o más, totalizando 22 asignaturas entre las que prima el carácter optativo. Es decir, la presencia es escasa en este tipo de titulaciones con un perfil relativamente generalista, si bien, en aquellas Escuelas donde se han introducido, lo han hecho con una presencial relevante.

CARLOS III DE MADRID	VIGO
CÁDIZ (Puerto Real)	ZARAGOZA
CANTABRIA	POLITÉCNICA DE CATALUNYA (Barcelona)
MÁLAGA	POLITÉCNICA DE CATALUNYA (Terrassa)
OVIEDO	POLITÉCNICA DE MADRID
SEVILLA	

Tabla 1 – Titulaciones de GITI con asignaturas sobre vehículos o transportes

En cuanto al número de créditos, suelen ser asignaturas relativamente largas, con 9 de 6 créditos y 6 de 4,5 créditos, promediando 4,7 créditos por asignatura. En cuanto a las temáticas tratadas, se suelen centrar en aspectos relacionados con los vehículos fundamentalmente, bien automóviles o bien ferrocarril. La Figura 1 muestra estas distribuciones.

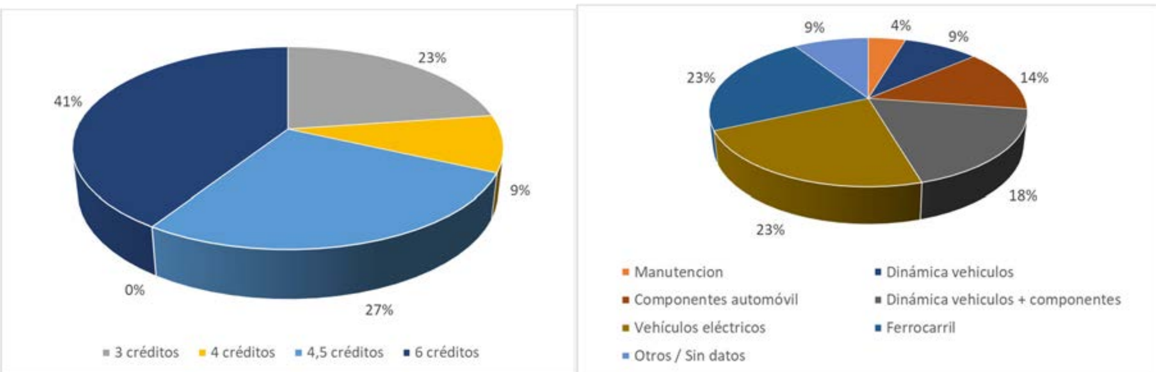

Fig. 1 – Número de créditos y temáticas de las asignaturas en GITI

2.2. Máster en Ingeniería Industrial (MII)

Se han analizado 47 titulaciones, de las cuales, en 44 se incluye alguna asignatura sobre transportes o vehículos (Tabla 2), identificando un total de 71 asignaturas (38 obligatorias, con una denominación bastante extendida de “Ingeniería del Transporte”, y 33 optativas). Esta mayor presencia viene motivada por las prescripciones incluidas en la Orden CIN/311/2009 donde se establecen que deben incluirse nociones de medios de manutención en los estudios de Ingeniería Industrial. Sin embargo, el tratamiento dado en cada titulación es diferente y, si bien en muchos casos se circunscriben a esos conocimientos, en otros casos, se incluye en la asignatura otros aspectos relacionados con el transporte, los automóviles o el ferrocarril, mientras que otras titulaciones incluyen en sus planes de estudios una carga superior, tanto en créditos totales como en número de asignaturas. En la Figura 2 se observa la distribución del número de asignaturas sobre estas temáticas en los planes de estudios, considerando algunos casos particulares en los que no existe una asignatura específica, sino que los conocimientos de transportes están integrados en otras materias. Tales situaciones son, por ejemplo, en la titulación de MII ofertada por la UNIVERSIDAD DE DEUSTO, en cuya asignatura obligatoria “Logística y Manutención Industrial” incluye un bloque sobre Gestión de la Distribución, aunque luego ofertan una Intensificación en Ingeniería de Automoción con 3 asignaturas de créditos sobre temas específicos. De igual modo, en la titulación de la UNIVERSIDAD DE LAS ISLAS BALEARES, se incluyen temas de métodos de transporte y manutención industrial en la asignatura “Calidad Industrial”, y temas sobre Infraestructuras de transporte y comunicación en la asignatura “Construcción y Explotación Industriales”. Lo mismo sucede en la UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA, donde la asignatura “Diseño, construcción y explotación de plantas industriales” incluye como uno de sus bloques temáticos la ingeniería de transporte. Por último, la UNIVERSIDAD DE VALLADOLID, incluye la asignatura obligatoria “Ingeniería de la construcción y del transporte” con una parte dedicada a construcción y otra a transporte que comprende aspectos de manutención industrial y vehículos.

ALFONSO X EL SABIO	SALAMANCA
ANTONIO DE NEBRIJA	SEVILLA
CARLOS III DE MADRID	VALLADOLID
A CORUÑA	VIC- CENTRAL DE CATALUNYA
ALCALÁ	VIGO
ALMERÍA	ZARAGOZA
BURGOS	PAÍS VASCO
CÁDIZ	EUROPEA DE MADRID
CANTABRIA	JAUME I DE CASTELLÓN
CÓRDOBA	LOYOLA ANDALUCÍA
DEUSTO	MIGUEL HERNÁNDEZ DE ELCHE
EXTREMADURA	UNED
GIRONA	POLITÉCNICA DE CARTAGENA
HUELVA	UPC (Barcelona)
JAÉN	UPC (Terrassa)
LA LAGUNA	POLITÉCNICA DE MADRID
LAS ISLAS BALEARES	POLITÉCNICA DE VALENCIA
LAS PALMAS DE GRAN CANARIA	PONTIFICIA DE COMILLAS
LEÓN	PÚBLICA NAVARRA
MÁLAGA	RAMÓN LLULL
MONDRAGÓN	REY JUAN CARLOS
OVIEDO	ROVIRA I VIRGILI

Tabla 2 – Titulaciones de MII con asignaturas sobre vehículos o transportes

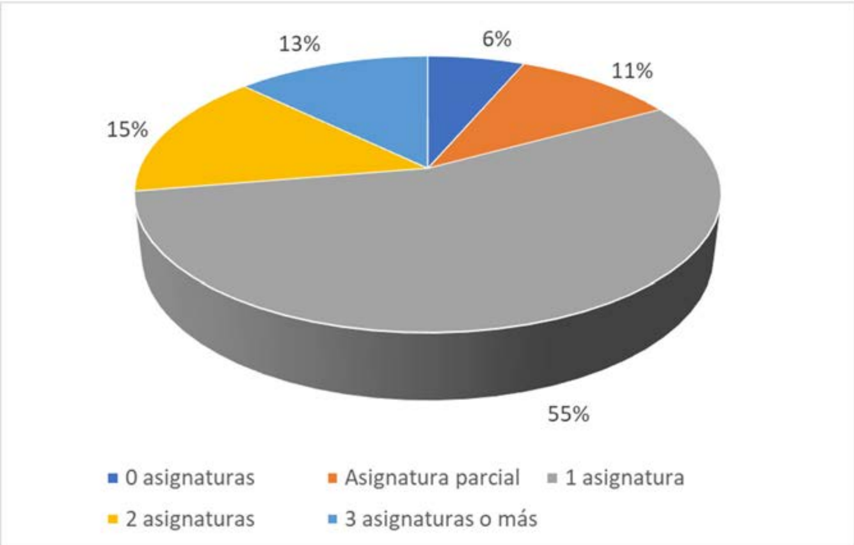

Fig. 2 – Número de asignaturas en las titulaciones de MII

La carga horaria asignada a dichas asignaturas está bastante repartida, más polarizada hacia asignaturas de 3 créditos, aunque también hay un número significativo de asignaturas entre

4,5 y 6 créditos. El promedio por asignatura resulta de 4,1 créditos, inferior al caso de las titulaciones de GITI y GIM. En cuanto al reparto de temas, más de la mitad de las asignaturas incluyen los temas de manutención, bien de forma exclusiva o bien juntamente con aspectos de transporte, vehículos automóviles y/o ferrocarriles. En el caso de las asignaturas obligatorias, el sesgo hacia asignaturas cortas de 3 créditos es mayor, con lo que el promedio de créditos por asignatura cae a 3,5 créditos, mientras que la distribución de temas se focaliza aún más en los contenidos de manutención, bien solos o con otros temas. Las Figuras 3 y 4 muestran estas distribuciones.

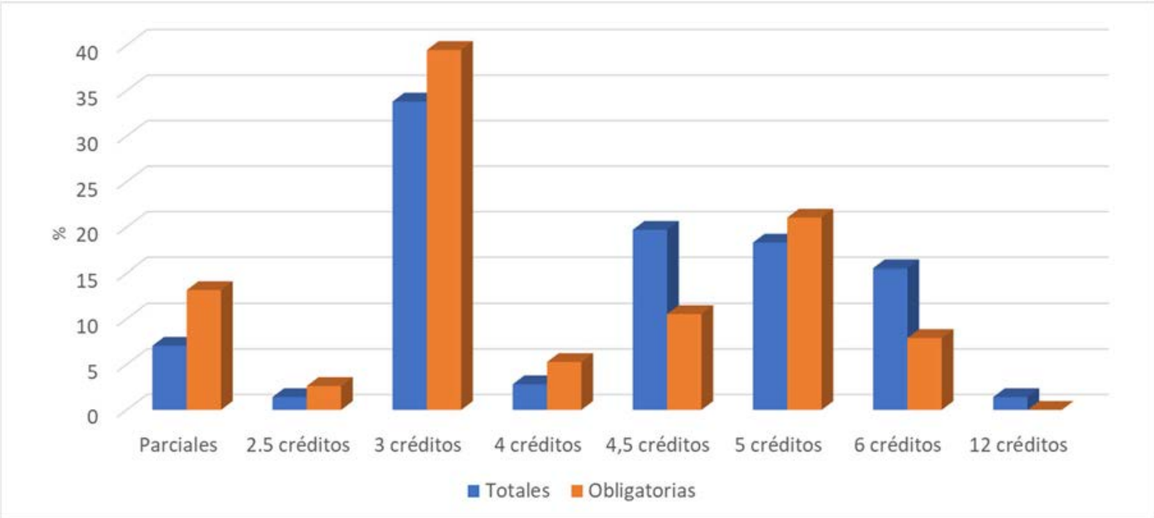

Fig. 3 – Número de créditos de las asignaturas en MII

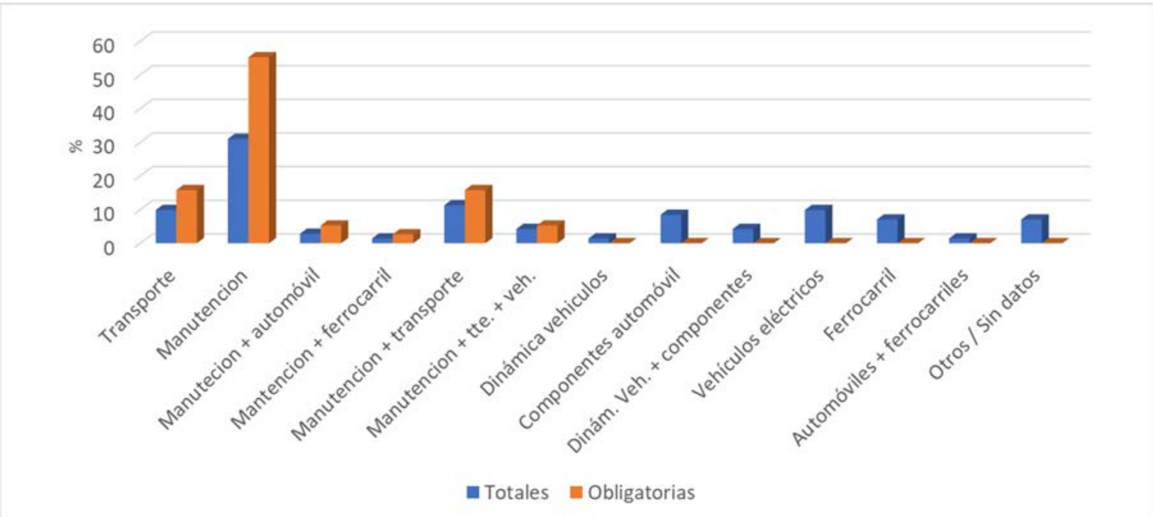

Fig. 4 – Temáticas de las asignaturas en MII

Como se observa en la Figura 4, tanto en las asignaturas totales como en las obligatorias, el tema de medios de manutención es el más incluido en los programas, desapareciendo los programas exclusivamente de vehículos o componentes de los mismos, tanto de automóviles como de ferrocarriles en las asignaturas obligatorias. También se observa que la combinación más usual con los temas de manutención es aquella de aspectos de transporte como temas de modos de transporte, tráfico o demanda de transporte. En cuanto al resto de asignaturas que no incluyen mención a los medios de manutención, los más usuales son los referentes a componentes de los automóviles y ferrocarriles, aunque resulta interesante remarcar la presencia de un número notable de asignaturas sobre vehículos eléctricos y sus componentes, si bien la cifra se encuentra algo sesgada por la oferta de la UNIVERSIDAD POLITÉCNICA DE CARTAGENA de 4 asignaturas sobre esta temática en un Bloque de asignaturas optativas, impartidas por grupos de Ingeniería de Sistemas y Automática, Ingeniería electrónica, e Ingeniería eléctrica.

Si bien no se han indicado las dobles titulaciones ofertadas a partir de la de Máster en Ingeniería Industrial, sí resulta relevante por su orientación hacia los temas que competen a este estudio citas las siguientes impartidas por la UNIVERSIDAD PONTIFICIA DE COMILLAS

- Doble Máster Universitario en Ingeniería Industrial y en Ingeniería para la Movilidad y la Seguridad (epígrafe 5.1.)
- Doble Máster Universitario en Ingeniería Industrial y en Sistemas Ferroviarios (epígrafe 5.3.)

3. TITULACIONES ESPECIALISTAS DE INGENIERÍA MECÁNICA

3.1. Grado en Ingeniería Mecánica (GIM)

En este caso, se han analizado 48 titulaciones, de las cuales, 21 de ellas incluyen asignaturas relacionadas con transportes o vehículos (Tabla 3), totalizando 33 asignaturas, la mayoría de ellas, de carácter optativo y siendo lo más común el incluir una única asignatura en el plan de estudios en 17 de las 21.

CARLOS III DE MADRID	SALAMANCA (Zamora)
CATÓLICA SANTA TERESA DE JESÚS DE ÁVILA	SALAMANCA (Béjar)
	SEVILLA
A CORUÑA	VIGO
CÁDIZ (Puerto Real)	MIGUEL HERNÁNDEZ DE ELCHE
CANTABRIA	UNED
EXTREMADURA	UPC (Barcelona)
JAÉN	UPC (Vilanova i la Geltrú)
LAS PALMAS DE GRAN CANARIA	POLITÉCNICA DE MADRID
MÁLAGA	PÚBLICA NAVARRA
OVIEDO	ROVIRA I VIRGILI

Tabla 3 – Titulaciones de GIM con asignaturas sobre vehículos o transportes

A pesar de esta presencia limitada en los planes de estudios, las materias son relativamente importantes en los mismos con una carga promedio de 5,1 créditos por asignatura, predominando aquellas de 5 y 6 créditos. Los contenidos se centran mayoritariamente en aspectos de componentes de vehículos o sobre estos componentes junto a su dinámica. La Figura 5 muestra estas distribuciones.

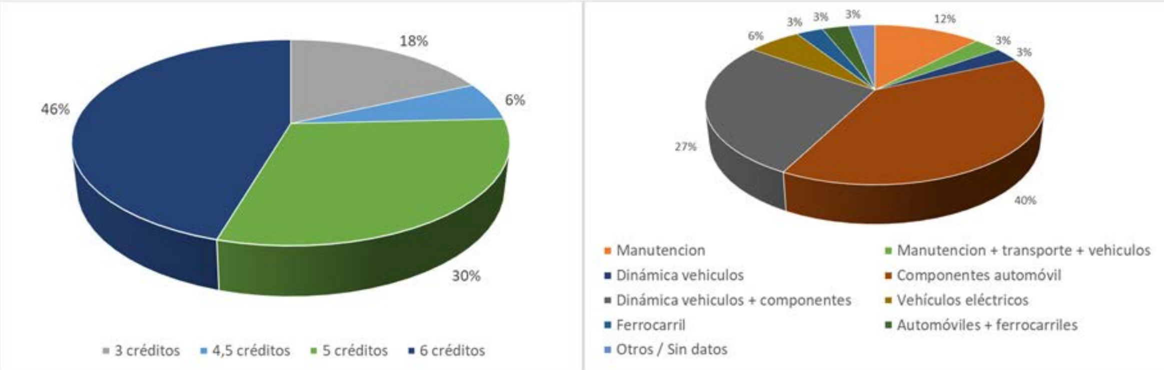

Fig. 5 – Número de créditos y temáticas de las asignaturas en GIM

Resulta un caso especial la titulación de GIM ofertada por la UNIVERSIDAD CATÓLICA SANTA TERESA DE JESÚS DE ÁVILA, donde se incluyen 9 asignaturas sobre vehículos automóviles, todas ellas optativas de 5 créditos: "Evaluación de Daños de Vehículos", "Sistemas Eléctricos del Automóvil", "Procesos y Técnicas de Reparación en Vehículos", "Estructuras Constructivas en Vehículos", "Reconstrucción de Accidentes de Tráfico", "Automóviles", "Proceso de Pintado de Vehículos", "Suspensión y chasis" y "Sistemas de freno", lo que hace crecer notablemente la proporción de asignaturas relativas a componentes del vehículo.

3.2. Máster en Ingeniería Mecánica (MIM)

Dentro de este apartado, se han analizado 7 titulaciones, de las cuales 5 tienen asignaturas relacionadas con transportes o vehículos (Tabla 4), totalizando 14 asignaturas. Se incluye en este grupo, las titulaciones con una denominación más amplia que MIM como son las de Máster en Ingeniería Mecánica, Diseño, Construcción y Fabricación de la Universidad de Oviedo y Máster Universitario en Ingeniería Mecánica Aplicada y Computacional de la Universidad Pública de Navarra.

ZARAGOZA	POLITÉCNICA DE VALENCIA
PAÍS VASCO	PÚBLICA NAVARRA
POLITÉCNICA DE MADRID	

Tabla 4 – Titulaciones de MIM con asignaturas sobre vehículos o transportes

En este caso, las asignaturas son más cortas que en estudios como GITI o GIM, con un promedio de 3,5 créditos por asignatura. En cuanto a las temáticas tratadas, aunque hay una dispersión mayor que en el caso de GITI, se focalizan, al igual que en esos estudios de Grado y en los GIM, en aspectos relacionados con los vehículos y menos con aspectos de transporte en general o aspectos de manutención englobados dentro de las enseñanzas de MIM establecidos por la Orden CIN/311/2009. La Figura 6 muestra estas distribuciones.

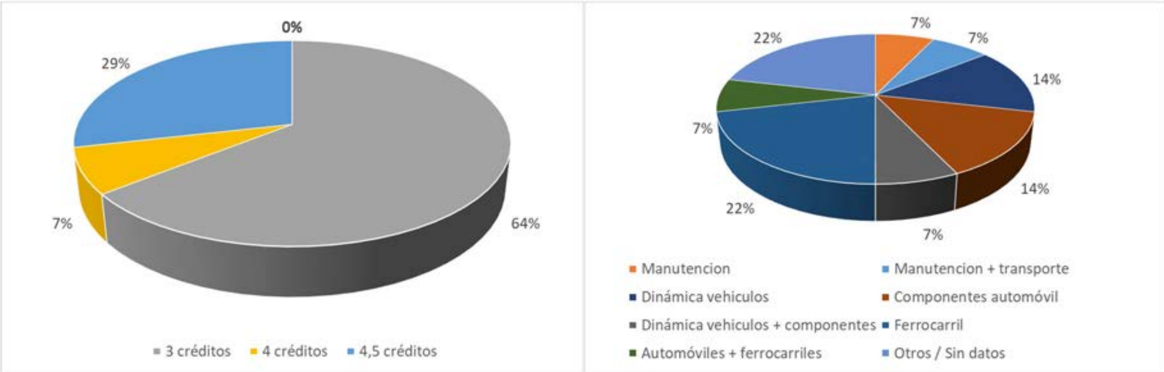

Fig. 6 – Número de créditos y temáticas de las asignaturas en MIM

4. OTRAS TITULACIONES ESPECIALISTAS (NO ORIENTADAS EXCLUSIVAMENTE AL TRANSPORTE)

También se han identificado otras titulaciones que, sin ser específicas de transportes o vehículos exclusivamente, ni ser titulaciones generalistas como las anteriormente citadas de GITI, MII, GIM, y MIM, sí incluyen una carga, cuanto menos, semejante, a la que se encuentra en aquellas. Se dividen en dos bloques en función de la relevancia de los temas que nos ocupan.

4.1. Titulaciones en las que el transporte o los vehículos forman una parte esencial de la misma o de un itinerario

- Máster Universitario en Ingeniería de Máquinas y Transportes, de la UNIVERSIDAD CARLOS III DE MADRID, con las asignaturas obligatorias de “Ingeniería del Transporte” e “Ingeniería de Vehículos”, incluyendo aspectos de transporte en general, automóviles y ferrocarril,
- Máster en Sistemas Inteligentes en Energía y Transporte, de la UNIVERSIDAD DE MÁLAGA y la UNIVERSIDAD DE SEVILLA, con las asignaturas optativas “Sistemas inteligentes de transporte y tecnologías avanzadas de vehículos”, que incluye modelos, simulación, sistemas de control y ensayos, y “Sistemas ferroviarios y tracción eléctrica”
- Máster Universitario en Investigación en Eficiencia Energética y Sostenibilidad en Industria, Transporte, Edificación y Urbanismo, de la UNIVERSIDAD DEL PAÍS VASCO, donde su orientación al transporte se focaliza más en sistemas de propulsión.
- Máster Universitario en Eficiencia Energética en la Edificación, la Industria y el Transporte, de la UNIVERSIDAD POLITÉCNICA DE MADRID, con un módulo dedicado a transporte de 16 créditos, incluyendo las asignaturas “Eficiencia Energética en el Transporte”, “Energía e impacto Medioambiental del Transporte”,

"Movilidad y Transporte", "Vehículos automóviles y ferrocarriles", éstas dos últimas del itinerario específico.

4.2. Otras titulaciones en las que se incluyen asignaturas de transporte o vehículos

- Grado en Ingeniería Eléctrica, de la UNIVERSIDAD DE CANTABRIA, que incluye una asignatura optativa de 6 créditos sobre "Vehículos Eléctricos e Híbridos".
- Grado en Ingeniería Electrónica, Robótica y Mecatrónica, de la UNIVERSIDAD DE MÁLAGA, con la asignatura "Mecanismos y Mecánica de Vehículos" de 6 créditos que incluye aspectos de dinámica y componentes de automóviles
- Grado de Arquitectura Técnica, de la UNIVERSIDAD JAUME I DE CASTELLÓN, con la asignatura "Gestión de recursos humanos y técnicos en la edificación", obligatoria de 6 créditos que incluye temas sobre medios de manipulación de cargas.
- Máster en Ingeniería Mecatrónica, de la UNIVERSIDAD DE MÁLAGA, con la asignatura optativa "Simulación numérica del flujo alrededor de vehículos" de 5 créditos sobre aspectos aerodinámicos de los vehículos.
- Máster en Hidráulica Ambiental, de la UNIVERSIDAD DE MÁLAGA, con la asignatura optativa "Movimiento fluido alrededor de vehículos" de 6 créditos sobre aspectos aerodinámicos de los vehículos.
- Master en Ingeniería Electrónica, Robótica y Automática, de la UNIVERSIDAD DE SEVILLA, con la asignatura " Control en vehículos" de 5 créditos, impartida desde el área de Ingeniería de Sistemas y Automática.

Por último, citar que la titulación Máster en Diseño Avanzado en Ingeniería Mecánica" de la UNIVERSIDAD DE SEVILLA no incluye materias específicas relacionadas con vehículos.

5. TITULACIONES ESPECÍFICAS SOBRE TRANSPORTES O VEHÍCULOS

Debido, entre otros factores, a la gran demanda por parte de las empresas de conocimientos y formación en diferentes aspectos de los transportes y los vehículos en el ámbito industrial, han surgido un número relevante de titulaciones orientadas específicamente a estos aspectos. Estas titulaciones suelen ser de Máster, aunque existen algunas excepciones de titulaciones de Grado. En el estudio no se han incluido menciones a cursos de menor entidad en cuanto a duración como cursos de especialización, salvo en aquellos casos en los que, con la concatenación de varios se pueda alcanzar un título de Grado o Máster. Esta simplificación da una visión parcial del escenario formativo en estas áreas ya que deja de lado toda la oferta más puntual de corta duración. Sin embargo, esta decisión está soportada por el hecho del alto dinamismo de este tipo de formación que cambia de un curso al siguiente y no resulta una oferta estable en el tiempo estando, en muchos casos, motivada por necesidades puntuales en lugares o momentos concretos.

5.1. Titulaciones específicas sobre transportes

Este bloque de titulaciones versa sobre aspectos del transporte que, en muchos casos, están rozando la frontera de la Ingeniería Industrial, aunque se mantiene una carga relevante de aspectos derivados de la misma como la organización, aspectos energéticos y la logística. Se trata de titulaciones Máster con la excepción de una titulación de Grado. Se describen a continuación:

- Grado en Ciencias del Transporte y la Logística, de la UNIVERSIDAD CAMILO JOSÉ CELA, enfocado a aspectos logísticos y de distribución de mercancías.
- Máster Universitario en Movilidad Urbana, Tecnología y Ecotransporte, de la UNIVERSIDAD CAMILO JOSÉ CELA, que trata aspectos de logística, impacto ambiental, energía, etc.
- Máster Universitario en Ingeniería del Transporte Terrestre y Logística, de la UNIVERSIDAD DE JAÉN, con asignaturas sobre transporte por ferrocarril, por carretea, ambas infraestructuras y logística.
- Máster Universitario en Sistemas de Transporte, de la UNIVERSIDAD DEL PAÍS VASCO, orientado a políticas, organización, gestión y modelización del transporte.
- Máster Universitario en Planificación, Economía y Operación del Transporte Urbano y Metropolitano, de la UNIVERSIDAD PABLO OLVIDE, con un enfoque que incluye temas de movilidad, estudios de mercado, modelización y economía del transporte.
- Máster Universitario en Cadena de Suministro, Transporte y Movilidad, especialidad de Transporte y Movilidad, de la UNIVERSIDAD POLITÉCNICA DE CATALUNYA , sobre movilidad y aspectos de economía del transporte y planificación.
- Máster Universitario en Transporte, Territorio y Urbanismo, de la UNIVERSIDAD POLITÉCNICA DE VALENCIA, sobre temas de urbanismo, infraestructuras y explotación.
- Máster en Ingeniería para la Movilidad y la Seguridad, de la UNIVERSIDAD PONTIFICIA DE COMILLAS, que combina aspectos tecnológicos de sensores, sistemas de asistencia, sistemas de retención, biomecánica y propulsión eléctrica, con otros como simulación, dinámica o logística. También se oferta el Doble Máster Universitario en Ingeniería Industrial y en Ingeniería para la Movilidad y la Seguridad con las asignaturas “Dinámica vehicular”, “Sistemas de Asistencia y Tecnología de Sensores”, “Sistemas de retención y seguridad integrados”, “Movilidad sostenible”, “Estructuras ligeras”, “Sistemas de Propulsión Eléctrica”, “Vehículo Autónomo”, “Biomecánica del daño”, “Logística y Transporte Global” y “Resistencia al Choque”.

5.2. Titulaciones específicas sobre automoción

Se ha identificado una amplia oferta en el campo de la formación en automoción, tanto en nivel de Grado, pero, sobre todo, en nivel de Máster. El enfoque de estos estudios da un mayor peso a los ámbitos tecnológicos de los vehículos, aunque, en muchos casos, se extienden a los ámbitos de fabricación, explotación, comerciales, etc.

Titulaciones de Grado:

- Grado en Ingeniería del Automóvil, de la UNIVERSIDAD ANTONIO DE NEBRIJA, que incluye asignaturas específicas sobre automoción en los semestres 6, 7 y 8 como Teoría de Vehículos, Vehículos Eléctricos, Instrumentación y Electrónica del Automóvil, y Sistemas y componentes.
- Grado en Ingeniería de la Automoción, de la UNIVERSIDAD DE VIC-UNIVERSIDAD CENTRAL DE CATALUNYA, con asignaturas específicas sobre automoción en los cursos 2, 3 y 4 como reglamentación, estructuras, instrumentación, electrónica, sistemas y fabricación.
- Grado en Ingeniería en Automoción, de la UNIVERSIDAD DEL PAÍS VASCO, que incorpora asignaturas específicas de automoción desde el primer curso con una línea temática semejante a los casos anteriores.
- Grado en Ingeniería de la Automoción, de la UNIVERSIDAD POLITÉCNICA DE CATALUNYA, que centra las asignaturas específicas en los dos últimos cursos, con una línea temática semejante a los casos anteriores.

Titulaciones de Máster:

- Máster en Ingeniería de Vehículos de Competición, de la UNIVERSIDAD ANTONIO DE NEBRIJA, único máster centrado en este tipo especial de vehículos.
- Máster Universitario en Ingeniería de Componentes de Automoción, de la UNIVERSIDAD DE BURGOS, muy focalizado hacia el diseño, materiales, cálculo estructural y sistemas electrónicos.
- Máster Universitario en Ingeniería de Automoción Sostenible, de la UNIVERSIDAD DE DEUSTO, con 4 módulos muy centrados en aspectos de propulsión, aunque no de forma exclusiva: Automoción y Tecnologías de motores, Tren de Potencia, Electromovilidad y Vehículos de próxima generación
- Máster Universitario en Diseño y Fabricación en Automoción, de la UNIVERSIDAD DE DEUSTO, que incluye aspectos de vehículo y de su fabricación y diseño.
- Máster Universitario en Dirección de Producción en Empresas del Sector de Automoción, de la UNIVERSIDAD DE NAVARRA, estudios menos técnicos que otros antes citados y más enfocado a aspectos de gestión.
- Máster Universitario en Ingeniería de Automoción, de la UNIVERSIDAD DE VALLADOLID, centrado en los diferentes sistemas del vehículo y su diseño y comportamiento, e incluyendo aspectos de fabricación.

- Máster Universitario en Ingeniería de la Automoción, de la UNIVERSIDAD DE VIGO, con un tronco común que incluye Tecnologías y Procesos, Mantenimiento y Medioambiente en la Automoción, Aprovisionamiento, Logística y Técnicas de Calidad, y Financiación, Sistemas de Prevención y Recursos Humanos, y 2 especialidades: Tecnologías Automoción y Procesos de Automoción
- Máster Universitario en Ingeniería de la Automoción, de la UNIVERSIDAD EUROPEA DE MADRID, con 5 módulos: Ingeniería de Vehículos y Motores, Subsistemas y herramientas de diseño, Proyectos de automoción, Sostenibilidad y legislación, e Ingeniería de fabricación.
- Máster Universitario en Ingeniería de Automoción, de la UNIVERSIDAD POLITÉCNICA DE CATALUNYA, orientado a profundizar en cada uno de los sistemas del vehículo, principalmente.
- Máster en Ingeniería de Automoción, de la UNIVERSIDAD POLITÉCNICA DE MADRID, que incluye 5 módulos (Módulo de Ingeniería de los Vehículos, Módulo de Gestión, Módulo de Impacto Socioambiental, Módulo de Ingeniería de Fabricación, y Módulo de Entrada al Sector) y conforma 3 especialidades: diseño en automoción, vehículos híbridos y eléctricos, y vehículos autónomos y conectados.

5.3. Titulaciones específicas sobre ferrocarriles

La oferta de estudios sobre ferrocarril es mucho más limitada que en el caso de automoción. En concreto, se han identificado 2 titulaciones de Máster y otras 2 titulaciones planteadas de forma modular para poder adquirir diferentes cualificaciones, siendo la más alta, la de Máster. Se describen a continuación:

Titulaciones de Máster:

- Máster en Ingeniería de Sistemas Ferroviarios, de la UNIVERSIDAD CARLOS III DE MADRID, que incluye 4 grandes bloques temáticos: fundamentos de ingeniería ferroviaria, señalización y tracción ferroviaria, seguridad y mantenimiento.
- Máster Universitario en Sistemas Ferroviarios, de la UNIVERSIDAD PONTIFICIA DE COMILLAS, que incluye 4 bloques temáticos: señalización y sistemas de control, rodante material, infraestructura y gestión. Adicionalmente, se oferta el Doble Máster Universitario en Ingeniería Industrial y en Sistemas Ferroviarios con las siguientes asignaturas del ámbito ferroviario: Normativa ERTMS Y RAMS, Señalización Ferroviaria, Planificación y programación, Sistemas avanzados de diseño y control de tráfico, Sistemas de control y supervisión, Electrificación, Elementos del material rodante, Ferrocarriles metropolitanos, urbanos y de cercanías, Obra civil y Estaciones, Alta Velocidad e Intercity, Dinámica de material rodante y freno y Mecánica de catenaria.

Cursos con estructura modular:

- Programa de módulos conducentes a titulaciones de Experto Profesional, Experto Universitario o Máster en Ingeniería y Mantenimiento Ferroviario, de la UNIVERSIDAD NACIONAL DE EDUCACIÓN A DISTANCIA, que incluye 15 módulos sobre vehículos, infraestructuras, comunicaciones, subestaciones, ciberseguridad, mantenimiento, etc.
- Programa de módulos conducentes a titulaciones de Experto Profesional, Experto Universitario o Máster en Ingeniería y Gestión del Transporte Terrestre, de la UNIVERSIDAD NACIONAL DE EDUCACIÓN A DISTANCIA, que incluye 14 módulos, principalmente centrados en los aspectos ferroviarios como alta velocidad, explotación y material rodante e infraestructuras ferroviarias, pero también tratando Infraestructuras y vehículos del transporte terrestre, transporte interurbano, urbano y metropolitano, y transporte de mercancías y logística

6. CONCLUSIONES

La prospectiva de las enseñanzas en transportes y vehículos dentro de las titulaciones de Ingeniería Industrial y afines ha demostrado que la presencia es mayor en títulos de MII y de GIM, siendo más residual en titulaciones más generalistas como GITI. La mayor presencia en MII viene motivada por las directrices marcadas por la Orden CIN/311/2009. Sin embargo, a pesar de la menor presencia en GITI y GIM, son las dos titulaciones en las que se han detectado asignaturas con mayor contenido en créditos con los promedios más altos. El enfoque y las temáticas tratadas también son diferentes en las titulaciones, siendo prioritarios aspectos de vehículos y sus componentes en GITI, GIM y MIM, mientras que se en el MII se focaliza hacia transportes y medios de manutención prioritariamente. En cuanto a formación específica, la limitada formación en aspectos de ferrocarril contrasta con la alta oferta en automoción, no solo de ámbitos técnicos sino también de otra índole como fabricación o administración. Esta alta oferta, sin embargo, no tiene su reflejo en titulaciones regladas.

Sin duda, este análisis pone de manifiesto que se trata de materias claramente aplicadas por lo que su presencia natural está en cursos de Máster y resultan muy proclives a formación especializada. Sin embargo, sí resulta relevante apreciar la alta dispersión entre los enfoques empleados en diferentes Universidades para una misma titulación, tanto en número de asignaturas, créditos de las mismas o contenidos impartidos. La tendencia a asignaturas cortas, sobre todo las obligatorias en Máster, obligan a una selección muy parcial en un ámbito tan amplio como es el transporte terrestre y sus vehículos, con lo que quedan, en muchos casos, aspectos que no son ni introducidos. Afortunadamente, en titulaciones como GITI, MII o MIM, entre los planes de estudios que incorporan alguna asignatura sobre transporte, hay un porcentaje relevante de casos en los que existe más de una asignatura (entre el 33% para los planes de MII y el 66% para los planes de MIM), lo que permite complementar enfoques y tratar, por ejemplo, en una materia aspectos de transporte y manutención y en otra aspectos de vehículos, como combinación más usual, así como introducir tecnologías novedosas como sistemas electrónicos o vehículos eléctricos.

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EL USO DE CLASSCRAFT PARA MEJORAR EL CONOCIMIENTO Y EL INTERÉS DE LOS ESTUDIANTES DE PRIMARIA EN LA MOVILIDAD SOSTENIBLE

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RESUMEN

En la sociedad actual necesitamos poner en marcha planes de formación orientados a la educación a la movilidad sostenible para garantizar un devenir mejor a las generaciones futuras. La manera en la que se ha comunicado y educado en la movilidad sostenible no ha sido completa hasta ahora. La mayoría de los estudios y proyectos formativos se han centrado en la seguridad de los niños, el tráfico callejero, las reglas de tráfico o fomentar comportamientos más saludables como andar o ir en bici al cole, por lo que existe la necesidad de ampliar las temáticas a tratar para fomentar el cambio de actitudes.

En este articulo, presentamos los resultados más relevantes de una experiencia basada en la técnica de gamificación que promueve la educación a la movilidad sostenible en las aulas de la escuela primaria. Este nuevo método formativo, dirigido a niños entre 10-12 años, permite la aplicación de metáforas de juego para tareas de vida real en entornos no lúdicos con el fin de aumentar la motivación al cambio de actitudes.

La intervención didáctica se ha desarrollado con el uso de la plataforma ClassCraft y se han creado actividades especificas que considerasen todos los componentes de la movilidad sostenible: ambiental, económica y social.

El análisis inicial ha demostrado que la percepción sobre la movilidad sostenible estaba orientada hacia los problemas medioambientales y muy poco hacia los componentes social y económico. Después de la experiencia, se han evaluado los conocimientos adquiridos sobre el tema y los cambios de actitud de los niños demostrando que, con el uso de la herramienta gamificada ClassCraft y actividades bien estructuradas sobre todos los aspectos de la movilidad sostenible, los alumnos han adquirido nuevos conceptos que clarifican la importancia de los componentes social y económico, empezando a desarrollar una conciencia sobre cómo ser parte activa en el cambio de sus conductas.

1. INTRODUCIÓN

Los niños son los ciudadanos del futuro y, por lo tanto, la educación y el sentimiento de ser parte de una comunidad juegan un papel fundamental en la configuración de nuestra sociedad futura. El reconocimiento del papel de la educación como un facilitador clave para el desarrollo sostenible y la movilidad sostenible ha ido creciendo constantemente. Facilitar y promover medios y hábitos de movilidad más sostenibles es un objetivo de creciente importancia para las ciudades de todo el mundo.

La manera en la que se ha comunicado y educado en la movilidad sostenible no ha sido completa hasta ahora. La mayoría de los estudios y proyectos formativos se han centrado en la seguridad de los niños, el tráfico callejero, las reglas de tráfico, fomentar comportamientos más saludables como andar o ir en bici al cole (Tabibi, 2009). Existe la necesidad de ampliar tanto las temáticas a tratar para fomentar el cambio de actitudes, así como las herramientas que puedan ser útiles.

El principal objetivo de nuestro estudio ha sido observar y evaluar el uso de técnicas de gamificación como clave para el impulso del aprendizaje y el cambio hacia hábitos de movilidad sostenible.

Para demostrar los cambios en el aprendizaje sobre la movilidad sostenible y el cambio de hábitos nos hemos centrado en los siguientes objetivos específicos:

- Evaluar la percepción que los alumnos tienen respecto a la movilidad sostenible.
- Evaluar el grado de conocimiento conseguido a través de la experiencia.

Después de la introducción, en el apartado 2 se presenta una revisión de la literatura relativa a como movilidad sostenible ha sido tratada con niños, así como a la gamificación y a su aplicación en temas de movilidad. En el apartado 3 se presenta la metodología adoptada y se describe el caso de estudio. En el apartado 4 se presentan los resultados obtenidos.

Finalmente, en el apartado 5 se presentan las conclusiones, junto con las limitaciones que el estudio ha encontrado y las posibles futuras líneas de investigación.

2. REVISION DE LITERATURA

Para el desarrollo de esta investigación es importante describir cómo, en la sociedad actual, se considera y se aborda el tema de la educación en movilidad sostenible relacionada con niños.

Al mismo tiempo es importante analizar la gamificación y su aplicación en temas de movilidad. La gamificación ha demostrado su potencial como un elemento socio-técnico estratégico para aumentar la participación y el compromiso, y promover comportamientos sostenibles, como el hábito ético, social, ecológico o saludable (Bielik et al., 2012). A continuación, analizaremos dichos aspectos de forma independiente.

2.1 La Movilidad sostenible y la infancia

Para entender cómo educar a la movilidad sostenible es necesario preguntarse porque es fundamental ocuparse de ese tema.

Durante la Conferencia de las Naciones Unidas sobre Medio Ambiente y Desarrollo (Keating, 1993), los niños fueron reconocidos como un grupo importante para el desarrollo de un ambiente sostenible. Dado que las actitudes hacia el medio ambiente ya comienzan a desarrollarse en la infancia, puede ser imperativo centrarse en los niños y los jóvenes (Lyons y Breakwell, 1994) para abordar el transporte en el futuro.

El transporte ha estado dominado tradicionalmente por campos como la ingeniería, por lo tanto, muchos de los conceptos centrales para la movilidad sostenible siguen siendo competencia de los especialistas técnicos en lugar de estar en manos de los consumidores, de los responsables de la toma de decisiones o de los jóvenes estudiantes (Schweitzer, Marr, Linford, y Darby, 2008).

Existe un creciente cuerpo de investigación sobre las actitudes de los adultos hacia los automóviles y el medio ambiente (Beirão y Cabral, 2008; Gärling, 2004; Joireman, Van Lange, y Van Vugt, 2004). Sin embargo, ha habido muy poca investigación sobre las actitudes de los niños hacia los automóviles y a la movilidad. Una excepción notable es un informe de investigación escocés sobre cómo los niños y los jóvenes consideran la sostenibilidad en relación con su transporte personal (Davison, Reed, Halden, y Dillon, 2003). Los resultados obtenidos demostraron que la mayoría de los niños conocían bien los problemas de transporte sostenible, pero sus conocimientos no necesariamente tuvieron un impacto en el cambio de actitudes.

Si bien la investigación sobre movilidad en general es muy amplia, existe una falta particular de investigación de movilidad en relación con los niños. Las pocas investigaciones realizadas se han centrado principalmente en los viajes de los niños a la escuela (Kerr et al., 2006; Mackett, Gong, Kitazawa, y Paskins, 2007; McMillan, Day, Marlon, Alfonzo, y Anderson, 2006; Pooley, Turnbull, y Adams, 2006).

Los niños desempeñan un papel fundamental en la movilidad sostenible, no solo por sus estilos de vida actuales dependientes de los automóviles, sino también por su capacidad única de ser "agentes de cambio" (Chawla, 2009; Chawla, 2007; Heft y Chawla, 2006; Malone, 2013, 2015; Sharpe y Tranter, 2010) para sus propias necesidades de viaje, así como las opciones de viaje de sus hogares en general (Tranter y Sharpe, 2012) para lograr vecindarios sostenibles ahora y asegurar los cambios necesarios para un futuro sostenible.

Cambiar el comportamiento de la movilidad personal en respuesta al cambio climático representa un gran desafío para los científicos sociales y los profesionales, dada la naturaleza integrada de la movilidad en la vida diaria (Barr, 2018). Los intentos por comprender, gobernar y promover una movilidad más sostenible han tendido a centrarse en la toma de decisiones individuales y los cambios en el comportamiento, como la reducción del uso de automóviles y el aumento del uso de caminatas, ciclismo y transporte público.

El comportamiento individual juega un papel importante en el transporte sostenible, sin embargo, los hábitos de movilidad diaria son difíciles de cambiar.

A lo largo de los años ha ido creciendo el interés sobre la relación entre movilidad sostenible y niños. Por ejemplo, históricamente, textos clave como “El niño en la ciudad” de Ward (1978) comenzaron a plantear la cuestión sobre cómo los niños se mueven en el espacio público. Del mismo modo, las series clásicas de estudios empíricos de Hillman et al. en 1971 y 1990 (Hillman, Adams, y Whitelegg, 1990) atrajeron la atención al hecho de que los niños se comprometen de hecho con la movilidad y los viajes. Para muchos niños en países desarrollados, sus vidas giran en torno a un territorio urbano expandido a medida que acceden diariamente a amplias áreas de la ciudad para asistir a actividades escolares, deportivas, educativas y culturales (Karsten y van Vliet, 2006). Esto forjó el camino para un número más amplio de estudios empíricos de los patrones de viaje de niños y jóvenes a través de los países industrializados occidentales que replicaron el estudio de Hillman y documentaron patrones similares de cambios en la movilidad de los niños, incluidos los de países como Dinamarca (Fotel y Thomsen, 2004), Italia (Rissotto y Tonucci, 2002), Suecia (Sandqvist, 2002) y Nueva Zelanda (Collins y Kearns, 2001).

Se están lanzando muchas iniciativas de base y participativas a nivel local que brindan soluciones de abajo hacia arriba que apoyan la libertad de movimiento de los niños (por ejemplo, pedibus, trenes de bicicletas, voluntarios en los cruces de peatones, viajes compartidos entre padres y similares). Sin embargo, cualquier programa innovador y costoso, introducido de arriba hacia abajo por las ciudades para aumentar la seguridad vial y la movilidad independiente de los niños tiene más probabilidades de tener éxito si se combina con iniciativas dirigidas a cambiar las actitudes de los padres y los niños, y a aumentar la conciencia de los ciudadanos sobre este tema. En este sentido, Gilbert, Whitzman, Pieters, y Allan (2017) afirman que no hay un lugar mejor que la vida diaria de los niños en edad escolar para originar un cambio en las actitudes hacia una movilidad más sostenible.

En Europa y América del Norte, la movilidad de los niños ha recibido una mayor atención pública y académica (Mikkelsen y Christensen, 2009). En España hay varios ejemplos de buenas practicas educativas en lo que se refiere a la movilidad sostenible. Destacan las iniciativas de “Camino escolar seguro” en Barcelona, Granollers, Madrid, San Sebastián, Segovia, Viladecans y Zaragoza. “Con Bici al Cole” o el programa de Educación Ambiental de Segovia, “Pies para que os quiero: movilidad y camino escolar”. Estos programas pretenden inculcar y promover, en los niños de primaria y en la comunidad en general, los hábitos de cuidado del entorno y de la salud propia mediante la incorporación de conceptos y conductas relacionados con la movilidad sostenible haciendo que la calle se convierta en un lugar propicio para convivir (Ferrando, Molinero, y Peña, 2007).

Para que cualquier actividad educativa para la movilidad sostenibilidad se traduzca en cambio de comportamiento y práctica en la vida diaria, es fundamental complementarlos con otras estrategias. Para una promoción eficaz de los viajes activos, es necesario combinar una gama de proyectos de infraestructura y no infraestructura. Davison, Werder, y Lawson (2008) destacaron el importante papel que desempeñan los programas comunitarios de educación en resultados exitosos de rutas seguras a proyectos escolares en los EE. UU. De manera similar, McDonald y Aalborg (2009) enfatizaron que la infraestructura por sí sola no es suficiente para políticas de viaje activo, además educar y alentar a las familias y los niños es esencial para lograr un cambio de comportamiento. En países como Dinamarca, Holanda y Alemania, la educación en viajes activos se ofrece más allá del plan de estudios formal y está respaldada por una amplia capacitación práctica, que se traduce en una práctica diaria para los niños y las comunidades en general (Faherty y Morrissey, 2014; Schwanen et al., 2012).

2.2 Gamificación y movilidad sostenible

Los juegos serios, los juegos persuasivos, así como las interacciones gamificadas, han demostrado ser herramientas útiles no solo para crear conciencia sobre un tema, sino también para promover una actitud o un cambio de comportamiento. La idea clave es aumentar la motivación de las personas para tomar ciertas decisiones, o llevar a cabo ciertas tareas que son instrumentales para alcanzar objetivos valiosos, convirtiéndolos en experiencias divertidas y gratificantes. La sostenibilidad ambiental es un área de aplicación donde los enfoques de gamificación han sido ampliamente aplicados, que van desde el ahorro de energía (Cowley, Moutinho, Bateman, y Oliveira, 2011; Orland et al., 2014; Shiraishi et al., 2009), la movilidad sostenible (Gabrielli et al., 2013; Holleis et al., 2012; Kazhamiakin, Marconi, Martinelli, Pistore, y Valetto, 2016; Kazhamiakin et al., 2015) y otras cuestiones ambientales como las misiones ambientales comunitarias (Lee et al., 2013), la gobernanza participativa de los barrios urbanos (Coenen, Merchant, Laureyssens, Claeys, y Criel, 2013) o el descubrimiento de la ciudad educativa (Hamari, Koivisto, y Sarsa, 2014). La gamificación para la conciencia ambiental y la sostenibilidad ha resultado exitosa en varios de esos casos; sin embargo, su impacto es a menudo transitorio y tiende a disminuir con el tiempo (Hamari et al., 2014), a menos que se refuerce con las motivaciones oportunas (Weiser, Bucher, Cellina, y De Luca, 2015), y los elementos y la mecánica de diseño del juego correspondientes (Khoshkangini, Valetto, y Marconi, 2017).

El uso de técnicas de gamificación en el ámbito de la movilidad sostenible, como forma para incentivar cambios de comportamiento voluntarios hacia soluciones de movilidad sostenible, se ha difundido mucho en estos últimos años en relación con la difusión de las Smart City en Europa (Kazhamiakin et al., 2015; Khoshkangini et al., 2017).

Una ciudad inteligente (Smart City) es una ciudad eficiente y avanzada de alta tecnología que conecta personas, información y elementos de la ciudad mediante el uso de nuevas tecnologías para crear una ciudad sostenible, más ecológica, competitiva e innovadora, y una mayor calidad de vida (Bakıcı, Almirall, y Wareham, 2013).

La mayoría de los estudios y aplicaciones desarrolladas están dirigidas a adultos. Merugu, Prabhakar, y Rama (2009) ilustran una aplicación para reducir la congestión del tráfico. Hoh et al. (2012) proponen gamificación de pareja y crowdsourcing para incentivar a los ciudadanos a compartir información sobre plazas de aparcamiento en la ciudad. Gabrielli et al. (2014) describen una metodología de diseño para la gamificación y la aplican a los estudios de caso realizados en cuatro ciudades europeas. Buningh, Martijnse-Hartikka, y Christiaens (2014) implementaron un sistema gamificado para estimular a los empleados de la empresa a elegir medios sostenibles de transporte para trabajar. Wells et al. (2014) proponen un modelo de gamificación para motivar a los usuarios a adoptar una movilidad sostenible, que rastrea los comportamientos de movilidad de las personas y propone desafíos modulados sobre la base de su progreso actual. De manera similar, la plataforma Tripzoom (Bie et al., 2012) se utilizó en tres ciudades europeas (Poslad, Ma, Wang, y Mei, 2015) para identificar los patrones de comportamiento de los ciudadanos en materia de movilidad, y luego propuso y recompensó soluciones de movilidad personalizadas y gamificadas que mejoran las emisiones de CO_2, la salud de los jugadores y el tiempo.

En el otoño de 2014, dentro del proyecto STREETLIFE EU, se llevó a cabo un experimento para evaluar el impacto de las recomendaciones de movilidad sostenible y los incentivos de gamificación en el comportamiento de movilidad de los pasajeros que necesitan viajar rutinariamente al centro de la ciudad en automóvil (Kazhamiakin et al., 2015). Se proporcionaron mecanismos para integrar e implementar políticas a nivel de ciudad dentro de un conjunto de servicios de movilidad inteligente: como servicios de planificación de viajes y recomendaciones de rutas que los ciudadanos utilizan habitualmente. Además, se proporcionaron mecanismos para incentivar a los ciudadanos a tomar decisiones de acuerdo con esas políticas de movilidad, mediante la gamificación. Este estudio puede permitir a un diseñador de gamificación concebir juegos que aumenten el conocimiento de los ciudadanos sobre las políticas y servicios de movilidad sostenible existentes y nuevos en la ciudad, y los motiva a adoptar las soluciones de TIC habilitantes correspondientes para obtener estatus y reputación en el juego y ganar recompensas (ya sean virtuales o materiales).

Por lo tanto, la gamificación puede desempeñar un papel clave y triple en este contexto: apoyar la sostenibilidad de las iniciativas de educación ambiental a largo plazo, promover el compromiso de la comunidad en general y fomentar la creatividad y la participación activa. Ya hay algunos ejemplos exitosos que aprovechan la gamificación para promover estilos de vida sostenibles en niños y padres (González, 2016; Hu, Fico, Cancela, y Arredondo, 2014; Jones, Madden, y Wengreen, 2014).

Sin embargo, hay algunos ejemplos de enfoques de gamificación que se dirigen específicamente a la educación ambiental de los niños. Por ejemplo, ECOMobile implementa un enfoque de aprendizaje situado para el aprendizaje de las ciencias del ecosistema, que puede aprovecharse para organizar excursiones a entornos de estanques locales (Kamarainen et al., 2013). Su combinación de una experiencia gamificada de realidad aumentada ha demostrado ser muy efectiva para que los niños comprendan e interpreten las mediciones de la calidad del agua.

Beat the Street (“Beat The Street - Delivered By Intelligent Health,” 2007) y Kids-Go-Green (Marconi et al., 2018) son unas aplicaciones similares en sus objetivos. La iniciativa "Beat the Street" es un plan de viaje activo, una experiencia propuesta en Reino Unido. La iniciativa convierte a toda la ciudad en un juego. De hecho, involucra a una comunidad local de personas dentro de una competición que los anima a caminar o andar en bicicleta en su vecindario, utilizando tecnología de rastreo y un esquema de recompensa. Este juego se ha aplicado también en las escuelas para promover la movilidad activa y sostenible de los niños, pero estudios preliminares muestran que el cambio inducido fue muy limitado (Coombes y Jones, 2016). Esto podría deberse al hecho de que Beat the Street no fue diseñado específicamente para niños, ni para integrarse en el entorno escolar y su programa didáctico. La mecánica del juego, las recompensas y la experiencia del usuario en Beat the Street están diseñadas para involucrar a una población de jugadores genéricos.

Mientras, Kids-Go-Green (Marconi et al., 2018) está diseñado específicamente para ser significativo y atractivo para los niños pequeños en un entorno educativo, como la escuela. Tiene como objetivo aumentar la conciencia y cambiar el comportamiento de los niños y sus familias con respecto a los hábitos de movilidad activa y sostenible. Además, busca provocar un compromiso a corto plazo hacia hábitos de movilidad diferentes, específicamente en lo que se refiere al viaje del hogar a la escuela, lo que eventualmente conduce a una actitud a largo plazo, mediante el aprovechamiento del potencial de las iniciativas educativas gamificadas. Kids-Go-Green se ha desarrollado como una aplicación web a la que se puede acceder desde cualquier navegador web y que se puede utilizar en la escuela por medio de pantallas grandes, pizarras interactivas, tabletas inteligentes u ordenadores.

3. METODOLOGÍA

Para hacer un diagnóstico sobre la percepción y el conocimiento de los alumnos sobre la movilidad sostenible, antes y después de la experiencia didáctica con la plataforma ClassCraft, la investigación se ha subdividido en 4 grandes fases:

1. Diseño de un cuestionario de conocimiento inicial y final, con preguntas de caracterización socioeconómica, hábitos de movilidad y propias del tema de estudio;
2. Diseño de las actividades en la plataforma de juego ClassCraft;
3. Recolección de datos, donde se han recogido las respuestas del cuestionario efectuado de modo presencial, antes y después de la experiencia;
4. Análisis de los resultados, donde se han analizado las respuestas de los estudiantes, antes y después de la experiencia, obteniendo con ellos la percepción previa y los conocimientos finales sobre el tema.

3.1 Diseño del cuestionario

Los cuestionarios se centraban sobre los conocimientos de los aspectos ligados a la movilidad sostenible a través de 38 preguntas de diversa tipología: algunas de respuesta con elección múltiple, otras de respuestas abierta, algunas de preferencias y otras de ranking. Para estructurar este tipo de cuestionario hemos tenido como referencia las encuestas utilizadas para estudiar la percepción del usuario sobre la calidad del servicio de transporte público (dell'Olio, Ibeas, y Cecín, 2010; dell'Olio, Ibeas, y Cecin, 2011; Rojo, Gonzalo-Orden, dell'Olio, y Ibeas, 2011; Rojo, Gonzalo-Orden, dell'Olio, y Ibeas, 2012).

Las 38 preguntas presentan diferentes temáticas:

- de carácter socioeconómico: se pregunta cuántos miembros tiene la familia, qué trabajo tienen los padres, dónde viven, si tienen coche y bicicletas.
- análisis de los hábitos de movilidad: cómo van al colegio, si utilizan la bici, los motivos de los desplazamientos y las diferentes modalidades de movilidad presentes en la ciudad.
- definición de algunas palabras y conceptos clave asociados a la movilidad sostenible como: carril bici, zonas peatonales, transporte colectivo, coche compartido, ciudad sostenible, transporte sostenible, *bike sharing*.

Este cuestionario, sin la parte inicial de caracterización socioeconómica, se ha propuesto después de la experiencia didáctica con técnicas de gamificación para evaluar los cambios en los conocimientos de los alumnos.

Para entender mejor los resultados hablaremos de *cuestionario inicial* cuando nos referimos a los datos antes de la experiencia didáctica y *cuestionario de verificación* cuando nos referimos a los datos después de la experiencia didáctica.

3.2 Diseño de las actividades en la plataforma ClassCraft

Inspirada en los videojuegos de rol o juegos de rol (por ejemplo, World of Warcraft), la primera versión de ClassCraft fue concebida por Shawn Young en enero de 2011.

Aunque inicialmente ClassCraft se desarrolló para la gestión de la clase en la escuela secundaria, hay ejemplos de su uso en la educación primaria (Mora Márquez, Camacho Torralbo, y Torralbo, 2019).

Se trata de una aplicación web, ya creada, que permite a los profesores dirigir un juego de rol en el que sus alumnos encarnan diferentes personajes. Los Role-Playing Game (RPG) se podrían definir como un sistema para crear historias basadas en una serie de reglas (Grande-de-Prado, Baelo, García-Martín y Abella-García, 2020). En este caso la idea es que los alumnos estén involucrados en un juego donde la evolución de su personaje está relacionada a sus capacidades escolares y de colaboración en clase.

El juego funciona en un motor web en tiempo real, por lo que los eventos del juego se envían en tiempo real a los dispositivos de otros usuarios, como en un videojuego normal en línea (Sanchez, Young, y Jouneau-Sion, 2017). ClassCraft no está relacionado con una materia escolar específica, y la duración del juego depende de las expectativas del maestro (desde unas pocas horas de clase hasta todo el año). Los estudiantes juegan durante las horas escolares y fuera de clase (Sanchez et al., 2017).

ClassCraft es una plataforma muy visual y atractiva que permite crear un mundo de personajes (magos, sanadores y guerreros) que deberán cooperar y participar en misiones para ir ganando puntos y monedas con el que mejorar su equipo. El objetivo, es ir avanzando de forma colaborativa a la vez que aprenden y desarrollan su conocimiento. Los maestros tienen acceso a una interfaz donde pueden elaborar una historia, crear un conjunto de actividades que los alumnos deben resolver para obtener puntos y recompensas. El estudiante tiene un perfil privado en línea donde puede ver cuántas insignias ha recibido, cuáles son las actividades, etc. Se supone que los estudiantes deben desarrollar lo que el maestro propuso y luego recibir puntos y distintivos que reconocen su trabajo.

Las reglas del juego son bastante simples. Un estudiante que demuestre un comportamiento positivo en la clase puede ganar "Puntos de experiencia (XP)". Si un estudiante “rompe” las reglas de la clase, perderá “Puntos de salud (HP)”, su energía vital en el juego, y eventualmente, caerá en la batalla.

En nuestro caso, se ha construido una historia donde los alumnos eran superhéroes llamados a salvar a los habitantes de una isla contaminada. Se han elaborado y presentado, en la plataforma, actividades de varias tipologías: crucigramas, sopas de letras, mensajes cifrados, imágenes, mapas conceptuales, problemas matemáticos, videos informativos y documentales, historias, discusiones en chat, ejemplos reales. En total el mapa de la historia con las actividades se componía de 48 etapas. Para resolver cada tarea los niños tenían a disposición un tiempo y podían recibir diferentes recompensas (XP y GP) si terminaban antes del tiempo dado o después.

3.3 Recolección de datos del caso de estudio: realización de la Encuesta antes y después de la experiencia

Los protagonistas de la investigación han sido alumnos de 5º de primaria del Colegio Marista Liceo Castilla de Burgos. El total de la muestra objeto de estudio se corresponde con 75 alumnos divididos en tres clases (25 cada una). Todos los estudiantes se incluían en el rango de edad 10-11 años, con una ligera prevalencia en el género de los niños sobre las niñas y observamos que esta tendencia se mantiene en las tres clases. En el total había un 53% de niños y un 47% de niñas.

La experiencia se enfocó como una actividad extracurricular y se planearon algunos encuentros presenciales para no interferir en el desarrollo de las actividades curriculares.

Para la realización de las encuestas, los alumnos han tenido a su disposición 60 minutos para responder a cada una, siendo ayudados por sus profesores, que solo tenían la posibilidad de ayudarlos desde el punto de vista práctico (cómo contesto) y no conceptual (qué significa). Se garantizó en todo momento el anonimato y la confidencialidad de las respuestas. Los cuestionarios se han suministrado antes de la experiencia y después de tres meses de actividades.

4. RESULTADOS

El análisis de los cuestionarios se ha hecho conjuntamente, las mismas preguntas se formularon antes de llevar a cabo la actividad gamificada y después. Por comodidad dividimos los resultados en tres grandes partes:

- la caracterización de los hábitos y percepción de movilidad de los alumnos;
- la evolución de los conocimientos básicos de movilidad sostenible.
- el análisis del aprendizaje con técnicas de gamificacion antes y después de la actividad.

El objetivo principal es ver cómo ha evolucionado su forma de pensar con el fin de evaluar y validar la efectividad de la actividad. Hay que tener en cuenta que en esta experiencia las actividades no eran obligatorias.

4.1 Caracterización de los hábitos y percepción de movilidad de los alumnos

A continuación, analizaremos y compararemos los hábitos y percepción sobre la movilidad antes y después de la actividad gamificada.

Analizamos la percepción de las distintas formas para ir al colegio, qué tipo de transporte hay en la ciudad, qué opiniones tienen respecto a diferentes temas relacionados con el ambiente, la contaminación y la sostenibilidad, y qué prioridades tienen a la hora de desplazarse.

Con el fin de establecer si las costumbres de movilidad están influenciadas por la zona donde viven, se preguntó acerca del lugar de residencia, teniendo en cuenta que la ubicación del colegio es periférica (respecto al centro de la ciudad) y se encuentra conectada con una de las vías principales de entrada/salida a la ciudad.

Aquí hay bastante heterogeneidad con prevalencia de niños que viven en el centro de la ciudad el 37%, pero se registra un porcentaje parecido, aunque inferior de niños que viven en la periferia un 30% o en pueblos un 22%.

También la posesión de coche es un factor importante que incide en los hábitos de movilidad de los alumnos y sus familias.

Se registra cómo la mayoría de los hogares tienen 2 coches, con un total de 155 coches en los 75 hogares, lo que supone una tasa de motorización de 2,07 coches por hogar.

La mayoría de los hogares (el 96%) tienen al menos una bici y la mayoría de ellos la usan una vez a la semana (el 40%) o más de una vez por semana (el 42%). Dos de ellos la usan a diario. La mayoría de ellos la usan para jugar y para desplazarse.

Se preguntó cuántas formas (modos o combinación de modos) distintas pueden elegir para ir desde casa al colegio. El intento de las preguntas es averiguar cuántas posibles formas de ir al colegio conocen, independientemente de si la utilizan o no.

Para ir al colegio, la mayoría de los alumnos se desplaza de forma habitual en coche (más del 60%) o a pie (el 21%) y un pequeño porcentaje se desplaza en bici (el 11%) y en bus (el 7%). Los niños van al colegio principalmente acompañados por sus padres y madres, y en forma menor con abuelos y hermanos. Se registra, después de la experiencia, un incremento de opciones de respuestas, esto quiere decir que en la actividad los alumnos han aprendido, recordado o conocido nuevos modos de transportes que han ampliado su visión. Los incrementos más importantes los tenemos en los siguientes modos: bici, pedibus, bus y a pie. Todos ellos son modos de transporte sostenible y por lo tanto desde este punto de vista podemos concluir que la actividad ha sido muy efectiva. Como era lógico también se incrementa el número de personas que eligen el coche y curiosamente baja el número de personas que eligen el modo combinado a pie + bus. La mayoría de los alumnos usa también medios de transporte distintos del coche, pero hay un 21,3% de alumnos que solamente usa el coche para sus desplazamientos. Como modos alternativos prevalecen los desplazamientos a pie, en bus, en tren y en bici. Entre los motivos de desplazamientos prevalecen: ir de compras, visitar amigos y familiares y hacer recados.

Conocer los modos de transporte público es un aspecto importante para poder favorecer su uso. Para verificar su nivel de conocimiento se preguntó qué medios de transporte público existen en la ciudad de Burgos. Globalmente el número de alumnos que conocen los diferentes modos de transporte público presentes en la ciudad aumenta de una forma importante después de la actividad gamificada. Las escaleras mecánicas, el tren y las bicis de alquiler, son los modos de transporte público que más incremento tienen respectivamente de un 29%, un 18% y un 14%, pero también se incrementa el número de alumnos que conocen el taxi (3%) y el bus (2%) (que es el modo de transporte publico más conocido por los alumnos). Hay que destacar que un número mínimo de alumnos indican la presencia del tranvía (1 alumno tanto antes como después de la actividad) y del metro (2 alumnos tanto antes como después de la actividad) en la ciudad de Burgos que actualmente no existen. Globalmente se puede concluir que también este objetivo se ha alcanzado con la actividad y por lo tanto los alumnos han incrementado de forma significativa su conocimiento de los modos de transporte publico de su ciudad.

4.2 Evolución de los conocimientos básicos de movilidad sostenible

En este apartado analizaremos las preguntas comunes de los cuestionarios considerando las referidas a los conocimientos básicos de movilidad sostenible antes y después de la actividad gamificada.

En los conocimientos empezamos por los *carriles bici*. Antes de las actividades, los alumnos demuestran conocer los carriles bici un 70%, pero lo que se pretende es ver si tras la actividad gamificada comprenden su utilidad. En la actividad gamificada, los alumnos aprenden que la bici no debe ser únicamente un modo de transporte para actividades de ocio y este logro es importante. También se incrementan de un 5% las respuestas donde los alumnos dicen que el carril bici favorece el uso de la bici e incrementa la seguridad de los ciclistas. Estos conceptos son importantes y evidencian el progreso de los alumnos en el aprendizaje de su función. Disminuye un 9% el número de alumnos que dicen que los carriles bici sirven para ir más rápido y que sirven para pasear los fines de semana y en el tiempo libre. También demuestran entender mejor que el carril bici no sirve para que lo usen los peatones y que no es una infraestructura que estorbe o perjudique al peatón. Globalmente podemos decir que con esta actividad se han logrado unos resultados muy satisfactorios.

Exactamente lo mismo pasa con las *zonas peatonales*, demuestran conocer su presencia en la ciudad de Burgos un 70%. Cuando se pregunta sobre la utilidad de las zonas peatonales, la mayoría opina que sirven para que los peatones puedan circular libremente, un 70%, también para que no haya coches en ellas un 50% y para que haya más espacio público un 38% y para reducir la contaminación un 26%.

Después de la actividad gamificada los mayores incrementos se obtienen justamente en las dos opciones menos elegidas (para que haya más espacio público incrementa del 4% y para reducir la contaminación incrementa del 3%). Esto es muy positivo puesto que nos demuestra que las actividades gamificadas han ayudado a entender mejor estos conceptos menos populares entre los alumnos.

A continuación, analizamos las respuestas relativas a algunas definiciones: *transporte colectivo, coche compartido, ciudad sostenible, transporte sostenible, bike sharing.*

En todos se analiza la frecuencia de respuesta desagregada por clase y total, y los porcentajes de variación del total de respuestas.

Para verificar si los alumnos conocían el significado de *transporte colectivo* se les dio a elegir entre tres definiciones:

Definición 1: Es un medio de transporte público que tiene unos horarios y rutas establecidos. Unos ejemplos son los coches, motos, furgonetas y camiones.
Definición 2: Es un medio de transporte público que tiene unos horarios y rutas establecidos. Unos ejemplos son los autobuses, trenes, tranvías, etc.
Definición 3: Es un medio de transporte que usan solo las personas que no tienen su coche.

Antes de la actividad, la mayoría de los alumnos eligieron la definición 2 un 65%, otros alumnos eligieron la definición 1 un 20% y la 3 un 15%. Después del juego sube el numero de los alumnos que eligen la respuesta correcta y en las otras el número baja, sobre todo en el caso de la definición 1 que podemos considerar como incorrecta.

Analizamos los datos considerando la variación de porcentaje en su percepción respecto al concepto de *transporte colectivo*: se ve cómo después de la actividad se incrementa en un 22% el número de alumnos que eligen la definición 2 y baja un 17% el número de alumnos que eligen la definición 1 y un 5% los que eligen la 3. También en este caso podemos concluir que la actividad ha sido efectiva en el conocimiento de las características y funciones del transporte colectivo.

Para verificar si los alumnos conocían el significado de *coche compartido* se les dio a elegir entre tres definiciones:

Definición 1: Consiste en compartir un coche con otras personas por un tiempo limitado.
Definición 2: Consiste en compartir un coche con otras personas, pero solo cuando no tengo mi coche disponible.

Definición 3: Consiste en compartir un coche con otras personas para ir al trabajo, al colegio, de viaje, etc. Con esta práctica se pueden reducir los atascos y la contaminación en las ciudades.

La mayoría de los alumnos conocen el significado de coche compartido y lo asocian principalmente a la definición 3 que es la más correcta.

Después de la actividad gamificada el número de alumnos que elige la definición correcta se incrementa sensiblemente. La variación del porcentaje demuestra que se incrementa en un 28% el número de alumnos que eligen la definición 3 y baja un 18% el número de alumnos que eligen la definición 1 y un 10% los que eligen la 2. También en este caso se puede comprobar la efectividad de la actividad.

Para verificar si los alumnos conocían el significado de *ciudad sostenible* se les dio a elegir entre tres definiciones:

Definición 1: Es una ciudad donde sus habitantes cuidan el medio ambiente sin dañarlo, desarrollan sus actividades económicas creando una ciudad respetuosa, de bienestar e igualitaria entre todos.
Definición 2: Es una ciudad donde sus habitantes cuidan el medio ambiente sin dañarlo y sin desarrollar actividades económicas de ningún tipo, siendo de esta manera muy respetuosos con el medio ambiente.
Definición 3: Una ciudad sostenible es una ciudad en la que sus habitantes no se encargan de cuidar el medio ambiente y desarrollan sus actividades económicas sin respetar el entorno, creando una sociedad desigualitaria y de poco bienestar.

Es evidente que la definición correcta es la 1 y la 3 es la que es totalmente incorrecta.

La definición 2 es la que normalmente la gente suele considerar puesto que se fija en el factor medioambiental ignorando las otras dos dimensiones de la sostenibilidad.

Si miramos a las frecuencias de respuestas los resultados parecen no satisfactorios, pero realmente esto se debe a que, en la primera encuesta, antes de la actividad gamificada algunos niños eligieron más de una definición, cosa que se limitó en la encuesta después de la actividad.

Por ello es interesante analizar el resumen de los resultados por porcentaje, se puede ver como el número de alumnos que elige la respuesta correcta se incrementa un 6% y disminuye el número de alumnos que eligen las otras dos definiciones, respectivamente del 4% por la definición 2 y de un 2% para la 3. Podemos considerar el resultado es satisfactorio, aunque el objetivo habría sido que el número de alumnos que eligen la definición 2 bajase de forma sustancial. Por lo tanto, la actividad puede mejorarse en este sentido incidiendo sobre estos puntos.

Para verificar si los alumnos conocían el significado de *transporte sostenible* se les dio a elegir entre tres definiciones:

Definición 1: El transporte sostenible consiste en utilizar cada uno su coche para ir al colegio, al trabajo, etc.
Definición 2: El transporte sostenible consiste en utilizar todos los modos de transporte disponibles en la ciudad.
Definición 3: El transporte sostenible ayuda a reducir los efectos negativos sobre el medio ambiente y consiste en utilizar modos de transporte menos contaminantes.

En este caso la definición correcta es la 3. La 1 y la 2 son incorrectas, aunque la 2 podemos considerarla menos incorrecta que la 1.

Después de la actividad gamificada la elección de la definición 3 se incrementa un 20%, disminuyendo también la elección de ambas definiciones 1 y 2. La elección de la definición 1 disminuye de un 13% y la de la 2 más de un 7%. También en este caso se puede comprobar la efectividad de la actividad.

Para verificar si los alumnos conocían el significado de *bike sharing* se les dio a elegir entre tres definiciones:

Definición 1: Es un servicio de transporte de pago en el que las bicicletas se ponen a disposición en varios puntos de la ciudad para que la gente las utilice, pudiéndola coger en un punto y dejándola en otro distinto.
Definición 2: Es un servicio para viajes de corta distancia en una zona urbana como alternativa al transporte público, que se coloca en varios puntos de la ciudad y es gratuito.
Definición 3: Es un servicio para que la gente utilice la bicicleta como un transporte público más, que te permite utilizar la bicicleta por el tiempo que quieras.

En este caso la definición correcta es la 1 aunque la 2 y la 3 aportan algunos conceptos importantes que se intenta transmitir en la actividad gamificada. En la definición 2 se insiste en el carácter urbano y en su gratuidad que son características que se pueden imponer a un servicio de *bike sharing*, mientras en la 3 se insiste en que el *bike sharing* es un transporte público, pero que las bicis se pueden tener el tiempo que cada uno quiera.

Tras la actividad, en porcentaje, la elección de la definición 1 disminuye un 10%, mientras la 2 y la 3 se incrementan un 6% y un 4% respectivamente. Puede parecer, a primera vista, que los resultados no demuestren un alto porcentaje de mejora después de la actividad, como para las nociones anteriores. Se considera oportuno, para futuras investigaciones, incidir más en una definición más clara de lo que es *bike sharing* y proporcionar más actividades al respecto.

4.3 Análisis del aprendizaje con técnicas de gamificación antes y después de la actividad
En los apartados anteriores hemos comentado los resultados de los cuestionarios describiendo la caracterización de los hábitos y percepción de movilidad de los alumnos y la evolución de los conocimientos básicos de movilidad sostenible antes y después de la actividad didáctica con técnicas de gamificación.

En este apartado compararemos más en el detalle el grado de conocimiento inicial y final de los alumnos. Para tal fin, a las preguntas de conocimiento se ha añadido una puntuación en función de las respuestas dadas. El recuento de esa puntuación en el cuestionario inicial y en el final nos permite definir numéricamente el nivel base del que el alumno empieza y el nivel final una vez que la actividad gamificada haya terminado.

A continuación, se propone una tabla que resume los resultados más relevantes (Tabla 1).

	Nº	% ALUMNOS	SUMA PUNTOS	% PUNTOS
Alumnos que mejoran	50	66,67	225	80,36
Alumnos que se quedan igual	3	4,00	0	-
Alumnos que empeoran	22	29,33	-55	19,64

Tabla 1 - Resumen de las puntuaciones de los dos cuestionarios antes y después

En la primera columna se puede apreciar que el número de alumnos que mejora su nivel es superior al número de alumnos que empeoran. En términos de porcentaje se puede observar como el 66,67% de los alumnos mejoran su puntuación (segunda columna).

Globalmente se puede observar en la tercera y cuarta columna como los que mejoran lo hacen mucho más (80,36%) que los alumnos que empeoran su puntuación (19,64%).

La justificación de esto quedará más clara más adelante, cuando consideremos los resultados relacionados con otros factores: como la satisfacción, el tiempo dedicado, el número de actividades desarrolladas, etc. A partir de dichas relaciones, explicaremos cómo esta circunstancia tiene un rol relevante en el éxito de esta metodología. La Figura 1 representa visualmente los resultados de los 75 alumnos, expresados en la tabla anterior, ordenados en función de la variación de puntuación (DELTA PUNTUACION = PFINAL – PINICIAL).

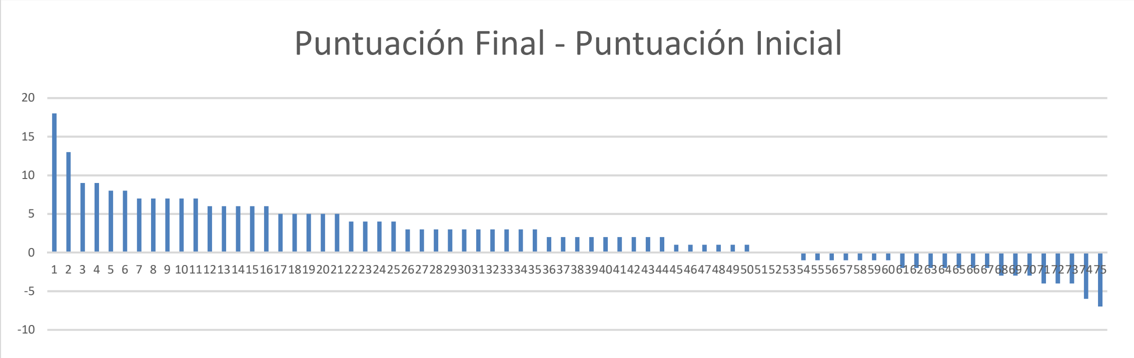

Fig. 1- Variación de puntuación entre los cuestionarios

Con el fin de analizar la relación entre la puntuación final y otras variables relevantes se proponen una serie de modelos de regresión lineal múltiple (9 modelos del MR1-MR9). En estos modelos se relaciona la puntuación final (PFINAL), alcanzada a través del cuestionario de verificación (final) que es nuestra variable dependiente, con las variables que hemos obtenido a través de la plataforma de ClassCraft, que nos indican el tiempo que cada jugador ha dedicado al juego, así como el nivel de satisfacción global del juego (SAT_GLOB) (Tabla 2).

En concreto utilizaremos las siguientes variables:

- desde la plataforma: el nivel del juego alcanzado por el alumno (NIV_JU), los puntos alcanzados en la plataforma de Classcraft al final del juego (P_JU), el número de actividades terminadas dentro de Classcraft (N_ACT), el número de conexiones (N_CON).
- Desde el cuestionario final en concreto las preguntas: los accesos semanales (ACC_SEM), las horas semanales dedicadas (HOR_SEM), el nivel de satisfacción global (SAT_GLOB).

	MR1	*MR2*	*MR3*	*MR4*	*MR5*	*MR6*	*MR7*	*MR8*	*MR9*
NIV_JU	2,275								
Estadístico t	11,869								
P_JU		0,003							
Estadístico t		10,765							
N_ACT			0,849						
Estadístico t			9,082						
N_CON				0,655					
Estadístico t				11,607					
ACC_SEM					6,179				3,355
Estadístico t					17,363				9,891
HOR_SEM						12,194		6,219	
Estadístico t						16,109		8,172	
SAT_GLOB							10,008	6,219	5,934
Estadístico t							18,713	10,237	10,954
R^2 ajustado	0,656	0,610	0,527	0,645	0,803	0,778	0,826	0,909	0,925
Observaciones	75	75	75	75	75	75	75	75	75

Tabla 2 - Resumen de los modelos de regresión

Como se puede observar en los modelos (Tabla 2) existe una correlación positiva entre todas las variables consideradas y la puntuación final alcanzadas por los alumnos. Además, en todos los casos los parámetros asociados a la variable dependiente considerada son estadísticamente significativos a más del 95% del nivel de confianza.

En el MR1 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función del nivel del juego alcanzado. Se obtiene una regresión significativa ($F(1,74) = 140,877$, $p < ,000$), con un R^2 de ,656. La predicción de la puntuación final es igual a 2,275 * (NIV_JU).

En el MR2 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función de los puntos alcanzados en la plataforma de ClassCraft al final del juego. Se obtiene una regresión significativa ($F(1,74) = 115,891$, $p < ,000$), con un R^2 de ,610. La predicción de la puntuación final es igual a 0,003 * (P_JU).

En el MR3 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función del número de actividades terminadas dentro de ClassCraft. Se obtiene una regresión significativa ($F(1,74) = 82,476$, $p < ,000$), con un R^2 de ,527. La predicción de la puntuación final es igual a 0,849 * (N_ACT).

En el MR4 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función del número de conexiones a ClassCraft. Se obtiene una regresión significativa ($F(1,74) = 134,726$, $p < ,000$), con un R^2 de ,645. La predicción de la puntuación final es igual a 0,655 * (N_CON).

En el MR5 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función de los accesos semanales a ClassCraft. Se obtiene una regresión significativa ($F(1,74) = 301,488$, $p <, 000$), con un R^2 de ,803. La predicción de la puntuación final es igual a 6,179 * (ACC_SEM).

En el MR6 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función de las horas semanales dedicadas a ClassCraft. Se obtiene una regresión significativa ($F(1,74) = 259,502$, $p < ,000$), con un R^2 de ,778. La predicción de la puntuación final es igual a 12,194 * (HOR_SEM).

En el MR7 se calcula un modelo de regresión para predecir la puntuación final obtenida a través del cuestionario de verificación en función del nivel de satisfacción global con la actividad. Se obtiene una regresión significativa ($F(1,74) = 350,162$, $p < ,000$), con un R^2 de ,826. La predicción de la puntuación final es igual a 10,008 * (SAT_GLOB).

En el MR8 se calcula un modelo de regresión múltiple para predecir la puntuación final obtenida a través del cuestionario de verificación en función del nivel de satisfacción global con la actividad y de las horas semanales dedicadas a ClassCraft. Se obtiene una regresión significativa (F(1,74) = 364,131, p < ,000), con un R^2 de ,909. La predicción de la puntuación final es igual a 6,207 * (SAT_GLOB) + 6,219 * (HOR_SEM).

En el MR9 se calcula un modelo de regresión múltiple para predecir la puntuación final obtenida a través del cuestionario de verificación en función del nivel de satisfacción global con la actividad y de los accesos semanales a ClassCraft. Se obtiene una regresión significativa (F(1,74) = 453,112, p < ,000), con un R^2 de ,925. La predicción de la puntuación final es igual a 5,934 * (SAT_GLOB) + 3,355 * (ACC_SEM).

Analizando los modelos MR1, MR2 y MR3 podemos concluir que indudablemente los alumnos que han aprendido más son los que han alcanzado un nivel del juego más alto, los que han totalizado más puntos y los que han terminado un número mayor de actividades. Esto es muy importante, porque valida la eficacia del método empleado y sobre todo justifica que los alumnos que no han mejorado y que hasta en algún caso han empeorado su rendimiento son los alumnos que se han quedado a un nivel inferior, han completado un número inferior de actividades y han sacado por lo tanto menos puntos.

Analizando los modelos MR4, MR5 y MR6 podemos observar cómo el tiempo dedicado tiene un impacto directo también en el rendimiento final del alumno. Se demuestra que los alumnos que se conectaron más veces, los que accedieron un mayor número de semanas y los que dedicaron más horas semanales también han aprendido más. Si unimos estos resultados con los anteriores, podemos concluir que el rendimiento de los alumnos está directamente relacionado con las actividades desarrolladas y con el tiempo dedicado. Si miramos con más detalle, podemos ver que los modelos MR5 y MR6 son los que presentan mejor R^2 ajustado de entre los 6 primeros modelos. Esto nos indica que para aprender los alumnos no solamente necesitan conectarse muchas veces, sino que es importante que cada semana dediquen algo de tiempo a las actividades.

El modelo MR7 pretende medir si el grado de satisfacción con la aplicación y con el juego afecta positivamente al aprendizaje. Como se puede ver podemos concluir claramente que es quizás lo más importante. Cuanto más atractivo sea el juego y cuanto más satisfechos estén los alumnos con él, más aprenderán.

Los últimos dos modelos (MR8 y MR9) combinan el efecto de la satisfacción con el tiempo dedicado. Como se puede ver la combinación de las dos cosas hace que los alumnos aprendan más.

5. CONCLUSIONES

En este articulo se describen los resultados de una experiencia educativa basada en la gamificación con el fin de mejorar la percepción de la sociedad sobre los problemas alrededor de la movilidad sostenible. El proyecto se ha diseñado para formar a alumnos de 10-12 años.

Se muestran las principales conclusiones obtenidas del presente trabajo teniendo en cuenta los objetivos generales y específicos que nos hemos planteado, valorando además el cumplimento de los mismos.

El objetivo general planteado ha sido el de observar y evaluar el uso de técnicas de gamificación como clave para el impulso del aprendizaje y el cambio hacia hábitos de movilidad sostenible. A éste hemos añadidos unos objetivos específicos que juegan un papel relevante, al servir como vehículo para conseguir el objetivo general. El nivel de cumplimiento tanto del objetivo general como de los específicos ha sido satisfactorio.

La revisión de la literatura, tanto en la parte de la gamificación como en la de educación en movilidad sostenible, nos ha servido como base para entender mejor esta metodología de enseñanza y verificar su uso en el campo de la educación. También hemos comprobado que hay poca investigación sobre cómo proporcionar temas de movilidad sostenible a niños de primaria, en nuestro caso entre los 10 y 12 años, y los tipos de metodologías de enseñanza usados a tal fin.

Podemos decir que nuestra experiencia ha contribuido a la comprensión del efecto que este tipo de metodología puede tener para mejorar la percepción de los conceptos de movilidad sostenible en todas sus vertientes.

En concreto, antes de la actividad gamificada propuesta se puede concluir que los niños poseen un conocimiento básico sobre el tema. Deducimos que los niños, antes de su participación en la actividad educativa, se centran únicamente en los aspectos ambientales de la movilidad sostenible, ignorando completamente los aspectos sociales y económicos. En definitiva, sus conocimientos parecen estar sesgados a la componente medioambiental.

Si comparamos los datos después de la actividad gamificada propuesta podemos concluir que los niños amplían sus conocimientos sobre la movilidad sostenible incluyendo también los conocimientos relativos a las componentes sociales y económicas que la movilidad sostenible favorece.

Consideramos nuestra investigación un punto de partida para futuras investigaciones, que deberán tener en cuenta las siguientes cuestiones:

- Se necesitan estudios futuros para determinar si nuestros hallazgos pueden generalizarse a una población más amplia. Se podrían dar diferentes resultados al considerar otras poblaciones y al comparar los resultados.
- El posible reflejo de los resultados en la modalidad de transporte adoptada en los viajes diarios a la escuela de los niños, adoptando modalidades sostenibles para llegar a la escuela.
- Un cuestionario de seguimiento que mida si los conceptos adquiridos se mantienen después de que finalice la actividad del juego.
- Un cuestionario para los padres en lo que se pueda verificar cómo el comportamiento sostenible también se generaliza a otros contextos, como el tiempo libre y los viajes familiares.
- Las opiniones de los docentes sobre la experiencia.

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ENSEÑANZA DE LA MOVILIDAD SOSTENIBLE A TRAVÉS DE LA LITERATURA INFANTIL

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RESUMEN

El diseño de nuestras ciudades y su organización, en general, se ha centrado en el vehículo motorizado y ha dejado muy poco espacio para peatones o ciclistas. Algunas de las consecuencias de esta movilidad urbana son altos niveles de contaminación, congestión, emisión de gases de efecto invernadero, ruido... La necesidad de cambio en el diseño de la movilidad urbana se contempla en el objetivo 11 de los Objetivos de Desarrollo Sostenible (ODS) 2030 promovidos por Naciones Unidas.

La comunidad educativa es fundamental para propiciar cambios de comportamiento que puedan beneficiar en un futuro no muy lejano a toda la sociedad. Claro está que no es la única forma, pero sí una de las de mayor peso. Teniendo esto en cuenta, este trabajo mostrará cómo la literatura infantil puede ser una buena herramienta para transmitir conceptos que pueden resultar complejos para los niños. Esta disciplina cuenta con diferentes recursos que permiten dar a conocer las ventajas de la movilidad sostenible en las materias escolares. En nuestro caso, vamos a ver cómo la literatura puede ayudarnos a fomentar esa necesidad de cambio entre los alumnos de 4.º y 5.º de primaria.

Para conseguirlo, hemos trabajado con alumnos del Grado en Maestro de Educación Primaria dotándoles de la formación general en recursos para transmitir diferentes conceptos a través de la narrativa infantil y, en paralelo, les hemos formado en movilidad sostenible. A continuación, les hemos guiado en la creación de material didáctico para poder llevarlo a las aulas de primaria con el objetivo de transmitir la necesidad de una movilidad sostenible en nuestras ciudades. En este trabajo se mostrarán algunos de los recursos generados.

1. INTRODUCCIÓN

Debemos cambiar la forma en la que nos movemos de forma habitual por nuestras ciudades y comenzar a ser conscientes de los beneficios y la necesidad de ser menos contaminantes y más eficientes. Cada uno de nosotros tenemos la responsabilidad de cuidar nuestro planeta y hacer que las ciudades sean más inclusivas y sostenibles, donde todos tengamos cabida y respiremos un aire más limpio. Para ello buscaremos un cambio de movilidad urbana que implique favorecer los desplazamientos a pie, en bicicleta y en transporte urbano sostenible.

1.1 Las ciudades y la movilidad sostenible

La movilidad urbana está basada principalmente en el consumo de combustibles fósiles que pone en riesgo la salud de los individuos y del medio ambiente (Calvo, 2013). En muchas de estas urbes sus habitantes respiran aire contaminado proveniente, en gran medida, del transporte motorizado, en especial, el privado. Este es causante de muchas de las emisiones de CO_2 a la atmósfera y, por tanto, del calentamiento global. Este problema de contaminación afecta directamente a nuestra salud, provocando enfermedades de tipo respiratorio, daños cardiovasculares o daños en el sistema nervioso que afectan en especial a personas enfermas, niños y ancianos, los sectores más vulnerables de nuestra población. En la Unión Europea el 74% de sus habitantes viven en ciudades y el 40% de las emisiones de CO_2 de transporte son causadas por la movilidad urbana (Diez et al, 2018).

Para reducir de forma considerable esta contaminación debemos cambiar de forma urgente nuestra forma de movernos. Para propiciar que una ciudad sea sostenible debemos diseñar medidas que incrementen la calidad del aire y del agua, reduzcan la contaminación acústica y generen espacios para los peatones, además de conseguir ciudades más amigables para todos (Torres-Porras y Arrebola, 2018). Para valorar los beneficios de las políticas de movilidad propuestas, así como de los cambios en nuestra forma de movernos, podemos recurrir a diferentes técnicas de modelización (Gonzalo-Orden et al, 2012). Son muchas las instituciones nacionales e internacionales, organismos públicos y privados los que buscan educar por y para la sostenibilidad y que proponen nuevos modelos de movilidad implicando directamente a la ciudadanía (Prieto y Cid, 2009).

No es posible lograr un desarrollo sostenible sin transformar radicalmente la forma en que construimos y administramos los espacios urbanos. Mejorar la seguridad y la sostenibilidad de las ciudades implica garantizar el acceso a viviendas seguras y asequibles y la mejora de los asentamientos marginales. También incluye realizar inversiones en transporte público, crear áreas públicas verdes y mejorar la planificación y gestión urbana de manera que sea participativa e inclusiva (ONU, 2015). El nuevo diseño urbano pasa por recuperar un modelo de ciudad compacta, con servicios de proximidad, amplias zonas peatonales y con un buen sistema de transporte público, para mejorar la calidad de vida y la calidad ambiental (Martín Carretero, 2016). Además, debemos favorecer el uso de la bicicleta con una buena red que carriles bicis, donde prime más la calidad que la extensión de los mismos. El carril bici tiene que ser seguro, conectado, accesible, directo, atractivo, conveniente, integrado con el sistema de transporte público y las instalaciones de estacionamiento de bicicletas ubicadas lógicamente y diseñadas para minimizar los robos (Gonzalo-Orden et al, 2014).

Debemos perseguir un uso muy ocasional del transporte privado, reducir su velocidad máxima en la ciudad y promover el uso de un transporte público más sostenible y menos contaminante. La reducción de la velocidad de los vehículos de motor conduce a calles más amigables y promueve un aumento de los desplazamientos a pie y en bicicleta. Adicionalmente, es una medida clave para reducir los atropellos y, en caso de que ocurran, la probabilidad de muerte de los peatones involucrados en esos accidentes (Gonzalo-Orden et al, 2016, 2018).

Otra ventaja de la movilidad sostenible a pie, en bicicleta o en transporte público es el desarrollo de la vida social de la ciudad a través de un contacto más directo entre las personas que participan en ella. Esta idea de hacer más participativa a la ciudad es el objetivo que persigue Francesco Tonnuci (2006) que desde 1991 trabaja en su proyecto *La ciudad de los niños*. Este autor considera que a los niños y niñas se les está privando de experiencias fundamentales para su desarrollo al no disponer de tiempo libre ni de un espacio público compartido. La idea es que los niños interactúen con otras personas más allá de su núcleo familiar, creando conciencia de barrio, donde todos nos conocemos. Además, se reduce la contaminación ambiental, las emisiones de gases de efecto invernadero a la atmósfera y se mejora la seguridad vial.

1.2 Movilidad sostenible y educación

Se precisan medidas y actuaciones que nos ayuden a concienciarnos de la necesidad de este cambio y por eso es fundamental la educación cívica y el ejemplo de todos. Necesitamos la colectividad social para conseguir avances en la movilidad sostenible (Torres Castejón, 2014). “Sin participación ciudadana no puede haber movilidad sostenible” (Carbonell, 2014). En este punto consideramos que un núcleo muy importante de actuación son los centros escolares y sus formadores. Educar a los maestros, a los alumnos y a sus familias en movilidad sostenible es una estrategia fundamental para que no se comentan los errores del pasado, fomentando la autonomía y la seguridad de todos. Dado el carácter obligatorio de los desplazamientos de la vivienda al colegio de los niños en edad escolar, hace que el realizar un proyecto sobre movilidad sostenible sea más factible. Hay que tener en cuenta que estos itinerarios los realizan además de los menores, los padres, los profesores y el personal de administración y servicios. Se trata de un entorno que engloba a un sector importante de la población y que viene avalado por el entorno educativo.

Una forma de hacerlo es diseñando caminos escolares sostenibles, donde los protagonistas deben desplazarse a pie o en bicicleta principalmente, “un proyecto de autonomía infantil está inexorablemente vinculado a la promoción de los modos no motorizados” (Román, 2011). En el diseño y puesta en funcionamiento de un camino escolar hay muchos actores, en primer lugar, los niños, ellos van a ser los grandes beneficiarios a corto y largo plazo, los desplazamientos al colegio van a incentivar su autonomía, prevenir la obesidad infantil, socializar fuera del entorno familiar, conocer su ciudad y explorar. Por otro lado, estarían las familias, sin ellas cualquier proyecto de camino escolar sería un fracaso. La mayor dificultad con la que contamos es el miedo de los padres y madres a dejar a los menores ir al colegio solos, les preocupan los accidentes y la inseguridad en las calles. Debemos convencerles de los beneficios que conlleva la autonomía de sus hijos y trabajar con ellos sus temores. Por último, tenemos a los docentes. Es fundamental que se reflexione en las aulas sobre movilidad sostenible, un cambio de los que los profesores pueden ser partícipes y se pueden sentir protagonistas del mismo. El equipo docente es el que hará de intermediario entre los alumnos, las administraciones y las familias. Esto será posible si desde las aulas se trabaja este concepto y se realizan actividades relacionadas con la autonomía y la movilidad (Román, 2011). Para implementar este tipo de proyectos en un colegio se puede trabajar desde cualquier disciplina (lengua y literatura, Ciencias Sociales, Ciencias Naturales, Matemáticas…).

Por ese motivo, vemos cómo la literatura dirigida a niños a través de los recursos que nos ofrece, puede convertirse en una gran aliada, ya que conecta con el mundo infantil y cuenta con unas características cercanas al niño.

1.3 La literatura como medio para llegar a los niños

La literatura es de suma importancia para el ser humano, surge por la necesidad de este de contar historias, de dejar constancia de ellas a las generaciones venideras para promover determinadas conductas y como un aprendizaje de la vida. (Colomer et al., 2018). De hecho, es el único animal que tiene la capacidad de fabular (Vallejo, 2020). La literatura presenta textos abiertos que permiten la interpretación y la comprensión del mundo, al tiempo que logra desarrollar el pensamiento. De hecho "cualquier narración, infantil o no, refleja la sociedad de su época y está repleta de reflexiones sobre las personas que pueden incluir valoraciones y mensajes más o menos intencionados y más o menos explícitos" (Colomer et al., 2018).

La literatura cuenta con una serie de rasgos y funciones que hacen que esta disciplina sea idónea para trabajar con los niños. Destaca, entre otras cualidades, su carácter lúdico cercano al mundo infantil y a su mundo interior. Provoca la reflexión en los más pequeños, la construcción de su propio pensamiento, el acceso a la representación de la realidad y la socialización, el contacto con otras personas que desembocará en cambios generados por ese contacto. Así mismo, la literatura se relaciona con los juicios de valores. La función axiológica tiene que ver con esas historias abiertas donde los niños son capaces de hacer su propia interpretación, con temas transversales, los valores humanos y que dejan a la imaginación del niño elaborar su propio pensamiento crítico (Guimarães, 2013). Además, nos ofrece una serie de personajes que se identifican con los lectores, los protagonistas suelen ser niños o adolescentes cuyas preocupaciones e intereses suelen coincidir con el lector al que va dirigida la historia (Gutiérrez, 2016). Por estas razones, creemos que puede ser un buen recurso para transmitir las ideas que persigue la movilidad sostenible e involucrar a niños y docentes en este cambio tan necesario.

2. LA MOVILIDAD SOSTENIBLE Y LA LITERATURA INFANTIL

En este apartado mostraremos algunos materiales y ejemplos de aplicación donde podemos ver cómo la narrativa es la protagonista para acercar la movilidad sostenible a los niños.

El Ministerio para la transición ecológica y el reto demográfico pone a disposición de los usuarios una serie de recursos para trabajar la movilidad sostenible. En muchos casos, estos vienen dados a través de la literatura infantil. Es el caso de *Caperucita camina sola* (Gea21, 2010), un cuento-exposición que pretende devolver la autonomía a los niños y que caminen por la ciudad donde se aboga por devolver el espacio que les ha sido arrebatado por el "coche feroz". En este cuento se repiten las fórmulas tradicionales, pero adaptándolo a la problemática que aquí se presenta, para más adelante, analizar los problemas de obesidad, contaminación urbana, diseño urbano… Otro recurso que hemos encontrado es *Detective de lo nunca observado. La movilidad urbana: el camino escolar* (Monterrubio et al, 2004) donde se busca incentivar que los niños lleguen al cole caminando, desarrollen su autonomía, fomenten las relaciones sociales y conozcan el barrio. En él se comienza con la lectura dramatizada del cuento *¿Sois vosotros los Reyes Magos?*, con el que se pretende introducir cómo una misma realidad se ve de manera diferente por parte de los adultos y de los niños. Con este recurso presentan el elemento mágico para acercar la narración a los más pequeños. En el 2005, el Ayuntamiento de Segovia lanza una propuesta titulada *Tras las huellas del camino escolar* donde la motivación e introducción del tema corre a cargo de un cuento, *La niña de la nube* (Monterrubio et al, 2005). En él, se muestra la invisibilidad de algunos colectivos, en el diseño de las ciudades y que afectan directamente a su movilidad urbana. También en 2005, la Diputación de Guipúzcoa edita una unidad didáctica titulada *¡Muévete!, una unidad didáctica sobre la movilidad sostenible* (Prieto de Blas y Cid, 2005) que propone la lectura de una serie de cuentos que se pueden relacionar con el tema de la movilidad sostenible. En estos casos, aunque se trata de libros de corte más informativo, cuentan con un personaje literario cercano al mundo infantil que facilitará el aprendizaje.

La Dirección General de Tráfico (DGT) lanza el *Proyecto Stars* que busca promocionar la movilidad sostenible a la escuela e incrementar la autonomía infantil. Así mismo, propone establecer un programa paneuropeo de acreditación y compartir el conocimiento entre ciudades, regiones y centros educativos. Se recomienda que las intervenciones sean continuadas en el tiempo para provocar el cambio que se pretende conseguir y de esta forma dejar el vehículo privado motorizado como forma de movilidad muy ocasional. Entre los recursos que nos ofrece encontramos herramientas literarias que nos permiten poner en contacto a los más pequeños con la necesidad de un cambio de comportamiento para movernos por las ciudades. Por ejemplo, *Clara tiene dos caminos*, editado por el Ayuntamiento de Madrid (2009). Clara tiene una edad parecida a los lectores lo que permite que se identifiquen con ella y se vean capaces de crear sus caminos "de la risa" y no "de la prisa". El elegir un camino u otro repercute en la conservación del planeta. Se muestran conceptos como el cambio climático, el efecto invernadero, los gases que provocan este efecto y qué podemos hacer para bajar los niveles de contaminación. Otro cuento que nos ofrecen es el de *Silvia y su triciclo* (Gómez y Urberuaga, 2013), que tiene que ver con las dificultades que encuentran muchos ciclistas a la hora de utilizar el carril bici ya que su mal diseño apenas deja sitio para que peatón y bicicleta puedan coexistir. Un buen diseño pasa por proporcionar suficiente sitio para cada usuario. En la novela infantil *La bicicleta* *crecedera de Óscar* (Gómez, 2013) los niños, liderados por Carlota, son los motores del cambio. En *La selva de Mario* (Frabetti, 2011) se equipara la ciudad a la selva donde hay que tener cuidado con los distintos vehículos motorizados que transitan por ella.

3. PROPUESTA. OBJETIVOS Y METODOLOGÍA

Como parte de la evaluación de la asignatura de *Didáctica de la literatura infantil y de la animación a la lectura y la escritura* de cuarto curso del Grado en Maestro de Educación Primaria se planteó este proyecto para fomentar la movilidad sostenible mediante la implicación de los alumnos en un problema real. Este proyecto contó con la financiación y ayuda que ofrece el centro de cooperación de la Universidad de Burgos.

Queríamos saber si desde nuestra asignatura podíamos diseñar materiales didácticos para trabajar la movilidad sostenible en la etapa de educación primaria. Como objetivos de nuestra intervención en el aula, marcamos los siguientes:

- Formar a los futuros maestros de educación primaria en movilidad sostenible.
- Ayudar y guiar a estos universitarios en el diseño de propuestas didácticas centradas en la movilidad sostenible a través de la narrativa infantil como recurso principal.
- Utilizar estas propuestas en las aulas de primaria para promover esta movilidad.

Comenzamos con la creación de grupos cooperativos formados por entre tres y cinco miembros. A continuación, se reservaron dos clases prácticas para la formación, con el apoyo de expertos, en movilidad sostenible y para marcar los contenidos esenciales que debería tener la unidad didáctica. En paralelo, se acordó con el CEIP Río Arlanzón de Burgos que las propuestas didácticas irían destinadas a 4º y 5º curso de primaria.

Debido a la COVID-19 nuestros estudiantes universitarios no pudieron tener contacto directo con las aulas de primaria por lo que se readaptaron las propuestas para poder ser grabadas en vídeo simulando una clase real. Como complemento se prepararon diversos materiales que fueron entregados a los profesores del colegio junto a los vídeos, así como guías con los diferentes pasos a seguir para poner en funcionamiento las propuestas.

4. EJEMPLOS DE APLICACIÓN

A continuación, se exponen tres de las propuestas diseñadas y que utilizan la narrativa infantil como recurso literario.

Propuesta 1: *Movilidad sostenible por mi ciudad. El camino al colegio*.
Los objetivos relativos a la literatura infantil son conocer e identificar personajes literarios; diseñar un camino escolar acompañados por alguno de estos personajes y trabajar el texto descriptivo. Los objetivos en movilidad sostenible son aprender en qué consiste dicha movilidad; promover el pedibús y el bicibús y desarrollar la autonomía de los niños.

Esta propuesta está basada en un artefacto literario titulado *En el Bosque* (Matute y Odriozola, 2017). Esta pequeña caja contiene una serie de cartas con personajes, reales e imaginarios, ubicados en un bosque y que les permite a los niños ir construyendo su propio camino y contar sus propias historias. A través de este recurso, los alumnos universitarios diseñaron cartas que representaban el camino desde la casa hasta el colegio. De esta forma pretenden que los niños creen su propio camino al cole, observando qué establecimientos encuentran y escogiendo los personajes que quieren que los acompañen en el trayecto al colegio. Esta propuesta se inicia con una actividad para saber qué medios de transporte conocen para desplazarse por la ciudad, cómo vienen los niños al cole, si su forma de desplazarse es sostenible o no y si les gustaría cambiar la forma en la que vienen al cole:

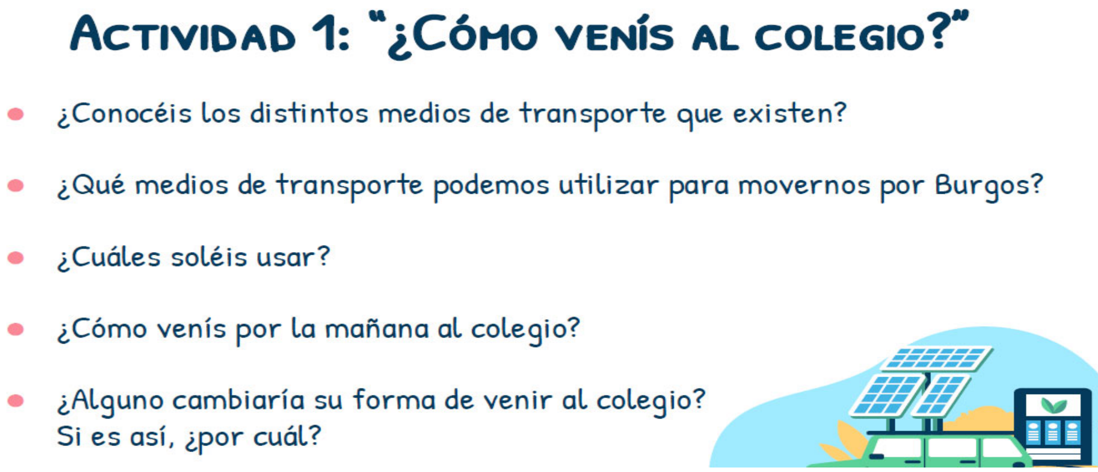

Fig 1. - Actividad de conocimientos previos. Realizada por María Gil, Miriam Morquillas, Paula Perdigones y Ana Saiz.

Con este ejercicio se pretende que los niños reflexionen sobre cómo nuestras acciones diarias son capaces de afectar a nuestro planeta y de las posibilidades que tenemos para poder cambiarlo. La siguiente actividad es un vídeo donde Lola, la protagonista, parece no estar muy contenta con ir en coche al colegio, le gustaría ir más en bicicleta o andando como hacen algunos de sus compañeros. Lola mandará una carta a la clase para que los niños propongan ideas para convencer a su madre para ir al cole con sus compañeros sin necesidad de utilizar el coche.

Fig. 2. - Lola va al colegio. Fotograma del vídeo realizado por María Gil, Miriam Morquillas, Paula Perdigones y Ana Saiz.

Lo más probable es que la protagonista represente la realidad de muchos de los alumnos, que de forma habitual acuden al centro escolar en coche. Las soluciones que le pueden dar a Lola se pueden aplicar para sus propios desplazamientos. Los alumnos escribirán a Lola una carta donde pondrán sus propuestas. Una vez que ellos hayan dado soluciones para que Lola vaya al colegio andando o en bicicleta, el docente les propondrá diseñar su propio camino al colegio, que se fijen en qué establecimientos se encuentran y con quiénes se cruzan. Para completar su camino deberán elegir alguno de los personajes literarios que les sean familiares (Tintín, Matilda, Jerónimo Stilton, Alicia, el Grinch…).

Propuesta 2: ***El futuro en tus manos.***
Los objetivos que se persiguen acerca de la literatura son reconocer textos e historias interactivas. En cuanto a los objetivos de movilidad sostenible se trata de concienciar a los alumnos de la importancia de esta movilidad, el gran impacto que puede tener en el medio ambiente y recordarles que nuestros actos tendrán repercusión en un futuro.

En este caso, la fuente literaria de inspiración va a ser *Pesadillas* de R. L. Stine que presentan una lectura interactiva donde el lector es quien elige qué ocurre en la historia. En publicaciones más actuales destaca ¡*Resuelve el misterio!* de Lauren Magaziner con el mismo tipo de lectura y que tiene gran éxito entre los jóvenes lectores. En este caso, los alumnos universitarios titularon su historia interactiva *El futuro está en tus manos*.

Fig. 3. - Lola va al colegio. Fotograma del vídeo realizado por Sergio Pellón, Javier Rodríguez y Jorge Sanz.

Para ello, se creó una historia de corte futurista donde nuestro planeta es prácticamente inhabitable por lo que se decide enviar a un grupo de tres personas al pasado, concretamente al año 2020, año en el que aún estamos a tiempo de salvarlo. En esta historia los alumnos de primaria deberán decidir cómo sigue la historia para preservar la Tierra y que sea habitable. El cómo nos desplazamos será importante para llegar al final de la historia con éxito. Además, los alumnos, a medida que avanzan en la lectura, realizarán *El manual de las buenas decisiones* donde apuntarán cuáles son las mejores opciones para cuidar el mundo y hacer que no haya cambios irreversibles en el planeta.

Propuesta 3: ***Voy al cole en bici*.**

El objetivo literario es el reconocimiento e identificación de las partes de un cuento. En cuanto a los objetivos en movilidad sostenible se persigue concienciar del grave problema que supone la contaminación en las ciudades; proponer alternativas para reducir la contaminación procedente de los distintos medios de transportes y promover y fomentar los desplazamientos por la ciudad en bicicleta. Esta propuesta se inicia con una actividad en la que se evalúan los conocimientos previos para contextualizar el tema:

Fig. 4. - Actividad previa realizada por Ángela Hernando, Jimena Manso, Mónica Merino, y Lorena Villagra.

El recurso literario con el que se va a trabajar es un cuento de Gianni Rodari titulado *El flautista y los automóviles* de su libro *Cuentos para jugar* (1993). Este cuento se basa en *El flautista de Hamelín*, pero en vez de ratones, esta ciudad está invadida de coches. Rodari diseña tres finales alternativos para solucionar el problema. A los alumnos se les va a pedir que inventen su propio final. Entre todas las posibilidades de movilidad sostenible que surgen de la actividad, se decidió trabajar el desplazamiento en bici. En este caso, los alumnos tendrán que proponer su propio carril bici, añadir o inventarse las señales y solucionar algunos de los problemas que presenta el carril bici actual:

Fig. 5. - Situación real del carril de Burgos. Información localizada por Ángela Hernando, Jimena Manso, Mónica Merino, y Lorena Villagra.

Para ponerse en contacto con los alumnos decidieron enviar un vídeo en formato de informativos, donde contaban todo lo acontecido sobre el carril bici.

5. CONCLUSIONES

En este proyecto hemos podido verificar que es posible crear material para trabajar la movilidad sostenible a través de la asignatura *Didáctica de la Literatura Infantil y de la animación a la lectura y escritura* que se imparte en 4.º de grado en Maestro de Educación Primaria.

Queda demostrado que la narrativa infantil es un buen recurso para trabajar esta temática ya que presenta unas características muy cercanas a la naturaleza del niño que hace que pueda servir de estímulo, de medio de reflexión, de desarrollo del pensamiento crítico…

Los alumnos universitarios se han formado en movilidad sostenible y han sido capaces de transmitir estas ideas a los alumnos de primaria. Todos ellos se han concienciado de la importancia de cuidar el medio ambiente y cambiar nuestros hábitos de movilidad.

La experiencia ha sido un éxito, los alumnos han estado muy involucrados en sus respectivos proyectos educativos. El proyecto se adaptó a los cambios inesperados por la pandemia del COVID-19. El estado de alarma sanitaria no nos permitió acceder al colegio, y tampoco que las actividades se llevaran a cabo en un tiempo determinado. Imprevistos como el confinamiento de clases, de tutores o de alumnos universitarios, hizo que no se pudieran llevar las propuestas cuando correspondía, dejando libertad a cada tutor del colegio para hacerlo cuando pudiera. No obstante, los futuros maestros desarrollaron material y propuestas didácticas que llegaron a los alumnos de primaria.

Todo esto abre nuevas líneas de trabajo, donde se pueda profundizar, no solo en el desarrollo de propuestas educativas relacionadas con la narrativa, sino también con otros géneros literarios y con la medición de los conceptos aprendidos y cambios de comportamiento sobre la movilidad sostenible.

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LA INGENIERÍA DEL TRANSPORTE EN LA UNIVERSIDAD ESPAÑOLA: ESTRUCTURACIÓN DE LAS ENSEÑANZAS Y DESCRIPCIÓN DE CONTENIDOS EN TITULACIONES VINCULADAS A LA INGENIERÍA CIVIL

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Profesor de Transportes. Universidad de Cantabria. España

RESUMEN

Para los que no es ajeno el mundo universitario, no es ninguna sorpresa el afirmar que la adaptación de los títulos universitarios españoles al Espacio Europeo de Educación Superior –EEES- ha supuesto una reforma profunda en la concepción de múltiples aspectos que abarcan desde el "diseño" de las titulaciones y la verificación oficial de las mismas hasta las metodologías docentes utilizadas o evaluación de los alumnos.

En el ámbito de la "Ingeniería Civil" –como en otras muchas ingenierías- una de las principales diferencias que separa la forma de "diseñar" los títulos que habilitan para las profesiones reguladas de "Ingeniero Técnico de Obras Públicas" y de "Ingeniero de Caminos, Canales y Puertos" antes y después de los cambios suscitados por el EEES, estriba en la manera de entender el cómo proporcionar la formación adecuada en las bases teóricas y en las tecnologías propias de estas Ingenierías: mientras en la situación anterior se determinaban las materias troncales de obligatoria inclusión en todos los planes de estudios, con descripciones de contenidos, créditos y vinculación a áreas de conocimiento, en la situación posterior se plasman los requisitos formativos en forma de adquisición de competencias, dando una mayor libertad y flexibilidad en la configuración de las materias (denominaciones, contenidos, duración).

Ante esa falta de referentes comunes que caracterizaban los planes de estudio en el pasado, el presente trabajo pretende ofrecer una "fotografía" actual y un análisis de cómo las Escuelas que ofertan títulos en el ámbito de la "Ingeniería Civil" han integrado en sus planes de estudio los contenidos ligados a la Ingeniería e Infraestructura de los Transportes, tanto de los Grados como de los Másteres que habilitan para el ejercicio de las profesiones arriba mencionadas. El objetivo no es otro que promover una "discusión" sobre la realidad actual de las enseñanzas en esta materia y sobre la necesidad o no de homogeneizar materias y contenidos. Para ello se han analizado los contenidos de un total de 209 asignaturas (68 de Máster y 141 de Grado) incardinadas en 13 títulos oficiales de Máster y 30 de Grado impartidos en las universidades públicas españolas.

1. ANTECEDENTES

En el pasado Congreso de Ingeniería del Transporte (CIT 2018) celebrado en Gijón en junio de 2018, este mismo autor presentó una ponencia bajo el título "La enseñanza universitaria en España de la Ingeniería del Transporte en el ámbito de la Ingeniería Civil".

En dicho trabajo se analizó con carácter general y global el papel de la enseñanza de la Ingeniería del Transporte en la diversidad de itinerarios formativos que habilitan para el ejercicio de profesiones reguladas de Ingeniero Técnico de Obras Públicas -en cada una de sus tres especialidades- y de Ingeniero de Caminos, Canales y Puertos. Para ello se realizó, en primer lugar, una introducción en la quedaron patentes los cambios más relevantes ligados a la adaptación de las enseñanzas al EEES y en concreto las de Grado y Máster en el ámbito de la "Ingeniería Civil" que habilitan para ejercer las profesiones reguladas mencionadas; para, a continuación, avanzar sobre el cómo esos cambios han afectado a la enseñanza de las disciplinas ligadas a la "Ingeniería del Transporte". Tras ello, se realizó un repaso muy sintético de los contenidos de las asignaturas englobadas en el campo de la Economía, Planificación y Explotación del Transporte, a las que se sumaron las de la Logística y la Intermodalidad, así como la Movilidad y el Transporte Urbano. Y finalmente se abordó un estudio de los recursos puestos a disposición del desarrollo de la docencia de la "Ingeniería del Transporte", en concreto el relativo al personal docente. El objetivo de aquel trabajo estaba orientado a perfilar una hipotética necesidad de coordinar las enseñanzas en este campo de la ingeniería que facilitase y garantizase el paso o tránsito entre los grados y los másteres, así como una homogeneización –que no uniformidad- en las condiciones de acceso a ambas profesiones.

Algunos elementos clave de aquel trabajo que pueden servir para "arrancar" y entender mejor el desarrollo de la presente ponencia, fueron los siguientes:

- En primer lugar, el proceso de adaptación al EEES conllevó un cambio en el diseño de los títulos, pasando de lo que era una determinación de las materias troncales de obligatoria inclusión en todos los planes de estudios a una nueva situación en la que se plasman los requisitos formativos en forma de adquisición de competencias.
- En segundo lugar, se ha pasado de una situación en la que la habilitación para el ejercicio de profesiones reguladas se obtenía con una única titulación a otra situación en la que la habilitación para algunas profesiones conlleva la consecución de dos títulos, uno de Grado y otro de Máster. Es el caso de la profesión "Ingeniero de Caminos, Canales y Puertos" cuya formación se "diseñaba" desde el primer curso de la titulación que habilitaba para dicha profesión mientras que en la actualidad su formación, a través de un Máster, toma como punto de partida un título de Grado diseñado para ejercicio de otra profesión. Además, los estudiantes que acceden actualmente al Máster lo hacen con perfiles diversos como consecuencia de la mención o especialización realizada en sus estudios del Grado que les habilita para la profesión de Ingeniero Técnico de Obras

Públicas, lo que implica necesariamente la existencia de diferencias en la forma de asimilar determinadas materias, especialmente las tecnológicas.

- Y, en tercer lugar, como consecuencia de lo anterior, se da la circunstancia que entre las competencias que recoge la Orden CIN/307/2009 de 9 de febrero, para la obtención del Grado que habilita para ejercer la profesión de Ingeniero Técnico de Obras Públicas, no existe referencia alguna a las diferentes disciplinas englobadas en la “Ingeniería del Transporte” en el tronco común de los títulos ni en el “Módulo de Tecnología Específica” de la especialidad de “Hidrología”. De ello pueden derivarse posibles “carencias” de competencias esenciales con las que algunos graduados acceden al Máster que habilita para la profesión de Ingeniero de Caminos, Canales y Puertos y que muy pocos centros universitarios en donde se imparte el Máster tratan de paliar mediante asignaturas complementarias que corrijan la situación.

Con estos antecedentes, el Foro de Ingeniería de los Transportes (FIT) quiso ofrecer a sus socios una “fotografía” lo más actual y concreta posible de cómo las diferentes Escuelas han decidido integrar en sus planes de estudio las asignaturas y contenidos ligados a la Ingeniería e Infraestructura de los Transportes en títulos universitarios oficiales, tanto de los Grados que habilitan para el ejercicio de las profesión de Ingeniero Técnico de Obras Públicas como de los Másteres que lo hacen para la profesión de Ingeniero de Caminos, Canales y Puertos. Y para ello, el autor de esta ponencia elaboró un documento que pudiera concebirse como material de trabajo para a posteriori promover una “discusión” sobre la realidad actual de las enseñanzas en esta materia.

Dicho documento se puso un año más tarde, en septiembre de 2019, a disposición de los socios del Foro de Ingeniería de los Transportes a través de su WEB. La información recogida en el mismo correspondía a 209 asignaturas (63 de Máster y 147 de Grado) incardinadas en 13 títulos oficiales de Máster y 30 títulos oficiales de Grado impartidos en un total de 22 universidades públicas españolas. Las disciplinas tratadas son las tradicionales de Economía, Planificación y Explotación del Transporte (más otras que se han ido incorporando en las últimas décadas como la Logística y la Intermodalidad o la Movilidad y el Transporte Urbano); las de Ingeniería de Carreteras (incluyendo la Ingeniería de Tráfico o la Seguridad Vial); la Ingeniería Ferroviaria y la Explotación Ferroviaria; y la Planificación y Explotación Portuaria.

La información asociada a cada una de las asignaturas hace referencia a la universidad en donde se imparte; al título que la acoge; el curso académico en el que están situadas dentro del Plan de Estudios de la titulación; el carácter obligatorio u optativo de las asignaturas; y el número de créditos que tienen asignados. Y tras ello le siguen los temarios y contenidos de todas y cada una de dichas asignaturas. La información aportada es la misma que aparece en las “Guías Docentes” de las mismas que ofrecen en “abierto” las universidades.

Toda la información recogida en este documento y actualizada al curso 2020-21 es la que se ha manejado y analizado para la redacción del presente trabajo. Antes de la celebración del CIT 2021 se ofrecerá de nuevo a través de la WEB del Foro de Ingeniería de los Transportes, la actualización elaborada del mismo.

2. DATOS DE SITUACIÓN

Antes de entrar en el análisis de cómo las Escuelas que ofertan títulos en el ámbito de la "Ingeniería Civil" han integrado en sus planes de estudio los contenidos ligados a la Ingeniería e Infraestructura de los Transportes, se ofrecen algunos datos generales sobre la implantación en España de Grados y Másteres que habilitan, respectivamente, para las profesiones reguladas de Ingeniero Técnico de Obras Públicas (según especialidad ligada a la tecnología específica cursada) y de Ingeniero de Caminos, Canales y Puertos.

<table>
<tr><th rowspan="2">UNIVERSIDAD DE:</th><th rowspan="2">TÍTULO: GRADO EN</th><th colspan="3">MENCIONES</th><th></th></tr>
<tr><th>C.C.</th><th>HIDR.</th><th>TSU.</th><th>MICCP</th></tr>
<tr><td>A Coruña</td><td>Tecnología de la Ingeniería Civil</td><td>●</td><td>X</td><td>X</td><td rowspan="2">●</td></tr>
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<tr><td>Córdoba (Bélmez)</td><td>Ingeniería Civil</td><td>●</td><td>●</td><td>X</td><td>X</td></tr>
<tr><td>Extremadura</td><td>Ingeniería Civil - Construcciones Civiles</td><td>●</td><td>X</td><td>X</td><td rowspan="3">X</td></tr>
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<tr><td>Extremadura</td><td>Ingeniería Civil - Transportes y SS.UU.</td><td>X</td><td>X</td><td>●</td></tr>
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<tr><td>Santiago Compostela (Lugo)</td><td>Ingeniería Civil</td><td>●</td><td>●</td><td>●</td><td>X</td></tr>
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<tr><td>Zaragoza</td><td>Ingeniería Civil</td><td>●</td><td>X</td><td>X</td><td>X</td></tr>
</table>

* Este título está siendo sustituido, curso a curso, a partir del 2020-21 por el Grado en Tecnologías de Caminos, Canales y Puertos, sin docencia aún en materia de Transportes.

Tabla 1 – Títulos habilitantes en el ámbito de la Ing. Civil. Universidades públicas.

Aunque son un total de 25 universidades, 22 públicas y 3 privadas, las que ofertan algunos de esos títulos de Grado y Máster, en este estudio repararemos únicamente en las primeras. En la Tabla 1 se muestra resumida, en una primera toma de contacto, la oferta de títulos de Grado y Máster en la universidad pública española. La oferta actual es de 30 títulos de Grado y 13 de Máster.

De entre los títulos de Grado, 26 ofertan la especialidad de Construcciones Civiles, 19 la de Hidrología y 16 la de Transportes y Servicios Urbanos. Son 13 de las 22 universidades públicas las que ofertan las 3 especialidades. Y de entre las 13 universidades que ofertan el Máster, una carece de la especialidad en Construcciones Civiles (Castilla-La Mancha); a dos de ellas le ocurre lo mismo con la de Hidrología (Burgos y Cantabria); y en tres no se imparte la de Transportes y Servicios Urbanos (Cantabria, Oviedo y Politécnica de Cartagena). La Universidad de Cantabria es la única que, ofreciendo el Máster, tan solo ofrece un Grado con una especialidad (Construcciones Civiles). Es verdad que hay otras 3 universidades (Coruña, Politécnica de Valencia y Politécnica de Cataluña) que imparten el Máster y tienen un Grado con la única especialidad de Construcciones Civiles, pero además de éste ofertan otro Grado con las 3 especialidades.

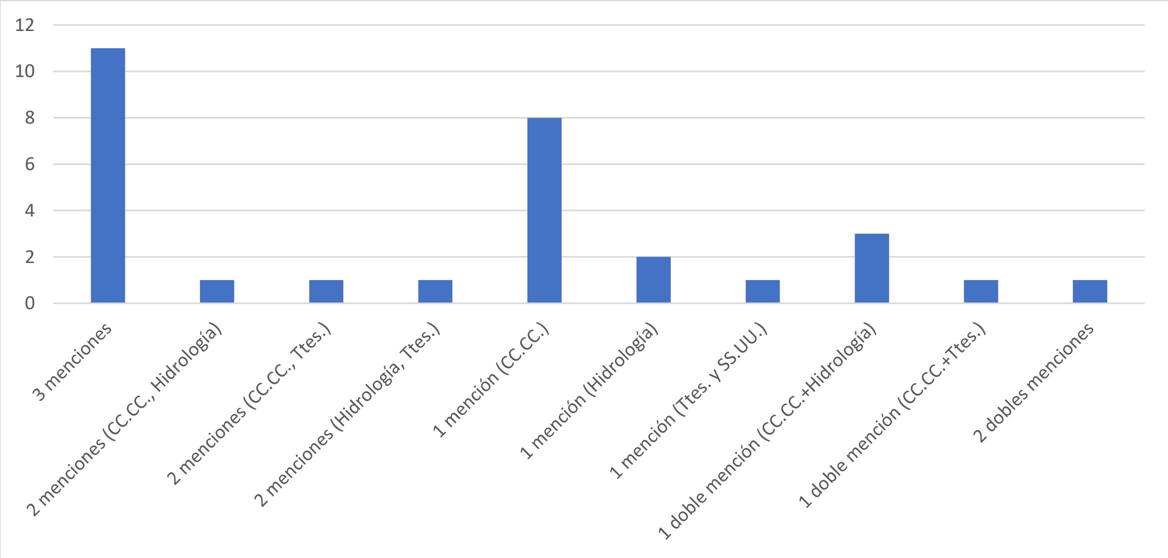

Figura 1 – Número de Grados según especialidades ofertadas

En la Figura 1 se plasma qué especialidades o menciones abordan los 30 Grados impartidos en las universidades públicas, destacando muy por encima de los demás los Grados con las tres especialidades -11 en total- y los 8 que plantean tan solo la especialidad de Construcciones Civiles. De entre los primeros hay que destacar que 8 de ellos se imparten en centros en donde también se imparte el Máster. Los Grados de 5 de los centros en donde se imparte el Máster (Burgos, Cantabria, Castilla-La Mancha, Oviedo y Politécnica de Cartagena) no se imparten las 3 especialidades.

En lo que respecta a los 8 títulos que solo tienen la especialidad de Construcciones Civiles, la mitad de ellos corresponden a centros que también imparten el Máster (Coruña, Cantabria y las Politécnicas de Cataluña y Valencia). En los 4 casos se trata de Grados cuyas enseñanzas han sido diseñadas para formar un itinerario orientado al propio Máster. Como ya se hizo referencia más arriba, salvo el caso de Cantabria, en el resto de los centros también se imparte otro Grado con las 3 especialidades.

Hacer notar finalmente de esta misma figura, que aparece al final un único título de Grado con 2 dobles menciones: Construcciones Civiles + Hidrología y Construcciones Civiles + Transportes y Servicios Urbanos. Corresponde al Grado en Ingeniería Civil que se imparte en la Escuela Técnica Superior de Ingeniería Civil de la Universidad Politécnica de Madrid y que desde el curso 2020-21 está en proceso de extinción.

Para finalizar este apartado de introducción general, y en lo que a los másteres se refiere, tan solo reflejar que únicamente 3 de los 13 títulos impartidos no tienen contempladas especialidades en los mismos. Es el caso de las 3 universidades andaluzas: Cádiz, Granada y Sevilla. Las otras 10 titulaciones abordan diferente número de especialidades, desde las 2 que se proponen desde la Universidad de Oviedo a los 11 “perfiles de intensificación” de la Politécnica de Valencia. Aun así, la mayoría de ellas, en número de 6, contemplan 3 especialidades, menciones o intensificaciones, siempre ligadas a la ingeniería de la construcción, la ingeniería del agua y la ingeniería del transporte y el territorio.

3. DATOS GENERALES EN TORNO A LA INGENIERÍA E INFRAESTRUCTURA DE LOS TRANSPORTES

Después de haber situado en el apartado anterior lo relacionado a las características generales de los títulos de Grado y Máster en el ámbito de la Ingeniería Civil en España y las especialidades que pueden seguirse en los mismos, llega el momento de abordar la docencia objeto de este trabajo, la ligada a la Ingeniería e Infraestructura de los Transportes. Las disciplinas que serán tratadas en este campo de la ingeniería son las tradicionales de Economía, Planificación y Explotación del Transporte (aquí se incorporarán también otras que se han ido incorporando en las últimas décadas como la Logística y la Intermodalidad o la Movilidad y el Transporte Urbano); las de Ingeniería de Carreteras (incluyendo la Ingeniería de Tráfico o la Seguridad Vial); la Ingeniería Ferroviaria y la Explotación Ferroviaria; y la Planificación y Explotación Portuaria.

En este apartado se estudiará dicha docencia de forma conjunta para en apartados posteriores individualizar los análisis de cada una de esas 4 disciplinas. Serán un total de 209 asignaturas las estudiadas, 141 correspondientes a estudios de Grado y 68 a estudios de Máster. En la Figura 2 se muestra una primera aproximación del reparto por disciplinas de esas 209 asignaturas, diferenciando a su vez las que se imparten en el Grado que habilita para la profesión de Ingeniero Técnico de Obras Públicas o el Máster que habilita para la de Ingeniero de Caminos, Canales y Puertos.

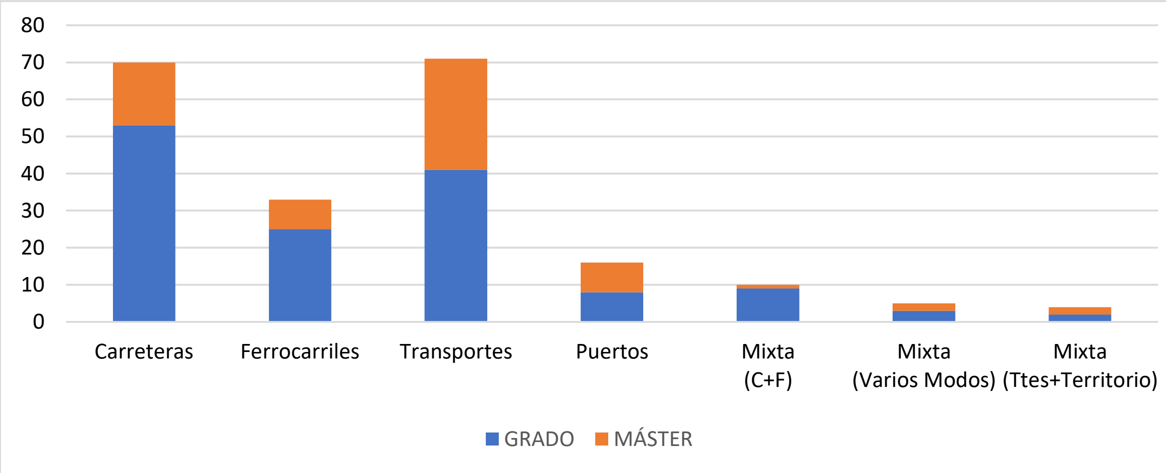

Figura 2 – Número de asignaturas según disciplinas

Aunque más adelante se profundizará sobre el carácter (troncal, obligatorio de especialidad u optativo) de dichas asignaturas, su tamaño en créditos y su ubicación en los planes de estudio de las titulaciones, baste adelantar que son la Ingeniería de Carreteras y la Ingeniería del Transporte las que agrupan las dos terceras partes de las asignaturas, siendo la primera la más importante en los títulos de Grado (su presencia es obligatoria en las especialidades de Construcciones Civiles y de Transportes y Servicios Urbanos) y la segunda en los de Máster (competencias en esa materia han de recogerse obligatoriamente en sus planes de estudio). Más reducida es la presencia de asignaturas ligadas a la Ingeniería Ferroviaria (25 asignaturas en los 30 Grados y 8 asignaturas en los 13 másteres) y más aún a la Explotación Portuaria, en este caso siempre insertadas dichas asignaturas en especialidades de Grados o Másteres. También se explicitan, finalmente, las asignaturas cuyos contenidos pertenecen a diferentes disciplinas y que se han denominado “Mixtas”, y que en muchos de los casos tienen la “misión” de satisfacer en una misma asignatura diversas competencias exigibles a la titulación. Las que mayor importancia tienen -sobre todo en los Grados- son las que engloban contenidos de Carreteras y Ferrocarriles (C+F) y de menor entidad las que asumen otras posibles combinaciones de las diferentes disciplinas o la que forman la Ingeniería del Transporte y la Ordenación del Territorio, esta última fuera del alcance de nuestro trabajo por sí misma.

	Carreteras	Ferrocarriles	Transportes	Puertos	Mixta Carretera + Ferrocarril	Mixta (Varios Modos)	Mixta Transportes + Territorio
GRADO	53	25	41	8	9	3	2
MÁSTER	17	8	30	8	1	2	2
TOTAL	70	33	71	16	10	5	4

Tabla 2 – Número de asignaturas según tipo de enseñanza oficial y disciplinas

Un siguiente paso para avanzar un poco más en el conocimiento de ese conjunto de 209 asignaturas y las disciplinas que las engloban, consiste en analizar el carácter de las mismas. De esa manera, se hablará de materia "troncal" cuando la misma haya de ser cursada obligatoriamente por todos los alumnos de una titulación; se denominará "Obligatoria de Especialidad" a toda aquella materia que, no siendo obligatoria para todos los alumnos de una titulación, sí haya de cursarse obligatoriamente en las menciones o especialidades de un Grado o en las intensificaciones, especialidades o perfiles de un Máster; y se hablará de "Optativa de Especialidad" y de "Optativa Genérica" cuando su elección corra a cargo por alumnos de una especialidad concreta o de cualquier especialidad, respectivamente.

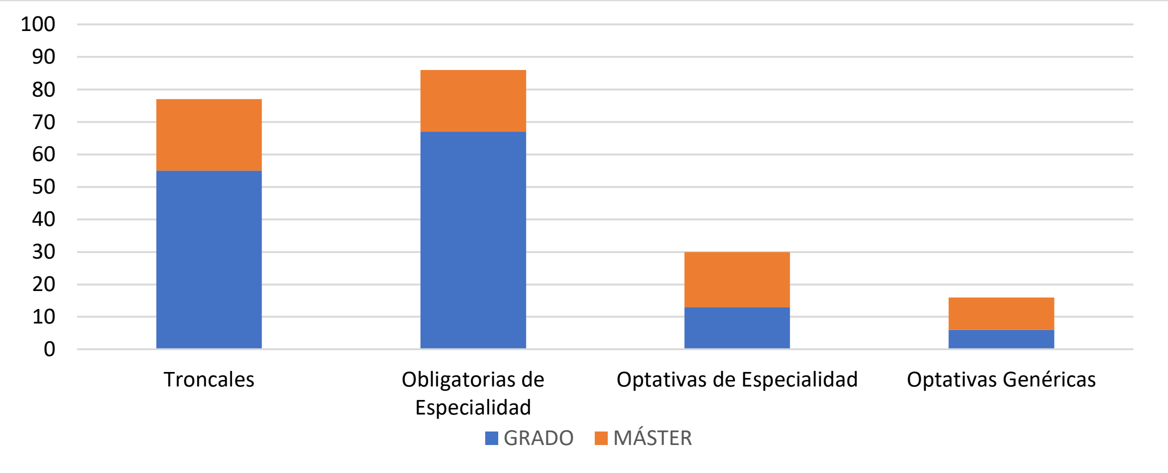

Figura 3 – Número de asignaturas según su "carácter" y tipo de enseñanza oficial

Con esta forma de caracterizar las asignaturas de un plan de estudios, se presentan en la figura 3 los datos que engloban al conjunto de asignaturas que forman parte de este trabajo. A primera vista podría pensarse que hay una buena "carga" de troncalidad en las titulaciones ofrecidas, tanto en los Grados como en los Másteres. Pero en referencia a los Grados, se veía en el apartado anterior que muchos de estos títulos solo ofrecen al alumno una única mención o una doble mención y en los que todas las asignaturas pueden considerarse "troncales" porque todas son obligatorias para todos los alumnos.

Es por ello que en la Figura 4 que se presenta a continuación puede apreciarse cómo cambia radicalmente el porcentaje de "troncalidad" en las dos situaciones presentadas: la primera de ellas corresponde al conjunto de los 30 Grados estudiados en este trabajo -con sus 141 asignaturas ya reseñadas- y la segunda a los 11 Grados que ofertan las 3 especialidades o menciones. Y es que son solo 6 Grados los que, ofreciendo las 3 especialidades en España, aportan "troncalidad" a las materias englobadas en la Ingeniería e Infraestructura de los Transportes. Corresponden esos Grados a las Universidades de La Coruña, Santiago, Sevilla y las Politécnicas de Cataluña, Madrid y Valencia. Son 10 las asignaturas troncales situadas en los planes de estudio de esas 6 titulaciones de Grado: las disciplinas de la Ingeniería de Carreteras, Ingeniería Ferroviaria e Ingeniería del Transporte aportan 2 asignaturas cada una; y las otras 4 asignaturas son con contenidos "mixtos" de Carreteras y Ferrocarriles.

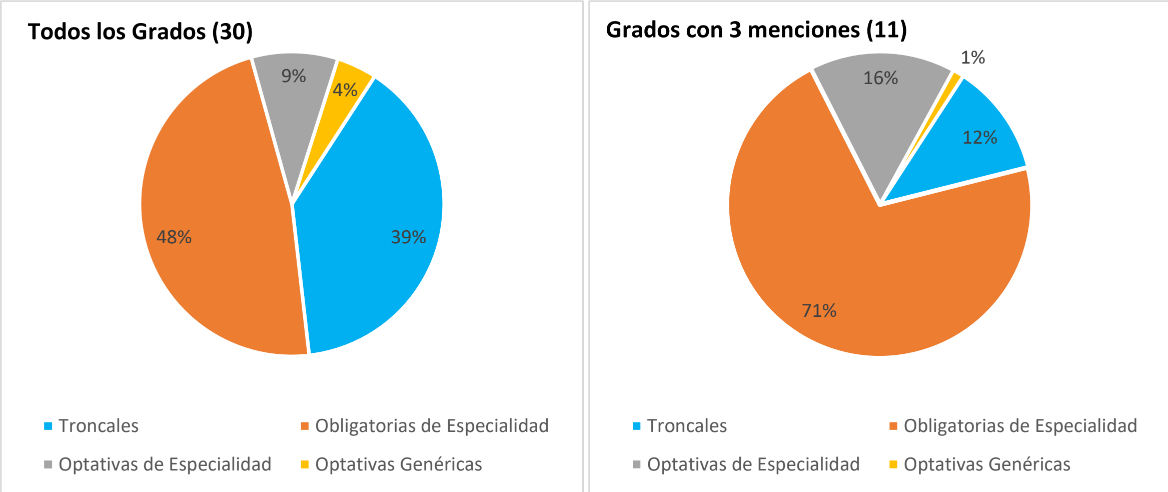

Figura 4 – Comparativa del reparto porcentual de asignaturas según su carácter para el conjunto de los Grados estudiados y los que ofertan las 3 menciones

De todo lo anterior se puede colegir que las materias cuyos contenidos pertenecen a la Ingeniería e Infraestructura de los Transportes no forman parte de la formación generalista de un futuro ingeniero técnico de obras públicas y tan solo de la formación de su itinerario de especialidad. Y eso conduce a realizar la siguiente pregunta, ¿cómo tratan las diferentes especialidades la presencia de estas materias?

En la tabla 3 que se muestra seguidamente aparece reflejado, para cada una de las menciones o especialidades de las titulaciones que habilitan para la profesión mencionada, el número de Grados en cuyos planes de estudio se recogen asignaturas ligadas a las diferentes disciplinas en que se ha dividido en este trabajo la Ingeniería e Infraestructura de los Transportes. Como ya se hizo anteriormente, además de mostrar las "monodisciplinares" (Carreteras, Ferrocarriles, Transportes y Puertos) se han incorporado las de las materias que comparten contenidos de 2 o más disciplinas y que se han denominado "Mixtas".

	Titulaciones de Grado en la que está presente	Carreteras	Ferrocarriles	Transportes	Puertos	Mixta Carretera + Ferrocarril	Mixta (Varios Modos)	Mixta Transportes + Territorio
Mención en Construcciones Civiles	26	22	19	10	0	6	1	1
Mención en Hidrología	19	8	6	3	0	5	0	0
Mención en Transportes y SS.UU.	16	14	10	16	5	5	2	1

Tabla 3 – Grados con asignaturas obligatorias de las diferentes disciplinas por tipo de mención

A la vista de esa tabla llama la atención que no todas las titulaciones de Grado con especialidad o mención en Construcciones Civiles o Transportes y Servicios Urbanos tengan asignaturas obligatorias "puras" de Carreteras y Ferrocarriles. Hay que recordar que la

"*Orden CIN/307/2009 de 9 de febrero*" en la que se plasman los requisitos formativos de los Grados que habilitan para la profesión de Ingeniero Técnico de Obras Públicas, se recogen como competencias para ambas menciones la "*Capacidad para la construcción y conservación de carreteras, así como para el dimensionamiento, el proyecto y los elementos que componen las dotaciones viarias básicas*"; y la "*Capacidad para la construcción y conservación de las líneas de ferrocarriles con conocimiento para aplicar la normativa técnica específica y diferenciando las características del material móvil*". Y la solución en varios casos para dar cumplimiento a las exigencias normativas es la de diseñar asignaturas con contenidos de dos o más disciplinas, y en concreto, para el caso reseñado más arriba, la de asignaturas con contenidos de Carreteras y Ferrocarriles.

Para comprobar que eso es así, se introduce a continuación la tabla 4 en la que se muestra de nuevo, para cada una de las menciones o especialidades de los Grados, el número de ellos en cuyos planes de estudio hay asignaturas con contenidos únicos o parciales de cada una de las 4 disciplinas.

	Titulaciones de Grado en la que está presente	Carreteras	Ferrocarriles	Transportes	Puertos
Mención en Construcciones Civiles	26	26	25	12	0
Mención en Hidrología	19	13	11	3	0
Mención en Transportes y SS.UU.	16	16	15	16	5

Tabla 4 – Grados con asignaturas obligatorias que acogen contenidos –total o parcialmente- de las diferentes disciplinas, por tipo de mención

La visualización de esta nueva tabla permite comprobar que la totalidad de los Grados que ofertan la mención de Construcciones Civiles y la de Transportes y SS.UU. acogen contenidos de Carreteras y, en el segundo de los casos, también de Transportes. Aparentemente hay una universidad cuyo título de Grado carece de contenidos obligatorios de Ferrocarriles. Y a efectos de este trabajo es así, pues aunque tiene una asignatura obligatoria denominada "Sistemas e Infraestructuras del Transporte" con un único tema genérico de Ferrocarriles, para este estudio ha sido considerada de Carreteras pues tiene 12 temas de esta disciplina en la que recorre todos los bloques habituales de la misma.

Al margen de estas disquisiciones, sí puede ser importante hacer hincapié en un hecho que puede tener trascendencia para aquellos alumnos que tras la realización de un Grado que habilite para la profesión de Ingeniero Técnico de Obras Públicas con la especialidad de "Hidrología", quiera hacer el Máster que habilita para la de Ingeniero de Caminos, Canales y Puertos. La realidad actual en España es que solo 13 de los 19 Grados que contienen esa mención, tienen asignaturas con contenidos de Carreteras (y 5 de ellas de carácter "Mixto" al repartir dichos contenidos con los de Ferrocarriles) y por tanto hay 6 Grados, impartidos en otras tantas universidades, que en dicha especialidad carecen de asignaturas obligatorias de Carreteras. Dos de esas universidades tienen la posibilidad de "solucionar" esa carencia con una asignatura en sus másteres respectivos, pero el resto no, ya sea porque su Máster no tiene esa posibilidad o porque carece de Máster y tienen que hacerlo en otra universidad. Teniendo en cuenta que solo 3 másteres de los 13 que se imparten en la universidad pública de España tienen asignaturas obligatorias de Carreteras y en general no de carácter básico sino de complemento a lo estudiado en el Grado; y que son muy pocas –un total de 4- las que imponen asignaturas con complementos de "nivelación" de conocimientos, se puede llegar a la sencilla conclusión de que hay muchas posibilidades de que alumnos que han realizado el Grado en alguna de esas universidades lleguen posteriormente a habilitarse para la profesión de Ingeniero de Caminos, Canales y Puertos sin haber recibido contenidos de Carreteras. Y si son 6 los Grados en lo que ocurre esa situación con la disciplina de Carreteras, llega al número de 8 si la que se analiza es la de Ferrocarriles, llegando a las mismas conclusiones. No es tan importante con la disciplina de Ingeniería del Transporte por la obligatoriedad de incluir contenidos de la misma en los Másteres.

Para terminar este apartado se aportarán también algunos datos de carácter global sobre los másteres que habilitan para la profesión de Ingeniero de Caminos, Canales y Puertos. Más arriba se ofrecieron dos figuras en las que se visualizaban el número de asignaturas según tipo de "disciplina" y según "carácter" de las mismas. En la tabla 5 que sigue se muestra de forma conjunta el número de másteres que dan cabida a las diferentes disciplinas de la Ingeniería e Infraestructura de los Transportes y el número de asignaturas de cada disciplina. Además, se ha hecho discriminando dichas asignaturas según el carácter troncal, obligatorio de especialidad u optativo que ya se utilizó con anterioridad.

	Carreteras		Ferrocarriles		Transportes		Puertos		Mixta	
	Másteres	Asignaturas	Másteres	Asignaturas	Másteres	Asignaturas	Másteres	Asignaturas	Másteres	Asignaturas
Troncales	3	3	2	2	13	15	0	0	2	2
Obligatorias de Especialidad	5	7	3	3	3	4	3	3	2	2
Optativas de Especialidad	3	5	2	2	3	6	3	4	0	0
Optativas Genéricas	2	2	1	1	4	5	1	1	1	1

Tabla 5 – Nº de másteres y asignaturas según su "carácter" y disciplinas de los contenidos

Teniendo en cuenta que son 13 los másteres impartidos en la universidad pública española, de la primera impresión de los datos se deduce la escasa presencia de troncalidad de la Ingeniería de Carreteras (tan solo en 3 másteres) y de la Ingeniería Ferroviaria (en 2 másteres). Mayor presencia, pero aun así escasa, en aquellos másteres que tienen una especialidad en "transportes". En apartados anteriores se aportaba el dato de que 10 de los 13 másteres impartidos participaban del hecho de tener especialidades. Pues de todos ellos, 9 másteres tienen la opción de seguir una especialidad en el campo del "Transporte". Es por ello que sigue resultando insuficiente que a pesar de ser numerosos los másteres con itinerarios de intensificación en el campo del transporte, son solo 5 los másteres que acogen obligatoriamente asignaturas de Ingeniería de Carreteras y 3 los que hacen lo propio con las de Ingeniería Ferroviaria. Con todo lo comentado vuelve a hacerse más crítica la situación comentada con anterioridad referida a los Grados: la práctica totalidad de la formación en estas dos disciplinas dependerá de lo recibido en los estudios de Grado. Reiterar por ello, el hipotético problema al que se pueden enfrentar los alumnos que cursen la mención de Hidrología cuando en sus planes de estudios de sus grados no exista troncalidad en estas disciplinas; o la carencia a la que se pueden encontrar -incluso en las otras 2 menciones- cuando los conocimientos en estas 2 disciplinas se solventen con asignaturas únicas que comparten contenidos de ambas. Y esto ocurre en 8 de los 30 Grados impartidos.

Finalmente volver a incidir de la presencia de troncalidad en todos los másteres de contenidos de Ingeniería del Transporte para cumplir con lo dispuesto en la Orden CIN/309/2009 de 9 de febrero por la que se establecen los requisitos formativos de los Másteres que habilitan para la profesión de Ingeniero de Caminos, Canales y Puertos, donde se recogen como competencias los "*conocimientos de la ingeniería y planificación del transporte, funciones y modos de transporte, el transporte urbano, la gestión de los servicios públicos de transporte, la demanda, los costes, la logística y la financiación de las infraestructuras y servicios de transporte*". Y la inexistencia de troncalidad para contenidos en Planificación y Explotación Portuaria, cuya presencia en los planes de estudio de los másteres quedan prácticamente limitados a itinerarios de especialización.

4. LA INGENIERÍA DE CARRETERAS

Ya se ha comentado anteriormente que la presencia de contenidos de la disciplina "Ingeniería de Carreteras" está principalmente recogida en las enseñanzas de Grado y muy escasamente en las de Máster. Seguidamente se adentrará en el análisis de esta disciplina discretizando la información según el tipo de titulación impartida.

4.1 La Ingeniería de Carreteras en los estudios de Grado

En referencia a los estudios de Grado, son 53 las asignaturas cuyos contenidos son íntegramente de esta disciplina. Su reparto es el siguiente:

- 2 asignaturas troncales en planes de estudio que incorporan las 3 menciones (los Grados en Ingeniería Civil de la UPM y de la Universidad de Sevilla).
- 17 asignaturas troncales en un total de 12 Grados que incorporan en sus planes de estudio 1 o 2 menciones (salvo en 2 de estos Grados, todos los demás tienen al menos la mención de Construcciones Civiles).
- 4 asignaturas obligatorias en la especialidad de Construcciones Civiles en Grados con las 3 especialidades.
- 1 asignatura obligatoria en la especialidad de Hidrología en un Grado con las 3 especialidades (Alicante).

- 13 asignaturas obligatorias en la especialidad de Transportes y Servicios Urbanos en 9 Grados con las 3 especialidades.
- 6 asignaturas obligatorias que se imparten tanto en la especialidad de Construcciones Civiles como en la de Transportes y SS.UU. de 4 Grados con las 3 especialidades.
- 1 asignatura obligatoria que se imparte tanto en la especialidad de Hidrología como en la de Transportes y SS.UU. en 1 Grado con las 3 especialidades.
- 1 asignatura optativa que se imparte en la especialidad de Construcciones Civiles
- 5 asignaturas optativas en la especialidad de Transportes y SS.UU. de 4 Grados distintos.
- 3 asignaturas optativas no ligadas a especialidad alguna de 3 Grados distintos.

Del análisis de esta información viene a corroborarse algo que ya se adelantó en apartados anteriores: la Ingeniería de Carreteras -como el resto de disciplinas aquí tratadas- tiene su principal encaje en las especialidades de los Grados o en la troncalidad de Grados con una única mención (lo que hace que todo el plan de estudios de ese Grado esté ya orientado a la especialización), generalmente la de Construcciones Civiles, o con dos menciones, siendo en todos los casos una de ellas la de Construcciones Civiles.

Respecto al tiempo asignado para la impartición de las asignaturas, el conjunto de las 53 estudiadas tienen un "tamaño" promedio de 5,89 créditos, abundando mayoritariamente las que tienen 6 créditos. De hecho, el promedio de las troncales y obligatorias se encuentra en esa cantidad, que disminuye algo en el caso de las optativas.

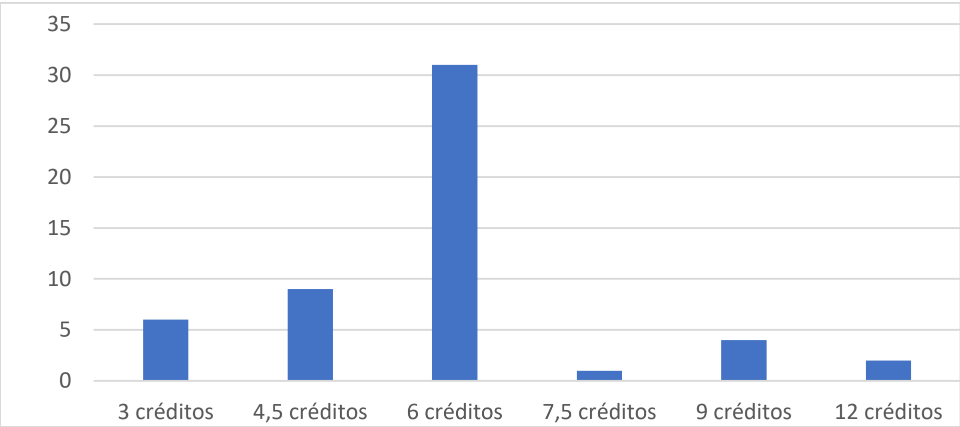

Figura 5 – Tamaño asignaturas de "Ingeniería de Carreteras" en Grados

En cuanto a los contenidos de las asignaturas, se han estudiado aquellas que se ofertan con carácter troncal o son obligatorias de las diferentes especialidades, principalmente de las de Construcciones Civiles o Transportes y SS.UU., dado que las optativas normalmente ponen su acento en cuestiones muy específicas y apenas suponen un 15% del total de asignaturas ofertadas en los Grados. Con carácter general, la inmensa mayoría de asignaturas tratan 4 aspectos esenciales de esta disciplina, normalmente en una única asignatura y en ciertos casos, en dos: ingeniería de tráfico; diseño geométrico; suelos, explanaciones y drenaje; y firmes y pavimentos. De forma más superficial, hay ciertas asignaturas que se introducen en la conservación y explotación de carreteras; en las dotaciones, señalización…; o en la seguridad vial.

En la figura 6 que aparece a continuación se muestra la importancia de esos bloques temáticos por su presencia en los contenidos de esas 43 asignaturas que de forma obligatoria -ya sea por troncalidad o en los itinerarios de especialidad- se ofertan en los Grados bajo la disciplina de la "Ingeniería de Carreteras".

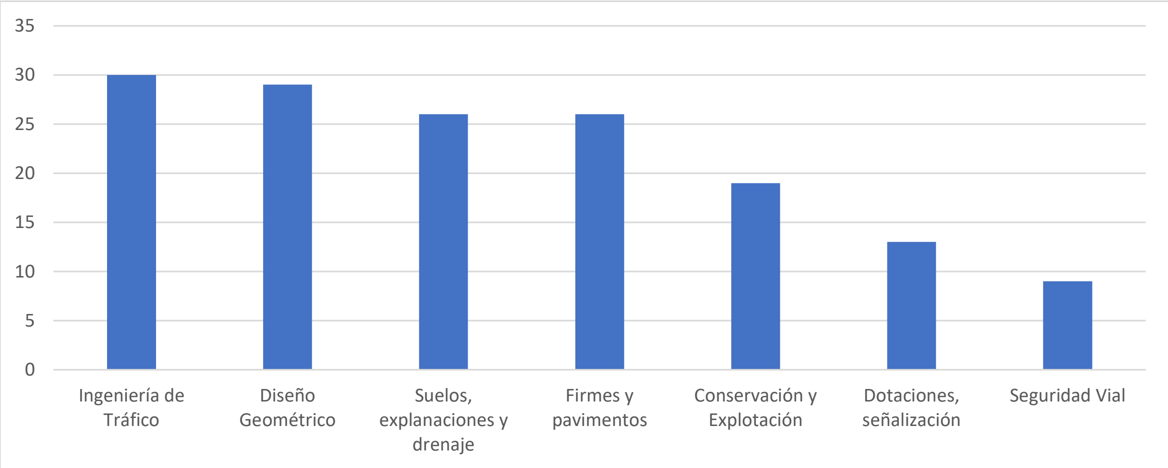

Figura 6 – Nº de asignaturas con presencia de los distintos bloques temáticos en Ingeniería de Carreteras

Como se indicaba al comienzo del apartado, todo lo reseñado hasta el momento se ha referido a asignaturas de Grado cuyos contenidos obedecen solamente a los de la disciplina de Ingeniería de Carreteras. Pero además de estas 53 asignaturas tratadas existen otras 12 asignaturas con contenidos parciales de esta disciplina. La inmensa mayoría, en número de 9, son asignaturas mixtas de Carreteras y Ferrocarriles, todas ellas troncales -6- u obligatorias -3- de las especialidades de Construcciones Civiles o Transportes y SS.UU. Su "tamaño" promedio es algo superior a las anteriores pues alcanza los 6,7 créditos, aunque mayoritariamente (7 asignaturas de las 9 mencionadas) son de 6 créditos. Y en cuanto a los contenidos que abordan de esta disciplina, son mucho más reducidos por tener que compartir "espacio" con Ferrocarriles, concentrándose en los bloques básicos de esta materia (Ingeniería de tráfico, Diseño geométrico, Suelos, explanaciones y drenaje, y Firmes y pavimentos) y sin presencia de las demás. Por lo general, las dos disciplinas comparten al 50% el temario de las asignaturas, aunque en un par de ellas predominan los contenidos de Carreteras -aproximadamente un 75%- y en una prevalecen los Ferrocarriles con un porcentaje semejante.

Finalmente, en lo relativo al Grado, existen otras 3 asignaturas que entremezclan contenidos habituales de la Ingeniería de Carreteras con los de Ingeniería del Transporte e incluso en una de ellas con los de Ingeniería Ferroviaria, de las que no se entra en valoración por su escasa incidencia en el panorama global de esta disciplina.

4.2 La Ingeniería de Carreteras en los estudios de Máster

Entrando en el análisis de la enseñanza de la Ingeniería de Carreteras en el ámbito de los Másteres, se acude de nuevo a la tabla 5 ya mencionada anteriormente, donde quedaba meridianamente clara la casi inexistencia de troncalidad de esta disciplina en los 13 másteres impartidos en España. Son solo 3 asignaturas de un total de 17 y salvo una, en la Universidad de Cádiz, que aborda temas básicos de Ingeniería de Tráfico y Trazado, las demás inciden específicamente en la seguridad vial y la explotación y conservación de carreteras.

La mayoría de las asignaturas (12 de ese total de 17) pertenecen a la especialidad de Transportes de diversas titulaciones, 7 de carácter obligatorio y 5 optativas. Las 2 restantes son optativas no sujetas a especialidad. Ninguna de las asignaturas tiene contenidos básicos de la disciplina (salvo una de la Universidad de Sevilla que ejerce de "nivelación" de conocimientos para los alumnos que no la cursaron en el Grado) e inciden, principalmente, en la Seguridad Vial (en 6 casos), en la conservación y explotación de carreteras (en 3 asignaturas), en el diseño de intersecciones, enlaces y glorietas (en 3 asignaturas) o en aspectos avanzados de ingeniería de tráfico (en 5 casos).

Antes de terminar este apartado dedicado a la Ingeniería de Carreteras, se presenta en la figura 7 cómo ha sido la evolución de la carga docente troncal en los planes de estudio que conducen a formar ingenieros de caminos, canales y puertos.

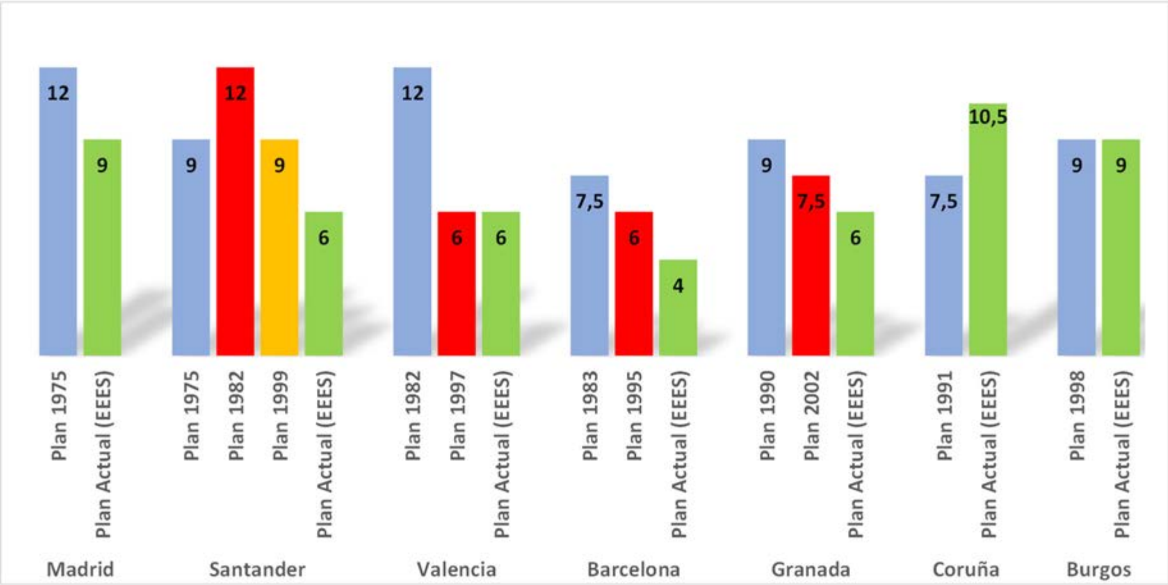

Figura 7 – Evolución del número de créditos de asignaturas troncales de Ingeniería de Carreteras en diversas Escuelas

Dado que en los primeros planes de estudio las asignaturas eran en su mayoría anuales y su carga docente se medía en "horas/semana" y que posteriormente en muchas escuelas se dio el paso a asignaturas cuatrimestrales que se "medían" de la misma forma para finalmente pasar a estructuras de planes con "créditos" y "créditos ECTS", se ha tomado para esta comparativa como valor del "crédito" el equivalente a 10 horas de docencia en aula, y asignando una duración de 15 semanas para las asignaturas cuatrimestrales y de 30 semanas para las anuales. Y dado que en el ámbito del EEES en España es necesario obtener un título de Graduado que habilita para la profesión de Ingeniero Técnico de Obras Públicas y uno de Máster para la de Ingeniero de Caminos, Canales y Puertos, los datos referentes a los actuales planes de estudio (EEES) son la suma de la troncalidad del Grado (y/u obligatoriedad en la mención de Construcciones Civiles) y del Máster en la disciplina de Ingeniería de Carreteras.

A la vista de la figura es más que evidente la pérdida de peso que esta disciplina está viviendo en los sucesivos planes de estudio de los últimos 20 años. Incluso con el incremento de duración total de los estudios, que salvo una excepción ha pasado de 5 a 6 cursos, contabilizando el Grado y el Máster, la tendencia decreciente es acentuada en la mayor parte de las Escuelas, y en especial en las de más “solera”.

5. LA INGENIERÍA FERROVIARIA

Al igual que ocurría con las asignaturas englobadas en la Ingeniería de Carreteras, las ligadas al campo ferroviario (ver de nuevo la tabla 2) están también más presentes en las enseñanzas de Grado que en las de Máster y tanto en unas como en otras, el número de asignaturas de la disciplina ferroviaria son aproximadamente un 50% inferior al de las carreteras.

5.1 La Ingeniería Ferroviaria en los estudios de Grado

En los estudios de Grado, son 25 las asignaturas cuyos contenidos son íntegramente de esta disciplina. Su reparto es el siguiente:

- 2 asignaturas troncales en planes de estudio que incorporan las 3 menciones (los Grados en Ingeniería Civil de la UPM y de la Universidad de Sevilla).
- 13 asignaturas troncales en un total de 13 Grados que incorporan en sus planes de estudio 1 o 2 menciones (salvo en 2 de estos Grados, todos los demás tienen al menos la mención de Construcciones Civiles).
- 3 asignaturas obligatorias en la especialidad de Construcciones Civiles en Grados con las 3 especialidades.
- 5 asignaturas obligatorias en la especialidad de Transportes y Servicios Urbanos en Grados con las 3 especialidades.
- 2 asignaturas obligatorias que se imparten tanto en la especialidad de Construcciones Civiles como en la de Transportes y SS.UU. de Grados con las 3 especialidades.

Es evidente que la Ingeniería Ferroviaria en el ámbito del Grado se ubica principalmente en las especialidades o en la troncalidad de Grados con una única mención. Salvo en una universidad, como ya se avanzaba al comentar la tabla 4, tiene cabida obligatoria en todos los Grados con menciones en Construcciones Civiles o en Transportes y SS.UU, en unos casos con asignaturas cuyos contenidos son exclusivos de esta disciplina (las que se acaban de relatar) o lo son de forma parcial (se hará mención de ello algo más adelante en este apartado). Es significativa también la ausencia total de asignaturas optativas -con contenido exclusivo ferroviario- en los Grados.

Respecto al tiempo asignado para la impartición de las asignaturas, el conjunto de las 25 estudiadas tienen un "tamaño" promedio de 5,58 créditos, 19 de ellas de 6 créditos.

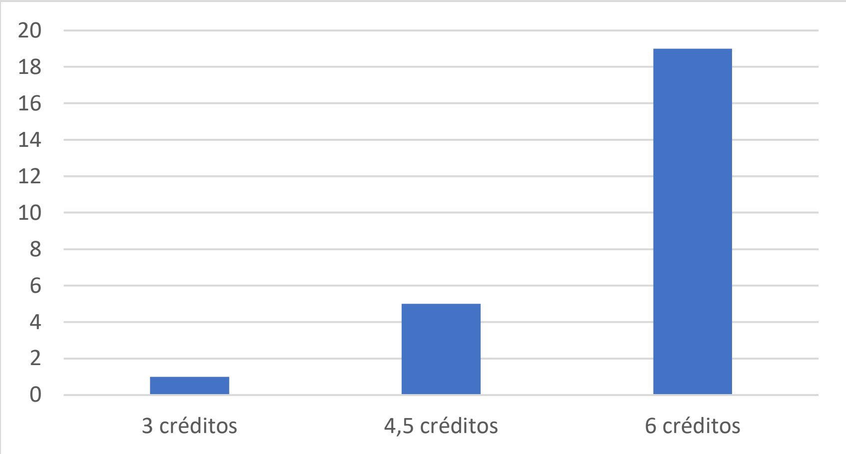

Figura 8 – Nº asignaturas de Grado con contenido exclusivo de Ingeniería Ferroviaria

En cuanto a los contenidos de las 25 asignaturas existe, con carácter general, una gran uniformidad de los mismos; es verdad que los tratan con diferentes estructuras de temarios, sin un orden preestablecido, dando en unos casos más profundidad a unos aspectos que a otros, pero a la postre van pasando con más profundidad o más de "puntillas" a los siguientes temas: el material móvil; al diseño de vía, tanto en los relativo a la superestructura como a la infraestructura; a la geometría de vía; a operaciones sobre la vía como la construcción, renovación, auscultación o conservación; a la tracción; la señalización, explotación, etc.; o a las terminales ferroviarias. De todos ellos, quizás los temas ligados al material móvil -el 40% de las asignaturas no entran en él- o el de las terminales ferroviarias -algo más del 50% no lo tratan- sean la excepción a esa homogeneidad de temarios.

Pero además de estas 25 asignaturas tratadas existen otras 11 asignaturas con contenidos parciales de esta disciplina. La inmensa mayoría, en número de 9, como ya se relató en el apartado anterior dedicado a la Ingeniería de Carreteras, son asignaturas mixtas de Carreteras y Ferrocarriles, todas ellas troncales -6- u obligatorias -3- de las especialidades de Construcciones Civiles o Transportes y SS.UU., que comparten -salvo en un par de casos- el 50% el temario de las asignaturas. Los contenidos que abordan de esta disciplina, son mucho más reducidos por tener que compartir "espacio" con la Ingeniería de Carreteras y se centran principalmente todas las asignaturas en el diseño de la vía y la geometría de la vía. El resto de temas que normalmente se tratan en las asignaturas de ferrocarriles no tienen asegurada su presencia en esas 9 asignaturas y pueden aparecer o no en las mismas.

Finalmente, en lo relativo al Grado, existen otras 2 asignaturas que entremezclan contenidos habituales de la Ingeniería Ferroviaria con los de Carreteras y los de Ingeniería del Transporte. Ambas son troncales, de 6 créditos y con muy escasa presencia de contenidos ferroviarios, pero que les sirve para “cubrir” con las exigencias en lo que a competencias se refiere.

5.2 La Ingeniería Ferroviaria en los estudios de Máster

Ya se vio al comentar la tabla 5 que, al igual que con la Carreteras, es casi inexistente la troncalidad -2 asignaturas- de esta disciplina en los 13 másteres impartidos en España. En total son 8 las asignaturas con contenidos íntegramente ferroviarios: además de las 2 troncales mencionadas (Cádiz y UPM) hay 3 asignaturas obligatorias de la especialidad de Transportes y otras 3 asignaturas optativas.

Ninguna de las 8 asignaturas tiene contenidos básicos de la disciplina (salvo una de la Universidad de Sevilla que ejerce de “nivelación” de conocimientos para los alumnos que no la cursaron en el Grado) optando la mitad de ellas por el desarrollo de sistemas ferroviarios específicos (alta velocidad, sistemas urbanos…) y el resto por la planificación, construcción y mantenimiento.

Como ya se hizo en el apartado dedicado a la Ingeniería de Carreteras, también aquí se presenta en la figura 9 la evolución de la carga docente troncal en los planes de estudio que conducen a formar ingenieros de caminos, canales y puertos. Se siguen los mismos criterios de cómputo de créditos mencionados en aquel momento y volviendo a aclarar que los datos referentes a los actuales planes de estudio (EEES) son la suma de la troncalidad del Grado (y/u obligatoriedad en la mención de Construcciones Civiles) y del Máster en la disciplina de Ingeniería Ferroviaria.

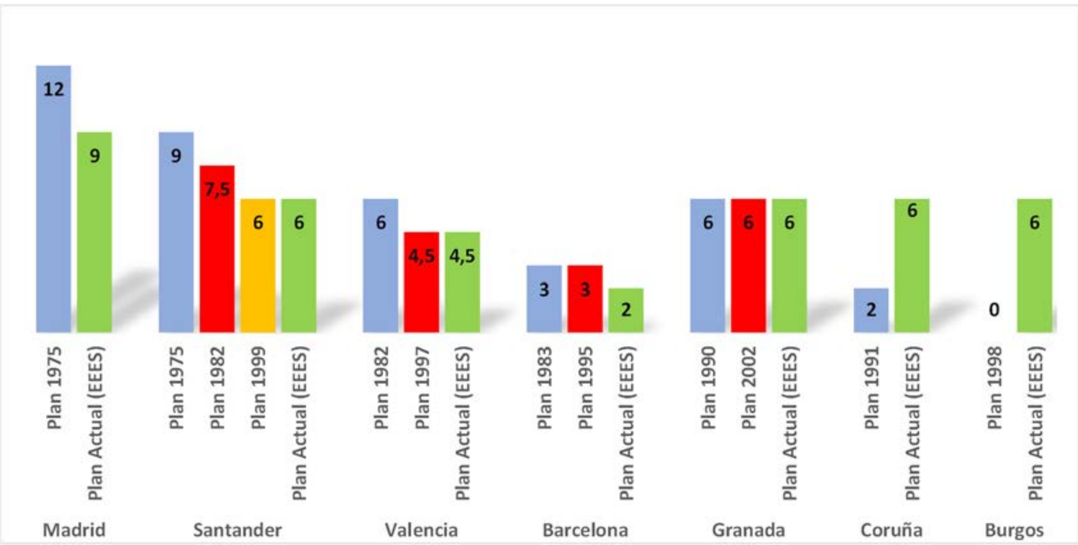

Figura 9 – Evolución del número de créditos de asignaturas troncales de Ingeniería Ferroviaria en diversas Escuelas

La figura 9 habla por sí sola de la pérdida de relevancia de esta disciplina con el paso de los años en las Escuelas con más tradición en España, llegando a ser en alguna de ellas casi intrascendente en el conjunto del plan de estudios. Y ello a pesar de los años "dorados" de inversión en alta velocidad o la reaparición en escena de los sistemas de transporte urbano ligero; y sin olvidarnos que con el actual marco de la EEES se ha incrementado la duración total de los estudios de 5 a 6 cursos, contabilizando el Grado y el Máster.

6. LA INGENIERÍA DEL TRANSPORTE

Ya se explicitó al comienzo de este trabajo que la disciplina tratada bajo la denominación "Ingeniería del Transporte" acogía las materias tradicionales de Economía, Planificación y Explotación del Transporte más otras que se han ido incorporando como son la Logística y la Intermodalidad o la Movilidad y el Transporte Urbano.

Si en el análisis realizado a las disciplinas de Ingeniería de Carreteras e Ingeniería Ferroviaria se detectaba una presencia mayoritaria de sus asignaturas en los Grados y muy escasa en los planes de estudios de los Másteres, no se puede decir lo mismo cuando se habla de la Ingeniería del Transporte, con una presencia más "equilibrada" en ambos tipos de estudios. De hecho, ya se recogía en la tabla 2 la presencia total de 71 asignaturas con contenidos exclusivos de esta disciplina en las titulaciones vinculadas a la ingeniería civil de las universidades públicas españolas, 41 de las cuales pertenecían a estudios de Grado y 30 a estudios de Máster. Y es que mientras en los estudios de Grado que habilitan para ejercer la profesión de Ingeniero Técnico de Obras Públicas, contenidos de esta disciplina solo son exigidos en la especialidad o mención de Transportes y Servicios Urbanos, en los estudios de Máster que habilitan para la profesión de Ingeniero de Caminos, Canales y Puertos, han de recogerse obligatoriamente requisitos formativos que permitan la adquisición de competencias ligadas a esta disciplina, lo que conlleva, a la postre, su presencia en la troncalidad de dichos estudios de Máster.

6.1 La Ingeniería del Transporte en los estudios de Grado

Como ya se hizo en los dos apartados anteriores, se comenzará este análisis con los estudios de Grado. Se decía un poco más arriba que son 41 las asignaturas con contenidos exclusivos de esta disciplina, que en función de su "carácter" se reparten de la siguiente forma:

- 2 asignaturas troncales en planes de estudio que incorporan las 3 menciones (los Grados en Ingeniería Civil de la UPC y de la Universidad de Santiago).
- 9 asignaturas troncales en un total de 7 Grados que incorporan en sus planes de estudio 1 o 2 menciones (solo en 3 de estos Grados está presente la Mención de Transportes y SS.UU.; y en 5 la de Construcciones Civiles).
- 19 asignaturas obligatorias en la especialidad de Transportes y Servicios Urbanos en 11 Grados (salvo 2 de estos Grados, en el resto se ofertan las 3 especialidades).
- 3 asignaturas obligatorias que se imparten tanto en la especialidad de Construcciones Civiles como en la de Transportes y SS.UU. de 3 Grados con las 3 especialidades.

- 6 asignaturas optativas en la especialidad de Transportes y SS.UU. de 5 Grados distintos.
- 2 asignaturas optativas no ligadas a especialidad alguna de 2 Grados distintos.

La información anterior vuelve a dejar patente que esta disciplina, al igual que las ya estudiadas, tiene cabida principalmente en las especialidades de los Grados y más específicamente en este caso en la de Transportes y SS.UU. La troncalidad se encuentra muy limitada y tan solo aparece en 2 de los Grados que imparten las 3 especialidades o menciones.

En la figura 10 que se muestra a continuación puede observarse cómo es el reparto de las 41 asignaturas impartidas con contenido exclusivo de esta disciplina en lo referente al “tamaño” de las mismas. Mayoritariamente son las de 6 créditos las que se encuentran en los planes de estudio y es cercano a ese valor -5,74 créditos- su dimensión promedio. Por lo general, las asignaturas optativas -su tamaño promedio es de 5,25 créditos- tienen menos envergadura que las troncales y obligatorias -5,86 créditos-.

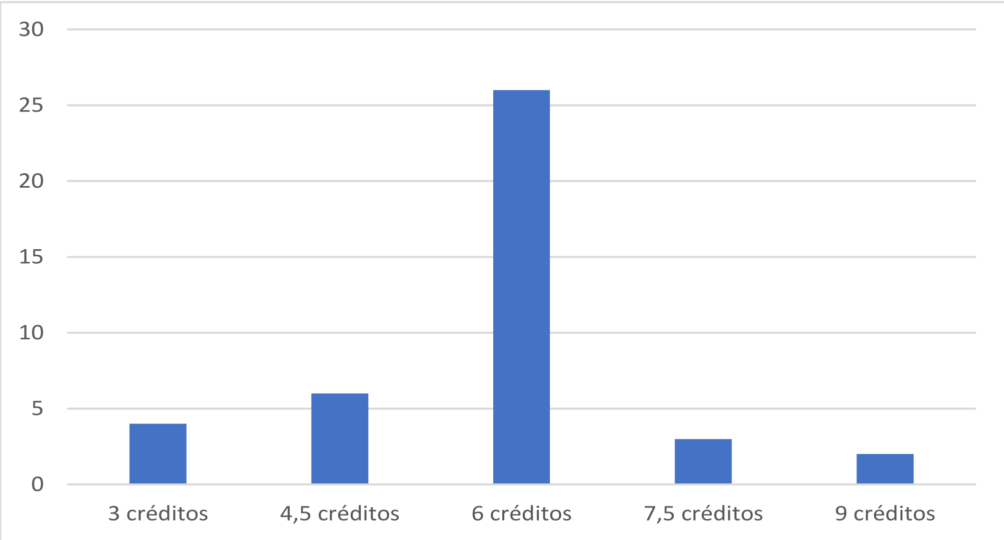

Figura 10 – Nº asignaturas de Grado con contenido exclusivo de Ingeniería del Transporte

Por lo que respecta a los contenidos de las asignaturas, la situación de esta disciplina difiere de las ya estudiadas con anterioridad, la Ingeniería de Carreteras y la Ferroviaria. Y difiere principalmente porque estas últimas han de tener contenidos obligatoriamente en las especialidades o menciones de Construcciones Civiles y de Transportes y Servicios Urbanos para satisfacer las competencias exigidas para las mismas, mientras que las de “Ingeniería del Transporte” solo son exigidas en la de Transportes y Servicios Urbanos. Y en concreto, según la Orden CIN/307/2009 de 9 de febrero, las competencias que deben adquirirse son el “*Conocimiento de la influencia de las infraestructuras en la ordenación del territorio y para participar en la urbanización del espacio público urbano, tales como distribución de agua, saneamiento, gestión de residuos, sistema se transporte, tráfico, iluminación, etc.*”; y el “*Conocimiento del diseño y funcionamiento de las infraestructuras para el intercambio* *modal, tales como puertos, aeropuertos, estaciones ferroviarias y centros logísticos de transporte*".

Son tan específicas las competencias y de alguna forma un tanto alejadas de las bases tradicionales de la Ingeniería del Transporte, que los contenidos que "cubren" dichas competencias no están, en casi ningún caso, en la troncalidad de las titulaciones y sí entre las asignaturas obligatorias de la especialidad de Transportes y Servicios Urbanos.

Debido a lo anterior, la mayoría de las asignaturas troncales ofertadas en el conjunto de los 30 Grados no están pensadas inicialmente para formar ingenieros de obras públicas especializados en Transportes y Servicios Urbanos, sino para ofrecer unos mínimos conocimientos de la disciplina a cualquiera de ellos, al margen de la especialidad; o como base sobre la que sustentar las asignaturas obligatorias de esta disciplina que aparecerán posteriormente en el Máster en Ingeniería de Caminos, Canales y Puertos. Es por todo ello que, en la mayoría de estas asignaturas troncales -8 de un total de 11- los contenidos están orientados a dar una visión general de esta disciplina; y solo 3 de las 11 asignaturas troncales son específicamente relativas a la formación de ingenieros en la especialidad de Transportes y Servicios Urbanos pues pertenecen a títulos (Extremadura y País Vasco) con plan de estudios "cerrados" conducentes a formar ingenieros en esta especialidad.

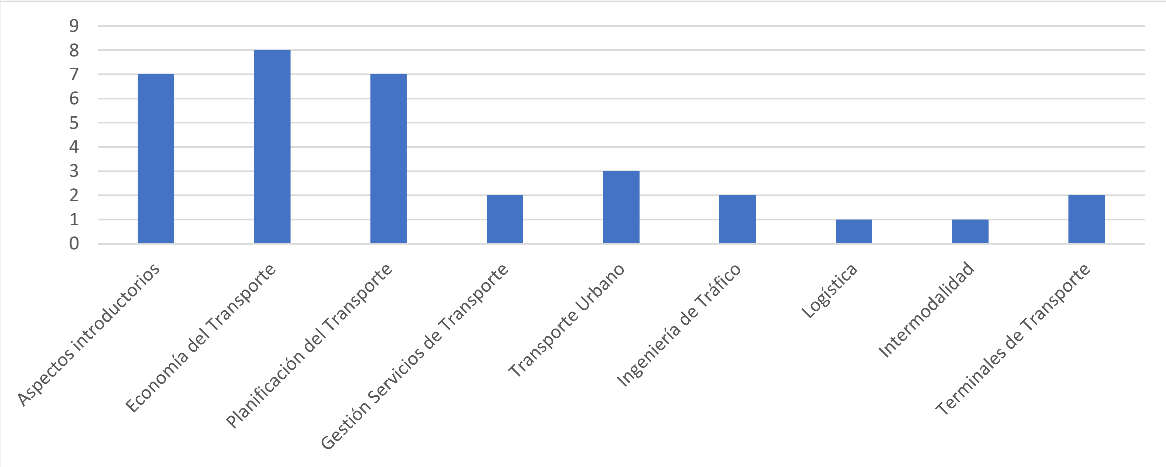

Figura 11 – Nº de asignaturas troncales en la que están presentes contenidos de diversas áreas temáticas en Ingeniería del Transporte

Y eso es lo que queda reflejado en la figura 11, en la que se representan cuáles son los contenidos principales en las 11 asignaturas troncales con contenidos exclusivos de esta disciplina en los 30 Grados estudiados en este trabajo. Salvando las 3 asignaturas mencionadas en el apartado anterior, las restantes se construyen principalmente entorno a aspectos introductorios del transporte (historia, características de los modos de transporte, datos para posicionar la materia...) y unas bases generales de Economía y Planificación del Transporte, a las que se complementa con pequeñas aportaciones de otras áreas temáticas.

Además de estas 11 asignaturas troncales con contenidos exclusivos en Ingeniería del Transporte, existen otras 4 asignaturas (3 en la Universidad de Extremadura y 1 en la UPV) en las que comparten "espacio" con otras disciplinas como la Ingeniería de Carreteras, la Ferroviaria o la Ordenación del Territorio.

Muy distinta es la configuración de las asignaturas "obligatorias" en la especialidad o mención de Transportes y Servicios Urbanos (ya se adelantó anteriormente que no existen asignaturas obligatorias de esta disciplina en la mención de Hidrología de ningún título y tan solo 3 en la de Construcciones Civiles, que a su vez se imparten también en la de Transportes y SS.UU.). Aquí se dan cita mayoritariamente los contenidos que sustentan las competencias de esa especialidad y así queda patente en la figura 12 donde se pone de manifiesto el número de asignaturas que acogen contenidos de Intermodalidad o Transporte Urbano.

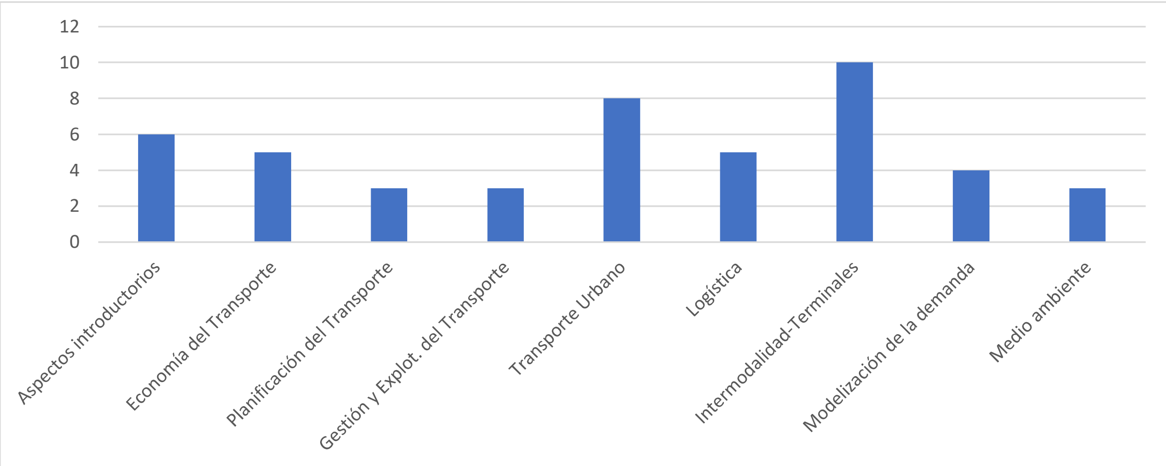

Figura 12 – Nº de asignaturas obligatorias de especialidad "Transportes y SS.UU." que incluyen contenidos de diversas áreas temáticas en Ingeniería del Transporte

Una última aportación en torno a la "Ingeniería del Transporte" en lo que a los Grados se refiere, es la relativa al número de asignaturas obligatorias con contenidos exclusivos de dicha disciplina y el número de créditos empleados en los currículos que dan opción a obtener la especialidad de Transportes y Servicios Urbanos en los 16 títulos que incluyen esta mención.

Como se constata en la figura 13, los planes de estudio afrontan de forma muy diversa los contenidos de esta disciplina para con ellos adquirir las competencias requeridas, oscilando entre una asignatura -en 5 títulos- y el número de 3, siendo los títulos con 2 asignaturas la mitad del total. Ello quiere decir que en el 30% de los títulos se introduce en una única asignatura toda la materia, por diversa que ella sea, para obtener las competencias. Ello conduce en algunos casos a observar temarios que son un verdadero "popurrí" de contenidos que, en algunos casos, por su exigua presencia, es complicado percibir los que dan cauce a la adquisición de las competencias exigidas.

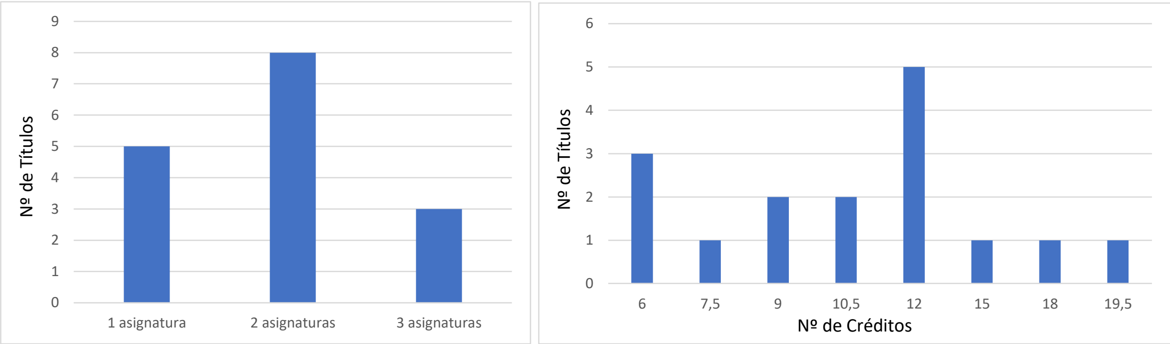

Figura 13 – Asignaturas obligatorias de la disciplina "Ingeniería del Transporte" y créditos empleados para obtener la especialidad "Transportes y SS.UU."

Algo semejante, en cuanto a la diversidad, puede decirse del número de créditos que han de cursarse obligatoriamente para obtener la especialidad. En esa misma figura 13 se constata cómo en algunos títulos se emplean hasta más del triple que en otros en impartir la docencia de esta disciplina. El valor promedio es de 11,06 créditos por titulación.

Solo una mención, antes de terminar con este apartado dedicado a los títulos de Grado, a las asignaturas optativas, de las que se relató al comienzo del mismo que eran un total de 8, de las que 6 estaban incardinadas en las menciones de Transportes y SS.UU. y 2 eran de carácter general no ligadas a especialidad alguna. Salvo un par de excepciones, los contenidos de las mismas se reparten equitativamente entre los ámbitos del Transporte Urbano y la Logística.

6.2 La Ingeniería del Transporte en los estudios de Máster

Como ya quedó reflejado al comienzo del apartado dedicado a esta disciplina, la presencia de la misma en los Másteres que conducen a la obtención del título de Ingeniero de Caminos, Canales y Puertos es mucho más elevada que en los casos de Ingeniería de Carreteras e Ingeniería Ferroviaria y ello venía dado porque en los estudios de Máster que habilitan para esa profesión deben acoger requisitos formativos para adquirir competencias relativas a esta disciplina, lo que hace obligada su presencia en la troncalidad de dichos estudios de Máster.

Como puede verse en la tabla 5 ya mencionada en varias ocasiones, son un total de 30 asignaturas las desplegadas en los 13 másteres estudiados, que según su "carácter" se reparten de la siguiente forma:

- 15 asignaturas troncales en el total de 13 másteres.
- 4 asignaturas obligatorias en especialidades de Transportes encuadradas en 3 másteres.
- 6 asignaturas optativas en especialidad de Transportes correspondientes a 3 másteres.
- 5 asignaturas optativas, pertenecientes a 4 másteres, que no están ligadas a especialidad alguna.

Todos los másteres tienen una asignatura troncal salvo los que se imparten en la Universidad de Oviedo y en la Politécnica de Cartagena. En estas 2 universidades no existen asignaturas de Ingeniería del Transporte en los Grados que también imparten, mientras que las 11 titulaciones restantes o tienen un Grado con la especialidad de Transportes y SS.UU. o tienen asignaturas troncales en Grados sin esa especialidad.

En lo relativo al "tamaño" de las asignaturas, las troncales -salvo una de ellas que alcanza 7,5 créditos- son abordadas con 4,5 créditos en 5 asignaturas y con 6 créditos las 9 restantes; las obligatorias de especialidad son más reducidas -entre 3 y 5 créditos- y las optativas de especialidad son todas de 4,5 créditos.

Entrando en el apartado de contenidos de las asignaturas, las troncales han de dar satisfacción a las competencias recogidas en la Orden CIN/309/2009 de 9 de febrero por la que se regulan los estudios de Máster que habilitan para ejercer la profesión de Ingeniero de Caminos, Canales y Puertos, y que textualmente dice: "*Conocimientos de la ingeniería y planificación del transporte, funciones y modos de transporte, el transporte urbano, la gestión de los servicios públicos de transporte, la demanda, los costes, la logística y la financiación de las infraestructuras y servicios de transporte*"; y "*Capacidad de planificación, gestión y explotación de infraestructuras relacionadas con la ingeniería civil*".

La diversidad de contenidos recogidos en la Orden Ministerial obliga en muchos casos a que la conformación de los temarios de las asignaturas troncales sea un reflejo de aquella en aras de cumplir las exigencias y vadear los procesos de acreditación. Bien puede decirse que al menos 8 de los 13 másteres impartidos son bastante fieles a ese perfil trazado por las competencias requeridas y además de forma relativamente equilibrada. El resto, aun "cumpliendo" las exigencias -en algunas ocasiones no es fácil percibirlo en los temarios-, no mantienen ese equilibrio y enfatizan el núcleo principal de la asignatura en aspectos muy concretos (Economía del Transporte en un caso; otra en Planificación del Transporte; Gestión y Explotación de los Servicios de Transporte; y en dos de ellas con una presencia principal de la modelización).

En lo relativo a las asignaturas obligatorias en especialidades de Transportes y a las optativas, tanto de especialidad como al margen de ellas, destaca ampliamente la oferta de las que centran sus contenidos en la Logística seguidas por las de Movilidad Urbana.

Para finalizar este apartado dedicado a la Ingeniería del Transporte en el ámbito de los Másteres, y al igual que se hizo anteriormente con otras disciplinas, se presenta en la figura 14 la evolución de la carga docente troncal en los planes de estudio que conducen a formar ingenieros de caminos, canales y puertos. Como ya se aclaró anteriormente, los datos referentes a los actuales planes de estudio (EEES) son la suma de la troncalidad del Grado (y/u obligatoriedad en la mención de Construcciones Civiles) y del Máster en la disciplina de Ingeniería del Transporte.

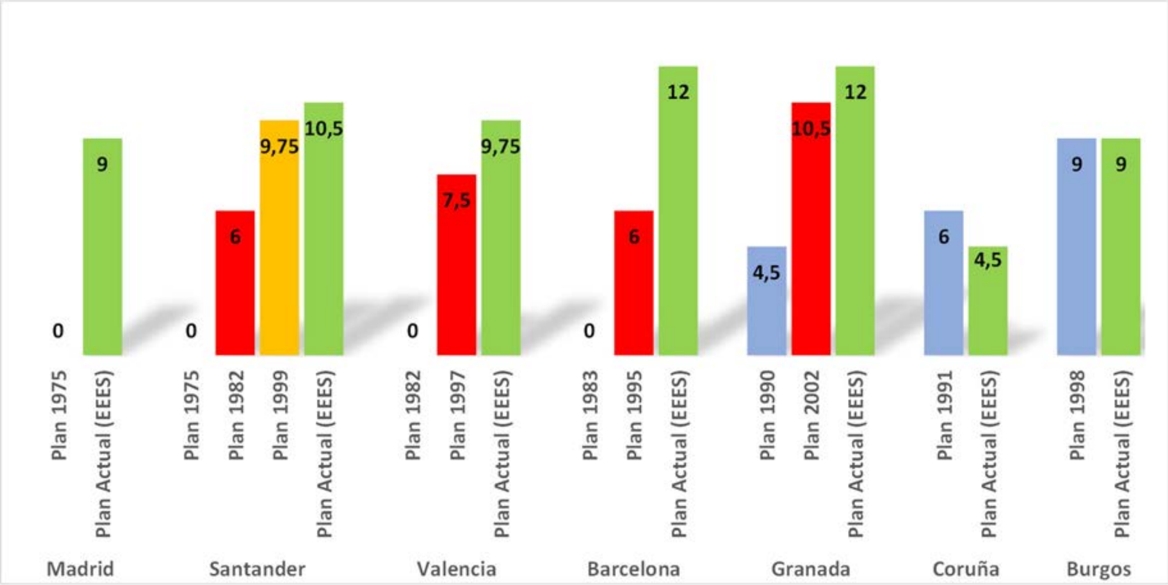

Figura 14 – Evolución del número de créditos de asignaturas troncales de Ingeniería del Transporte en diversas Escuelas

A la vista de la figura es más que evidente el crecimiento que esta disciplina está viviendo en los sucesivos planes de estudio de los últimos 25 años, más si cabe en las escuelas “tradicionales” que en sus primeros planes dejaban los contenidos de la “Ingeniería del Transporte” al ámbito de las especialidades. La tendencia contrasta mucho con las estudiadas anteriormente de la Ingeniería de Carreteras y la Ferroviaria.

7. LA PLANIFICACIÓN Y EXPLOTACIÓN PORTUARIA

Será muy breve la exposición en lo que respecta a esta disciplina, en otro tiempo siempre presente en los planes de estudios de la Ingeniería de Caminos, Canales y Puertos, aunque fuera en las vías de especialización de los últimos cursos. Y es que en la actualidad esa presencia ha pasado a ser testimonial pues apenas son 16 asignaturas las que se están impartiendo (8 en títulos de Grado y 8 en los de Máster) en las 43 titulaciones que se están analizando en este trabajo (30 de Grado y 13 de Máster). Y si además se tiene en cuenta que la mitad de ellas se imparten en 3 Escuelas (Ingenieros de Caminos de Madrid, y las Escuelas Politécnicas Superiores de la Universidad de Alicante y de Algeciras, perteneciente esta última a la Universidad de Cádiz) pues la sensación de exclusión de esta disciplina de los planes de estudio actuales es más que manifiesta.

Por lo que se refiere a los estudios de Grado, se decía más arriba que son 8 las asignaturas con contenidos de esta disciplina. Su reparto es el siguiente:

- 6 asignaturas obligatorias en la especialidad de Transportes y Servicios Urbanos en 5 Grados con las 3 especialidades (una de ellas se imparte también en la especialidad de Construcciones Civiles. Corresponden a los Grados en Ingeniería Civil de Alicante,

Cádiz, UPM y Sevilla; y al Grado en Ingeniería Civil y Territorial de la UPM (2 asignaturas).
- 1 asignatura optativa en la especialidad de Transportes y SS.UU. (Universidad de Santiago).
- 1 asignatura optativa no ligada a especialidad alguna (Universidad de Burgos).

En cuanto a los estudios de Máster en Ingeniería de Caminos, Canales y Puertos, el reparto de las 8 asignaturas, según su carácter, es el siguiente:
- 2 asignaturas obligatorias en la especialidad de Transportes (Alicante y Cantabria).
- 1 asignatura obligatoria en la especialidad de Hidráulica (Oviedo).
- 3 asignaturas optativas en la especialidad de Transportes (2 en la UPM y una en la UPV).
- 1 asignatura optativa en la especialidad de Hidráulica (Coruña).
- 1 asignatura optativa no ligada a especialidad alguna (Cádiz).

Salvo alguna excepción en la que la asignatura se encuentra ligada a la especialidad de Hidráulica, o alguna optativa de acceso general, por lo general se encuadran en las especialidades de Transportes, tanto en los grados como en los másteres. Y salvo una asignatura de Grado en la Universidad de Alicante que tiene 6 créditos, todas las demás se imparten en formato de 3 o de 4,5 créditos (7 y 8 respectivamente).

En cuanto a los contenidos de las asignaturas, salvo una muy orientada a la logística portuaria, las demás abordan con más o menos profundización los temas relativos al transporte marítimo y el comercio internacional, el espacio portuario y las infraestructuras al servicio de la planificación portuaria, y la gestión y explotación portuaria. Es obvio que aquellos centros universitarios que imparten 2 asignaturas (una de Grado y otra de Máster) como es el caso de las mencionadas EPS de Alicante y Algeciras, o el caso de la E.T.S.I.C.C.P. de Madrid, que llega a impartir 4 asignaturas (2 de Grado y 2 de Máster) llegan a abarcar cualitativa y cuantitativamente aspectos de la disciplina que las demás perfilan o abordan más sucintamente.

8. ALGUNAS CONCLUSIONES

El presente trabajo ha pretendido ofrecer una “fotografía” actual y un análisis de cómo las Escuelas que ofertan títulos en el ámbito de la “Ingeniería Civil” han integrado en sus planes de estudio los contenidos ligados a la Ingeniería e Infraestructura de los Transportes, tanto de los Grados como de los Másteres que habilitan para el ejercicio de las profesiones de Ingeniero Técnico de Obras Públicas y de Ingeniero de Caminos, Canales y Puertos, respectivamente. Para ello se han analizado los contenidos de un total de 209 asignaturas (68 de Máster y 141 de Grado) incardinadas en 13 títulos oficiales de Máster y 30 de Grado impartidos en las universidades públicas españolas.

Las disciplinas tratadas, en este orden, han sido las de Ingeniería de Carreteras (incluyendo la Ingeniería de Tráfico o la Seguridad Vial); la Ingeniería Ferroviaria y la Explotación Ferroviaria; la Ingeniería del Transporte (incluye las tradicionales de Economía, Planificación y Explotación del Transporte más otras que se han ido incorporando en las últimas décadas como la Logística y la Intermodalidad o la Movilidad y el Transporte Urbano; y la Planificación y Explotación Portuaria.

Con carácter general puede afirmarse que las materias cuyos contenidos pertenecen a la Ingeniería e Infraestructura de los Transportes no forman parte de la formación generalista de un futuro ingeniero técnico de obras públicas y tan solo de la formación de su itinerario de especialidad. Y salvo materias ligadas a la "Ingeniería del Transporte", tampoco forman parte de la troncalidad de los másteres. Por ello, existe un problema de carencias formativas al que se pueden enfrentar los alumnos que cursen la mención de Hidrología cuando en los planes de estudios de sus grados no exista troncalidad de disciplinas como la Ingeniería de Carreteras o la Ferroviaria y accedan a un máster sin troncalidad de estas mismas disciplinas.

Tanto la Ingeniería de Carreteras como la Ferroviaria (la 1ª tiene aproximadamente el doble de asignaturas que la 2ª) tiene su principal encaje en las especialidades de los Grados o en la troncalidad de Grados con una única mención, generalmente la de Construcciones Civiles. Con carácter general, los contenidos de ambas disciplinas en los Grados abordan en todos los títulos los aspectos esenciales de las mismas. Los niveles de profundización dependerán del "tamaño" de las asignaturas y del número de ellas, ya que en bastantes casos se da la circunstancia de asignaturas únicas que acogen los contenidos de ambas disciplinas.

Los contenidos de la disciplina Ingeniería del Transporte tienen una presencia más "equilibrada" en los estudios de Grado y de Máster. En los primeros muy ligada a la especialidad o mención de Transportes y Servicios Urbanos y en los estudios de Máster con una carga importante de troncalidad derivada de las exigencias de competencias que han de recogerse en los títulos que habilitan para la profesión de Ingeniero de Caminos, Canales y Puertos. La conformación de "temarios" de las asignaturas de Grado se inclinan por cuestiones básicas de la disciplina en los casos de asignaturas troncales; y por áreas como el transporte urbano o la intermodalidad en las de especialidad o mención, para dar cumplimiento a las competencias. En el caso de los másteres, los "temarios", salvo excepciones, son "popurrís" que procuran ser reflejo de la diversidad de contenidos recogidos en la Orden Ministerial que ordena sus enseñanzas y que hay que cumplir para vadear los procesos de acreditación.

Finalmente dejar patente la más que evidente pérdida de peso que la Ingeniería de Carreteras y la Ferroviaria están viviendo en los sucesivos planes de estudio de los últimos 25 años. Incluso con el incremento de duración total de los estudios, que ha pasado de 5 a 6 cursos, contabilizando Grado y Máster, la tendencia decreciente es acentuada en la mayor parte de las Escuelas, y en especial en las de más "solera". Muy al contrario ocurre con los contenidos de Ingeniería del Transporte, que en estos mismos años ha visto un indudable crecimiento de su presencia troncal cuando antaño estaba reducida al ámbito de las especialidades.

INFRAESTRUCTURAS
INFRASTRUCTURES

BITUMINOUS BASE COURSES FOR FLEXIBLE PAVEMENTS WITH STEEL SLAGS

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ABSTRACT

The purpose of this research was to study the feasibility of incorporating steel slags into coarse bituminous mixtures. The objective was twofold: to reduce dependence on natural aggregates, and to provide a use for industrial by-products. The slags studied come from the manufacture of carbon steel in electric furnaces and are divided into two types: Electric Arc Furnace (EAF) slag and Ladle Furnace (LF) slag. The mixture designed is coarse bituminous concrete (AC22G), for base courses in flexible pavements.

In a first phase, the physical characterization of the materials was carried out to check their suitability. In a second phase, three types of mixes were designed: a control mix (made with natural limestone aggregates), a mix where LF slag was introduced to replace the filler and the fine fraction (sand) of the mix; and finally, the feasibility of manufacturing a totally sustainable mix was analyzed, which would fully incorporate EAF slag as coarse aggregate and LF slag as fine aggregate and filler. In a third and final phase, the designed mixes were subjected to different mechanical, water sensitivity, and durability tests.

The research demonstrated that the incorporation of EAF and LF steel slag as a substitute for natural aggregate in coarse bituminous mixtures is feasible, meeting regulatory requirements, improving sustainability in the construction industry, as well as reducing emissions, and contributing to climate change mitigation.

1. INTRODUCTION

Since the end of the 20th century, social pressure to protect the environment has forced the scientific community to study different ways of recycling the by-products generated in industrial processes (Revilla-Cuesta et al., 2020; Rodríguez-Fernández et al., 2019). This recycling would reduce the amount of waste generated and convert the residues into valuable and sustainable resources (Gonzalo-Orden et al., 2019; Martinho et al., 2018).

One of the most studied industrial by-products is iron and steelmaking slags (Teo et al., 2020). These materials were first considered as waste and they were mainly dumped in landfills, producing important landscape impacts and posing a pollution risk to runoff waters that came into contact with them (Riboldi et al., 2020).

The growth of the world steel industry, which from 1950 to the present has increased from 189 to 1,600 million tons of steel produced annually, has led to an equally significant increase in the production of slag (Branca et al., 2020). Today, a wide variety of applications for steel slags have been developed (Gökalp et al., 2018), but slag consumption is far from reaching its production, resulting in a surplus of this waste that continues to be stored in landfills.

Among the multiple uses of steel slag, the most widespread are: its reincorporation into the steel production process (Li et al., 2020; Varanasi et al., 2019) and its use in the construction sector, mainly as a substitute for natural aggregates and binders in the manufacture of concrete and cementitious composites (Brand and Fanijo, 2020; Piemonti et al., 2021) or bituminous mixtures (Li et al., 2018; Pasetto et al., 2017). One of the applications with the greatest potential is the incorporation of these materials in road pavements, replacing natural aggregates (Dondi et al., 2021; Maharaj et al., 2017).

A bituminous mixture is a combination of coarse aggregates (>2 mm), fine aggregates (0.063-2 mm), mineral powder or filler (<0.063 mm) and a hydrocarbon binder, so that all the particles are covered by a homogeneous film of binder. On the other hand, road pavements can be defined as a set of overlapping layers, relatively horizontal and several centimeters thick, composed of different materials, suitably compacted and supported on the natural ground. Bituminous mixtures can be used in the surface layer of the pavement (wearing course) or the inner layers (base course and binder course).

The purpose of this research was to study the feasibility of incorporating two types of steel slag in coarse bituminous mixtures that are used for the base layer of a road pavement. The objective of this research was twofold: to reduce the dependence on natural aggregates, whose extraction is harmful to the environment, and to give a use to industrial by-products, which reduces the volume of stockpiles and improves sustainability both in the construction and steel industries.

2. MATERIALS

The two types of slags studied in this research proceed from the manufacture of carbon steel:

- **Electric Arc Furnace (EAF) slag**: it originates during the melting process of the scrap in the primary metallurgy. It is a coarse material, with a rough texture and blackish gray color. It is mainly composed of calcium silicates and metallic oxides, the latter being responsible for its dark color and high density and hardness. Its good mechanical characteristics (hardness, absorption, roughness and angularity) and its particle size allow it to be used as coarse aggregate in concrete and bituminous mixtures (Skaf et al., 2017).
- **Ladle Furnace (LF) slag**: it is obtained during steel refining in ladles. It is a fine material, whitish in color and powdery in texture. It is mainly composed of calcium and magnesium silicates and aluminates, which provides it with soft hydraulic properties (Parron-Rubio et al., 2019). Due to its size, which is usually under 2 mm, it can be used as fine aggregate in construction, while its hydraulic properties mean that it can be used as a mineral powder to replace lime or cement traditionally used in bituminous mixtures (Terrones-Saeta et al., 2021b).

Fig. 1 – Ladle Furnace (LF) slag (left) and Electric Arc Furnace (EAF) slag (right) used in this research.

3. MIX DESIGN

For the investigation, an AC22G mix was adopted, which according to the Spanish standard PG-3 (2015) is defined as a coarse bituminous concrete with a maximum size of 22 millimeters. This type is one of the most commonly used in base layers of flexible and semi-rigid pavements.

The slags were introduced into the bituminous mix in two phases:

- The first type was a mix consisting partly of steel aggregate, with LF slag as fine aggregate and mineral powder, and traditional limestone aggregate as coarse aggregate. This mix was labeled CBB

- The second type was a 100% sustainable mix, composed entirely of slags, with EAF slag as coarse aggregate and LF slag as fine aggregate and filler (labeled as NBB).

Finally, it was necessary to manufacture a third traditional mix, composed entirely of limestone aggregate, to serve as a reference, to assess the effect of the slag incorporation. This standard mix was labeled CCC.

Fig. 2 – Specimens of CBB (left) and NBB (right) mixtures

4. PERFORMANCE OF THE MIXTURES

4.1 Volumetric properties

The incorporation of the slags generated a greater void content in the mix, which increased the optimum binder content to achieve the target air voids. The mixtures studied, CBB and NBB, required a 15% and 35% higher volume of bitumen, respectively.

This greater void content was attributed to the fact that the bituminous mastic (filler+binder) formed by the LF slag is more rigid than that formed by the limestone mineral powder, and therefore has a lower capacity to penetrate the voids in the aggregate (Pasetto et al., 2020). On the other hand, the greater roughness of the EAF slag reduces its compactability and results in a higher porosity within the mineral skeleton. These adverse effects could be partly compensated by increasing the binder temperature (Pasquini et al., 2020).

4.2 Stability

Stability was measured by the Marshall test (EN 12697-34) and is defined as the ability of a mixture to withstand traffic loads and resist the resulting stresses with tolerable deformations. This feature is of the most important in base layers.

The results of this test showed that the introduction of LF slag as fine aggregate and mineral powder improved the stability of the mix by 12% with respect to the standard mix, while its joint incorporation with EAF slag as coarse aggregate greatly improved stability (around 40%), as some other researchers have found (Terrones-Saeta et al., 2021a).

The increase in stability was attributed to the higher stiffness of the siderurgic mastic mentioned above and the high roughness of the EAF slag, which increases the internal friction in the mineral skeleton. The above combined effect managed to overcome the effect of the higher binder content, an unfavorable circumstance for the stability of the mix as it implies higher flexibility/lower stiffness of the pavement.

4.3 Indirect tensile strength

The Brazilian test (EN 12697-23), which analyzes the indirect tensile strength (ITS) of a bituminous mix, showed that the mix with LF slag as fine aggregate and filler had a slightly better tensile performance (6%) than the standard mix. This proves a good adhesion of the mastic to the

On the other hand, the introduction of EAF slag as coarse aggregate was unfavorable for the tensile behavior of the mix. The NBB mix had a 25% lower ITS than the standard mix. This circumstance is attributable to the greater discontinuity of the mix due to its higher porosity, which is highly adverse under tensile stress.

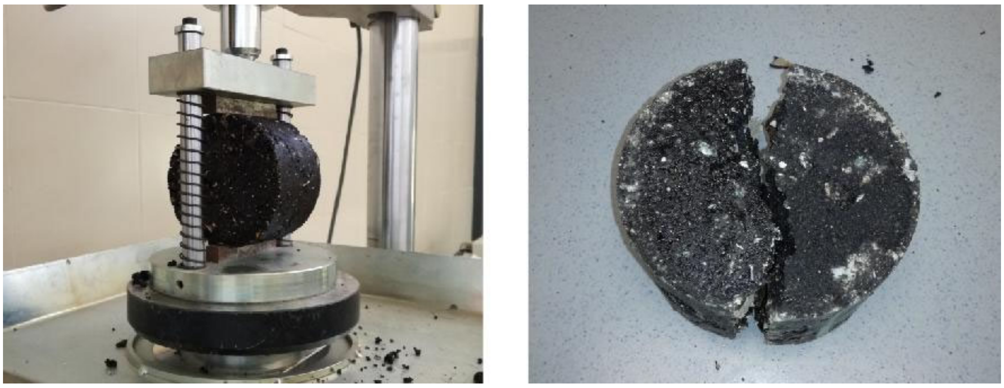

Fig. 3 – CBB mix during and after the ITS test

4.4 Abrasion resistance

Abrasion resistance was determined by the Cantabro test (EN 12697-17). The results of the mixtures studied were all excellent, with particle losses (PL) below 10% in both cases. In addition, both mixes gave results similar to those of the standard mix, so the incorporation of both the LF slag and the EAF slag did not have a detrimental effect on the wear resistance of the resultant mixes. The resistance to abrasion in slag mixtures has also proved to be excellent in other researches, and this feature is particularly relevant in open-graded and porous mixtures (Skaf et al., 2019).

4.5 Durability

The durability test results showed that the mechanical properties of the mixtures studied were hardly affected by the ageing process. For both mixtures, the loss of abrasion resistance after aging was below 3%.

These excellent results are in part due to the higher binder content of the slag mixes, but they also prove a good affinity of the LF slag to the binder, a quality mastic that provides good adhesion to the aggregates and improves the cohesion of the mixes and their resistance to ageing.

Fig. 4 – Specimens of the standard mix prior to testing, after the abrasion test and after the durability test (from left to right)

4.6 Water Sensitivity

Water damage is one of the primary causes of distress in flexible pavements, reducing their durability (Soenen et al., 2020). The moisture susceptibility test (EN 12697-12) showed that the incorporation of slag reduced the water sensitivity of the mix. This reduction was especially noticeable in the mix composed entirely of slag (NBB mix), whose mechanical properties were hardly affected by the action of water. This is due to the good affinity between the EAF slag and the binder, and also attributable to the higher binder content of these mixes (Pathak et al., 2020).

5. CONCLUSIONS

The main results of the investigation can be summarized as follows:

- The incorporation of LF slag as fine aggregate in coarse bituminous mixes is feasible, since it produces similar o superior results to those of the conventional mixes in most of the properties studied.
- The integral replacement of the traditional limestone aggregate with slags (EAF and LF) in base layers fulfilled all regulatory requirements in volumetric terms, stability, abrasion resistance and durability. However, the tensile strength performance was significantly worse than the conventional mix.
- The commercial use of the slags studied in this research should be subject to a prior study of the economic viability of two aspects: the higher cost of transporting EAF slag, due to its higher density, and the higher binder content that these mixtures require.

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MEJORA DEL DISEÑO DE GLORIETAS EN SERVICIO CON MEDIDAS DE BAJO COSTE

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RESUMEN

Las glorietas son un tipo de nudo que canaliza los flujos procedentes de tres o más accesos mediante una calzada anular. De la experiencia acumulada en países de todo el mundo se deduce que, en muchos casos, este tipo de nudo tiene numerosas ventajas frente a una intersección convencional. Por este motivo, se ha extendido su aplicación como solución alternativa a las intersecciones convencionales tanto en zonas urbanas como interurbanas.

En general, las glorietas en servicio ofrecen unas buenas condiciones de circulación y un elevado nivel de seguridad. Sin embargo, existen casos en los que una inadecuada definición de su diseño en el proceso de proyecto da lugar posteriormente a problemas de funcionamiento o, incluso, de seguridad vial, que pueden corregirse si se identifican las deficiencias de diseño que los originan.

En este trabajo se presentan dos casos de estudio de mejoras del diseño de glorietas en servicio con medidas de bajo coste. El primer caso se refiere a una glorieta multicarril implantada en un entorno urbano con problemas de capacidad. El conocimiento de los parámetros con mayor influencia en la operación de los tráficos ha permitido proponer una serie de ajustes en el diseño geométrico. El segundo caso corresponde a una glorieta multicarril situada en entorno interurbano con problemas de seguridad derivados de las altas velocidades de entrada en los accesos del eje principal. La actuación propuesta se basa en la modificación del trazado y de la señalización.

1. INTRODUCCIÓN

Las glorietas son un tipo de nudo que canaliza los flujos procedentes de tres o más accesos mediante una calzada anular. De la experiencia acumulada en países de todo el mundo se deduce que, en muchos casos, este tipo de nudo tiene numerosas ventajas frente a una intersección convencional. Por este motivo, se ha extendido su aplicación como solución alternativa a las intersecciones convencionales tanto en zonas urbanas como interurbanas.

En el caso de España, la primera glorieta con preferencia para el tráfico en la calzada anular fue construida en 1976. Desde entonces, se ha producido una masiva extensión superando en la actualidad, en valor aproximado, las 35.000 unidades. A nivel internacional, esta cifra sitúa a España como uno de los países con mayor número de glorietas.

A pesar de contar con esta importante experiencia, en la actualidad se pueden encontrar en las carreteras españolas una serie de glorietas cuyos problemas de funcionamiento y seguridad tienen su origen en la propia concepción del proyecto y en su desarrollo posterior y que son susceptibles de mejora si se identifican y se corrigen las deficiencias de diseño.

El diseño de una glorieta es una tarea compleja y que requiere del trabajo de un especialista que lleve a cabo múltiples iteraciones hasta satisfacer una serie de objetivos. Las normas de diseño son un excelente recurso, pero no garantizan el éxito ya que la mayor parte de las glorietas presentan unas condiciones únicas que no se pueden ajustar a ningún estándar.

Las carencias en la aplicación de los principios de diseño a las condiciones específicas de cada proyecto pueden terminar manifestándose en la fase de explotación con pérdidas de funcionalidad y problemas de seguridad vial. Por este motivo, resulta de interés analizar las posibilidades de mejora del diseño en estos casos y su efecto en las condiciones de operación y seguridad.

En esta línea, la presente investigación propone la aplicación de una serie de ajustes de menor entidad en el diseño de glorietas en servicio y que, por este motivo, se han denominado de bajo coste. Estas se fundamentan en el conocimiento de los principios generales de diseño que gobiernan el proyecto de las glorietas.

El objetivo del presente trabajo es evaluar el efecto en la circulación y la seguridad de la aplicación de medidas de menor entidad en el trazado y señalización de glorietas con un funcionamiento deficiente.

Para ello se ha seleccionado dos casos típicos en la red de España:

- Glorieta multicarril urbana con problemas de capacidad.
- Glorieta multicarril interurbana con problemas de elevadas velocidades.

2. GLORIETA URBANA CON PROBLEMAS DE CAPACIDAD

El primer caso que se analiza es una glorieta de gran diámetro que resuelve la conexión de una vía de gran capacidad con el entramado urbano de un municipio (Fig. 1). Presenta las siguientes características:

- Elevado número de accesos distribuidos de manera no uniforme en los cuadrantes este y oeste de la intersección.
- Presencia de edificaciones y multitud de servicios en el entorno.
- Altas intensidades de tráfico en la glorieta (IMD = 38.232 veh/día).
- Presenta iluminación.

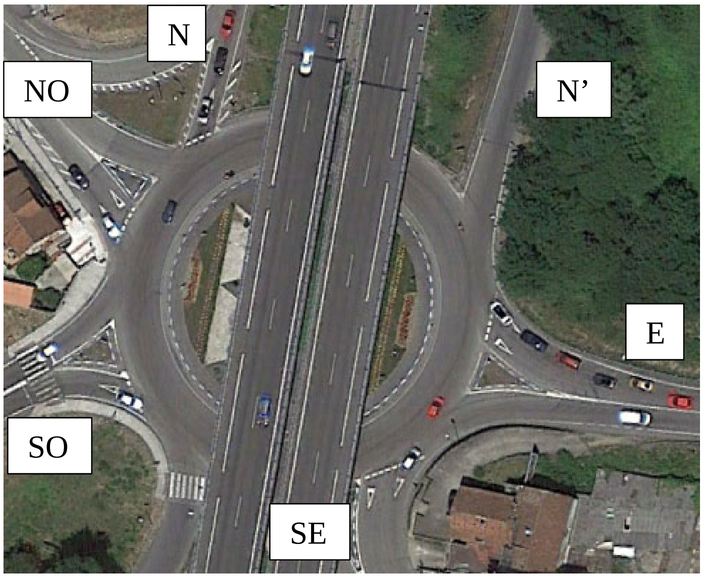

Fig. 1 Caso de estudio: glorieta multicarril con problemas de capacidad. Fuente: Google Earth.

La glorieta presenta problemas de capacidad, principalmente en las patas N y E (aspecto que se aprecie en la imagen satélite). Se plantea mejorar las condiciones de operación y el nivel de servicio a través modificaciones menores del diseño actual.

2.1 Datos de partida

2.1.1 Geometría

Se ha parametrizado la glorieta obteniendo todos los datos necesarios para la evaluación de la capacidad siguiendo el método clásico de Kimber (1980). Los valores se resumen en la siguiente tabla:

Entrada	v (m)	e (m)	l (m)	fi (g)	r (m)	D (m)
SE	6.43	6.93	0.00	21.0	18.9	64.0
E	4.08	7.29	5.70	36.0	17.7	64.0
N	4.15	4.15	0.00	31.0	12.0	64.0
NO	3.78	6.80	3.75	15.0	32.0	64.0
SO	3.78	4.86	4.56	19.0	20.0	64.0

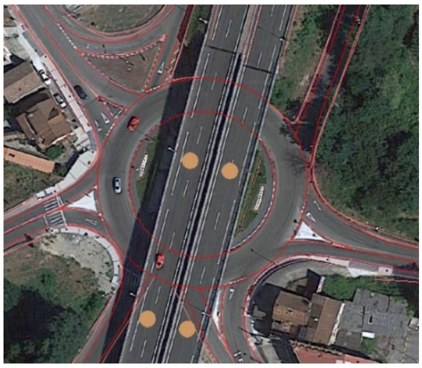

Tabla 1. Parámetros geométricos utilizados en el cálculo de capacidad.

Siendo:
v = la mitad de la anchura de aproximación.
e = anchura de la entrada.
l = longitud media efectiva del abocinamiento de la entrada.
fi = ángulo de entrada.
r = radio del borde exterior de la entrada.
D = diámetro del círculo inscrito.

Los círculos sombreados representan los apoyos de la estructura superior.

2.1.2 Tráfico

Se parte de un aforo de 16 h (entre las 6 h y las 22 h) realizado mediante cámaras de visión artificial en un día laborable de noviembre de 2018. No se pudieron obtener datos de accidentalidad.

2.2 Análisis de la situación actual

A partir de los datos registrados, y con la referencia de una estación permanente situada en las proximidades, se han obtenido las intensidades horarias IH-100 de vehículos totales en todos los movimientos:

	SE	E	N	NO	SO	
SE	46	170	16	149	326	706
E	74	0	562	282	152	1,070
N	120	169	26	59	302	676
NO	70	154	198	0	66	487
SO	232	273	192	0	0	696
	542	765	993	490	846	**3,636**

Tabla 2. Matriz origen – destino de intensidades IH-100.

Se consideró de acuerdo al aforo realizado un porcentaje de pesado del 6,5 %.

De los resultados del cálculo se concluye un funcionamiento deficiente, principalmente en dos entradas. Este aspecto se ha podido comprobar también en las visitas de campo.

	Ie (veh/h)	**Is (veh/h)**	**Qe (veh/h)**	**Qc (veh/h)**	**isat = Ie / Qe**	**NS**	
SE	707	542	1,424	1,012	0.50	A	Adecuado
E	1,070	766	1,072	953	1.00	F	Congestión
N	676	994	795	1,029	0.85	E	Saturado
NO	488	490	883	1,215	0.55	C	Adecuado
SO	697	846	976	857	0.71	B	Adecuado

Tabla 3. Resultados del cálculo de capacidad.

Donde:
Ie = intensidad de entrada.
Is = intensidad de salida.
Qe = capacidad en la entrada.
Qc = intensidad anular que corta dicha entrada.

Nivel de servicio global F. El trazado en planta es compatible con el paso de los vehículos más largos.

2.3 Propuesta de mejora

Debido a la configuración y el número de accesos lo ideal en estos casos es plantear dos glorietas, siempre que se garantice que las colas en la vía que conecta las glorietas no bloqueen las mismas. En el caso particular, dada su implantación en un medio urbano, no resulta factible debido al impacto en el entorno.

Por este motivo se plantea la mejora del diseño con medidas de menor entidad de manera similar a como lo han propuesto otros investigadores. McCulloch (2011) propone la mejora de la capacidad y de las condiciones de la canalización de los vehículos mediante la modificación de la señalización horizontal aprovechando el espacio generado en el diseño existente. Pochowski (2017) presenta la corrección de una glorieta multicarril en servicio con exceso de capacidad mediante la reducción del número de carriles. Para ello utiliza señalización horizontal. El efecto directo es la reducción del número de puntos de conflicto (aspecto muy favorable para la seguridad). En el trabajo de Gallelli y Vaiana (2019) se evaluó la transformación de la tipología de glorieta (de multicarril convencional a una turboglorieta) aprovechando el mismo espacio que la actual. La simulación resultó favorable en términos de capacidad y seguridad.

De manera particular para el caso de estudio, las correcciones de diseño que se proponen consisten en la mejora de las condiciones de las entradas con peor funcionamiento, las patas E y N, en base a la modificación de la geometría de los parámetros con mayor influencia: la anchura de entrada y la longitud media del abocinamiento. Además, se ha intentado facilitar la operación en el resto de accesos con una mejora de la canalización. Esto permite mejorar las condiciones de seguridad.

La estrategia, dadas las limitaciones de espacio, ha sido reducir la anchura de la calzada anular y el diámetro exterior, y aprovechar algún espacio adicional en las zonas sin servicios y edificaciones (espacio interior en las patas N y N'). La propuesta se puede observar en la siguiente imagen y se ha apoyado principalmente en las normas de diseño MF(2012), MF(2014) y MF(2016):

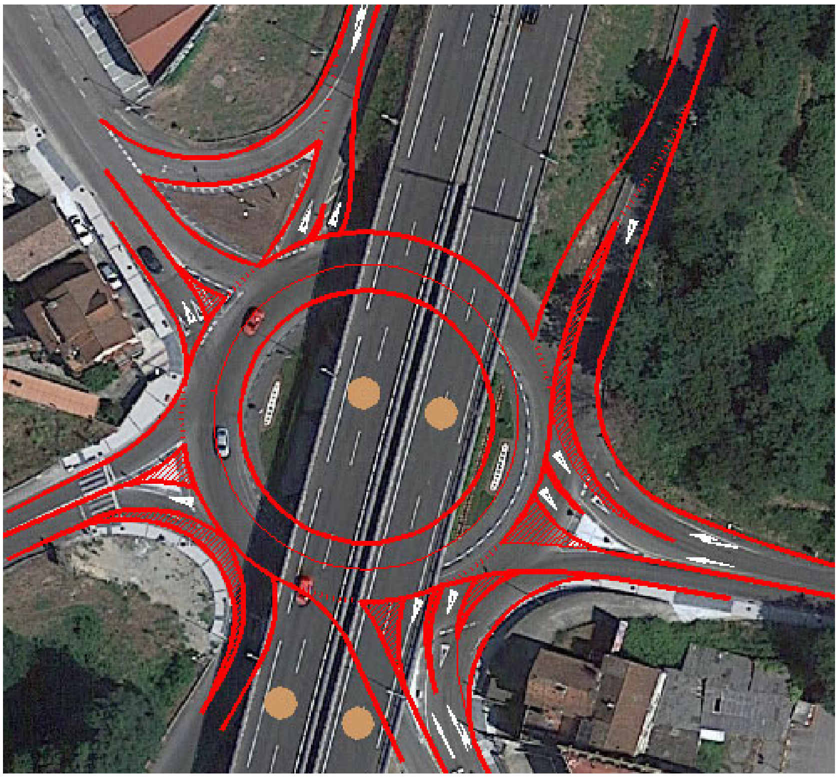

Fig. 2 Geometría de la propuesta de mejora.

Entrada	v (m)	e (m)	l (m)	fi (g)	r (m)	D (m)
SE	6.43	8.00	17.00	30.0	30.0	57.0
E	4.08	7.50	10.00	25.0	25.0	57.0
N	4.15	6.00	6.00	36.0	25.0	57.0
NO	3.78	4.50	4.00	27.0	17.5	57.0
SO	3.78	4.60	6.00	30.0	17.5	57.0

Tabla 4. Parámetros geométricos utilizados en el cálculo de capacidad.

El trazado propuesto no interfiere con ningún servicio y requiere adoptar nueva señalización en los accesos, principalmente en aquéllos que se han dotado con carriles segregados. Como se observa en la imagen el diseño es compatible con el paso de un vehículo articulado y, en la calzada giratoria, de manera simultánea con un turismo.

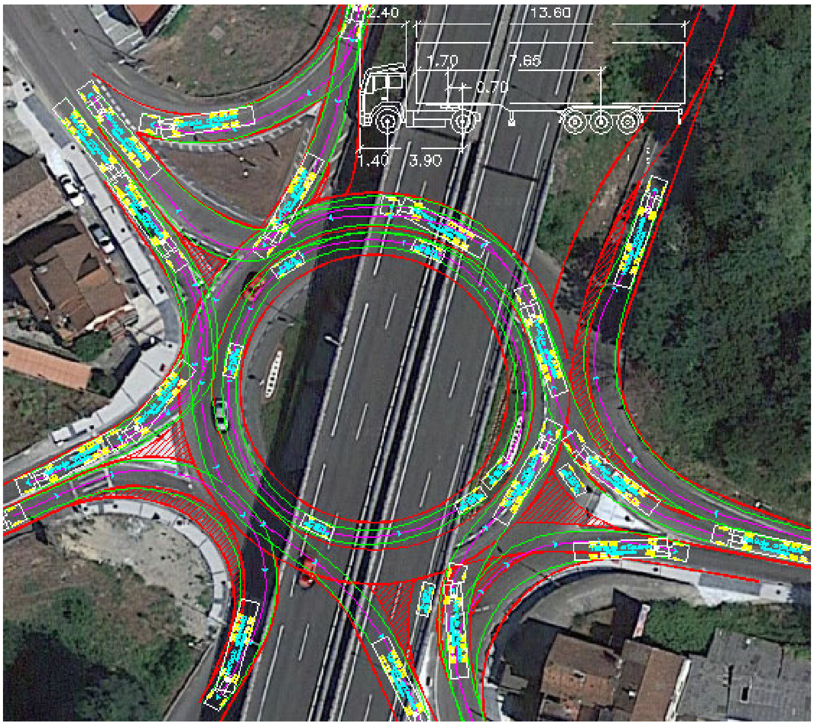

Fig. 3 Caso de estudio: comprobación de áreas barridas en la propuesta.

En cuanto a la capacidad, y como se observa en la tabla, el resultado es satisfactorio ya que los niveles de servicio se han mejorado notablemente. Un estudio de la evolución de la demanda de tráfico puede concluir hasta qué año el diseño podría mantenerse con unos niveles adecuados.

	Qe (veh/h)	**Qc (veh/h)**	**isat = Ie / Qe**	**NS**	**NS acceso**	
SE	1.510	1,012	0.35	A	A	Adecuado
SE (Bypass)	561	1,012	0.31	A		Adecuado
E	927	953	0.55	C	B	Adecuado
E (Bypass)	923	432	0.61	A		Adecuado
N	1073	1.029	0.63	C	C	Saturado
NO	822	1.215	0.6	B	B	Adecuado
SO	972	857	0.71	C	C	Adecuado

Tabla 5. Cálculo de capacidad en la propuesta de mejora.

Nivel de servicio global B.

3.GLORIETA INTERURBANA CON PROBLEMAS DE VELOCIDADES

3.1 Datos de partida

En el segundo caso se analiza una glorieta interurbana que resuelve la intersección entre una vía principal de doble calzada (carretera multicarril) y una secundaria (Fig. 4). Presenta las siguientes características:

- Elevadas intensidades de tráfico en la vía principal. Según los datos de aforos de una estación muy próxima, en el año 2018, se registró una IMD de 26.663 veh/d.

- La velocidad media en la vía principal de acuerdo a los datos publicadas por la Administración que gestiona la vía es de 79 km/h. Presenta una velocidad máxima señalizada de 80 km/h.

- A unos 300m, y en el movimiento norte – sur, se localiza un radar fijo de control de la velocidad.

- En los accesos de la vía principal se disponen bandas transversales de alerta (tipo resaltadas).

- Existe iluminación.

Fig. 4 Caso de estudio: glorieta multicarril con problemas de altas velocidades. Fuente: Google Earth.

3.2 Análisis de la situación actual

La problemática de esta glorieta se puede resumir en los siguientes puntos:

- No existe deflexión en el perfil de velocidades en los movimientos de paso por la vía principal (se puede cruzar mediante una trayectoria casi rectilínea). Esto genera altas velocidades en las entradas a la glorieta desde la vía principal (se recurre a un radar fijo) y, en consecuencia, un aumento de la probabilidad de accidente, tanto por pérdida del control del vehículo como por colisión con vehículos que circulan por la calzada anular durante la propia maniobra de entrada. Adicionalmente esta configuración puede provocar una pérdida de capacidad.

- No hay equilibrio en el número de carriles: accesos de uno y dos carriles y calzada anular de tres.

- La canalización de las trayectorias es inadecuada. Los movimientos de entrada y salida desde la vía secundaria se producen, observando las rodadas, hacia y desde el carril más interior (la salida desde el anillo debe hacerse desde el carril más exterior).

- La dimensión de los elementos no se ajusta a los movimientos reales de los vehículos. Como en el punto anterior, observando las rodadas de los vehículos, se pueden diferenciar amplias zonas de la glorieta que no son necesarias.

3.3 Propuesta de mejora

De forma general, en aquellos casos en los que se ha identificado una problemática similar a la del caso de estudio presentado, los investigadores han propuesto y analizado diferentes medidas con correcciones menores en el trazado y la señalización.

Price (2011) presenta varios casos en los que mediante ligeras correcciones de trazado se mejoran las condiciones frente al control de las velocidades y el guiado de los vehículos. Según la autora se deben evitar puntos angulosos en la delimitación de los bordes de calzada. A nivel normativo, cabe destacar la propuesta de la guía de diseño del estado de Queensland (Australia) (QDMR, 2006) para la mejora de la deflexión: ajuste de las dimensiones en las entradas de forma que se limiten las trayectorias de los vehículos más rápidos e imposición de curvas sucesivas de sentido contrario en las aproximaciones para favorecer una deceleración uniforme. Hu (2011) expone que, de acuerdo a las observaciones de campo, el 70% de los accidentes se producen en las entradas por lo que propone una serie de medidas para reducir la velocidad en las aproximaciones y mejorar la percepción de los carriles y la calzada giratoria. Estas se basan en la mejora de la señalización horizontal con marcas viales de selección de carriles, la señalización vertical y la implantación de reductores de velocidad y bandas transversales de alerta.

De manera particular para el caso de estudio, se realiza una corrección de la geometría de la aproximación en las dos entradas con problemas de velocidad. Además, se propone el ajuste de las dimensiones de la calzada anular y las patas para mejorar la canalización y el equilibrio de carriles. Se reforma la señalización horizontal y se aplican medidas complementarias de mejora de la señalización y el balizamiento como pueden ser bandas transversales de alerta, si se evalúa que no suponen afecciones sonoras a las viviendas del entorno. Para la definición de las marcas viales se sigue el criterio de la Guía de Nudos (MF, 2012) aunqueno es coherente con el actual Reglamento de Circulación.

En la siguiente imagen se muestra la geometría y las trayectorias más rápidas (en verde) en los accesos principales que puede establecerse siguiendo la metodología recogida en Rubio et. al 2019 y en Rubio (2017).

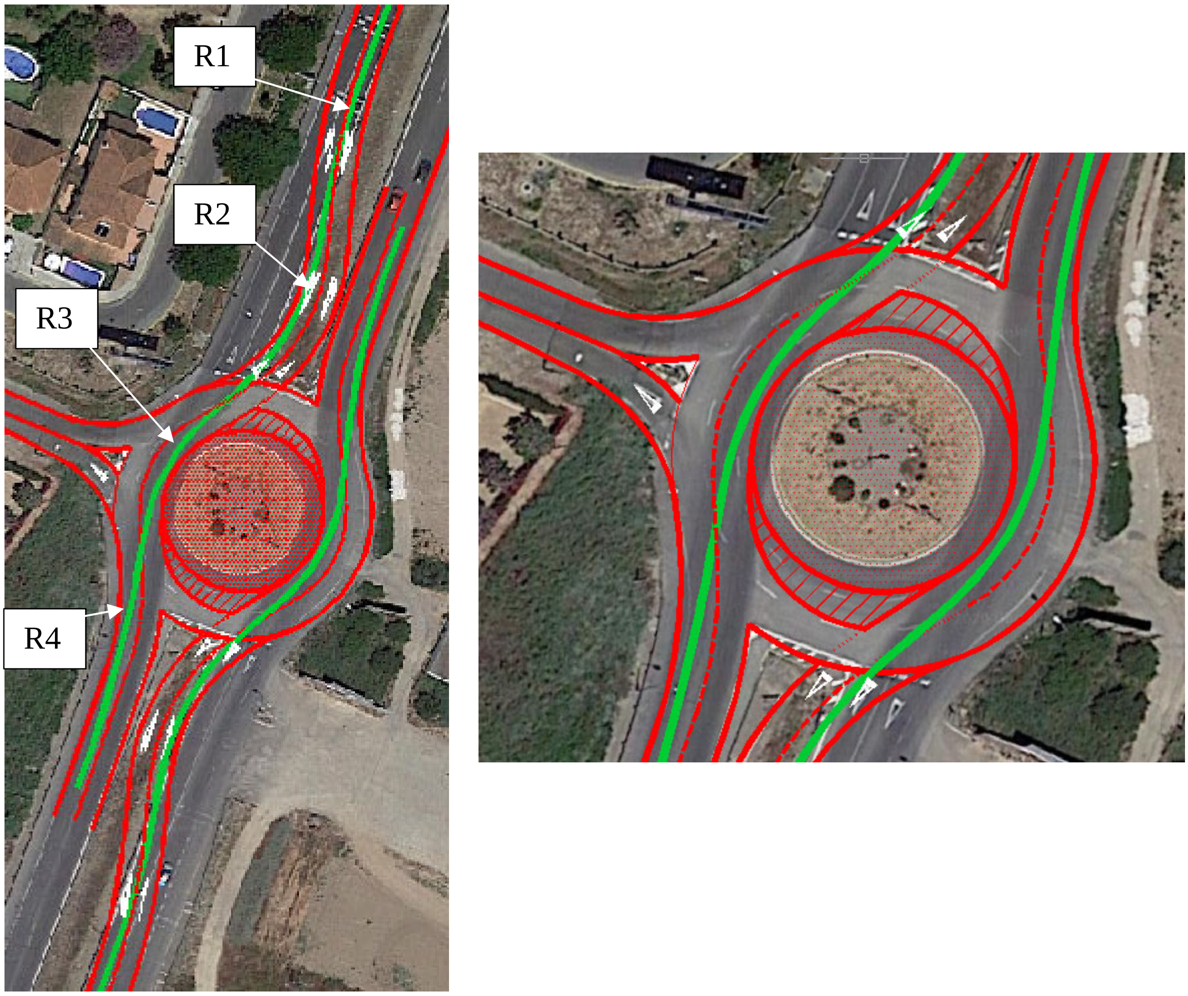

Fig. 5 Caso de estudio: glorieta multicarril con problemas de altas velocidades. Fuente: Google Earth.

Como se observa, la mejora del trazado en las aproximaciones permite el curvado de las trayectorias más rápidas y el descenso de las velocidades lo cual favorece la consistencia y, en definitiva, la seguridad viaria. El criterio que se ha seguido supone realizar una reducción gradual de la velocidad en la aproximación y hasta el paso por la calzada anular donde posteriormente se inicia la maniobra de aceleración hacia la salida. El resultado se considera satisfactorio como se puede concluir de los valores obtenidos, similares en ambas patas, y que se presentan a continuación:

- El primer radio de la trayectoria (R1) está en el orden de los 140m, luego se puede asumir una V_{85} de 55 km/h.

- El segundo radio de la trayectoria (R2) está en el orden de los 55m, luego se puede asumir una V_{85} de 35 km/h.

- El tercer radio (R3), en la calzada anular, está en el orden de los 35m, luego se puede asumir una V_{85} de 30 km/h.

- El radio de salida (R4) está en el orden de los 180m, y las velocidades dependen de la capacidad de aceleración de los vehículos.

Por tanto, con esta configuración se favorece la moderación de las velocidades y su consistencia.

4.CONCLUSIONES

En este trabajo se ha analizado el efecto sobre la circulación y la seguridad de la aplicación de mejoras de menor entidad en glorietas en servicio que presentan problemas de funcionamiento. Estas se han basado en el conocimiento y aplicación de los principios de diseño de glorietas y consisten fundamentalmente en la mejora del trazado y de la señalización y el balizamiento, de manera similar a como lo han propuesto otros investigadores.

El primer caso analizado se refiere a una glorieta multicarril implantada en medio urbano con problemas de capacidad. El conocimiento de los parámetros con mayor influencia en la operación de los tráficos ha permitido proponer una serie de ajustes en el diseño geométrico. Estos se han compatibilizado con el medio en el que se inserta la glorieta aprovechando los espacios anexos e interiores libres y minimizando de esta forma las afecciones. Los resultados del cálculo muestran una mejora significativa de los niveles de servicio y la sensibilidad del diseño al valor de la anchura de entrada, la longitud de abocinamiento y los carriles segregados de giro directo. Es conveniente en este caso y, en general, contrastar estos resultados con otros deducidos de un método de cálculo de capacidad diferente.

Por otra parte, los ajustes en la geometría permiten mejorar el guiado efectivo en las trayectorias naturales. La actuación se complementa con la mejora de la señalización y el balizamiento en coherencia con la nueva configuración que, en conjunto, proporcionan una mejor respuesta frente al condicionante de seguridad vial.

En el segundo caso se presentó una problemática diferente. La intersección de estudio es una glorieta multicarril situada en entorno interurbano con problemas de seguridad derivados de las altas velocidades de entrada en los accesos del eje principal. Como en el caso anterior, el conocimiento de los principios de diseño permitió enfocar la actuación que, en este caso, se basó en la modificación del trazado (curvado de las trayectorias) y la señalización (selección del carril en las entradas y la calzada anular). De manera adicional se modificó la sección transversal de la calzada giratoria proporcionando continuidad a los flujos y evitando afecciones en el exterior de la misma. Los resultados muestran que, en ambos accesos, se obtiene un perfil de velocidades similar en el que se observa una deceleración gradual hasta la llegada a la calzada anular. Así, el primer radio definido sitúa la velocidad para la trayectoria más rápida por debajo de 60 km/h y, para el segundo localizado de manera previa a la entrada a la calzada anular, por debajo de 40 km/h. En el perfil de velocidades original no existían restricciones (trayectoria más rápida casi rectilínea) más allá de la que prescribe la señalización vertical. El complemento mediante señalización y balizamiento permiten asimismo mejorar la percepción de la intersección y el guiado.

En definitiva, la aplicación de correcciones menores en el trazado y la señalización en glorietas con un impacto reducido en el entorno y en los costes se demuestra como una alternativa viable para la solución de determinadas problemáticas de funcionalidad y seguridad viaria.

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PROYECTO EMULCELL: NUEVAS EMULSIONES BITUMINOSAS FABRICADAS CON NANOCELULOSAS. RESULTADOS PRELIMINARES.

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RESUMEN

En la presente investigación se detallan los resultados de la investigación preliminar llevada a cabo en el marco del proyecto EMULCELL. Este proyecto nace con el objetivo de desarrollar nuevos tipos de emulsiones bituminosas mediante el empleo de nanocelulosas como agentes emulgentes. La finalidad de la presente investigación es la de minimizar los impactos ambientales asociados a la producción de este tipo de materiales de construcción y fomentar el uso de mezclas en frío, que presentan menores emisiones de gases de efecto invernadero y son de puesta en obra más sencilla y segura para los operarios.

Para llevan a cabo la presente investigación se ha utilizado un molino coloidal con el fin de fabricar diferentes emulsiones bituminosas, de tipo C60B5, pero sustituyendo parte del agente emulgente comercial por nanocelulosa. Con las emulsiones así fabricadas, se han llevado a cabo ensayos de envuelta con el fin de determinar la cantidad más adecuada de agua de envuelta y de comprobar la mayor o menor facilidad de estas emulsiones para recubrir toda la superficie del árido durante el proceso de fabricación de mezclas bituminosas en frío. Los resultados se han comparado con los obtenidos para una emulsión de control de tipo C60B5 comercial.

En general, cabe destacar la dificultad encontrada para obtener una emulsión catiónica. Finalmente, puede decirse que, en cuanto a envuelta, los resultados obtenidos son, en buena parte de los casos, similares a los obtenidos con la emulsión convencional. Sin embargo, se aprecia a simple viste una mayor cantidad de sedimento en las emulsiones fabricadas con nanocelulosa.

Por tanto, para obtener resultados concluyentes, se requiere profundizar en la investigación. En fases posteriores se realizará un detallado análisis de la sensibilidad al agua de las mezclas fabricadas con estas emulsiones, así como un análisis de su rigidez, deformación permanente y susceptibilidad térmica.

1. INTRODUCCIÓN

En 1997 se crea en Europa el Foro Alemán del betún, cuyos objetivos fundamentales eran aclarar los posibles peligros del betún y resolver problemas específicos de salud y seguridad de los trabajadores (Rühl y Musanke, 2006). También en 1997, se adoptó el Protocolo de Kyoto, cuyo objetivo fundamental era el de reducir las emisiones de gases de efecto invernadero (GEI) hasta los niveles de 1990 (Croteau y Tessier, 2008). La utilización de mezclas en frío claramente se encuentra alineada tanto con los objetivos del Foro Alemán del betún como con los del Protocolo de Kyoto.

El proyecto EMULCELL nace, por tanto, con esta doble motivación: reducir gases de efecto invernadero y favorecer la seguridad y salud de los trabajadores. Para ello, en el marco de este proyecto, se estudia la posibilidad de utilizar nanocelulosa como agente emulgente de emulsiones bituminosas para la fabricación de mezclas en frío mejoradas y más sostenibles. Esto permitiría sustituir agentes químicos comerciales por productos elaborados a partir de residuos de, por ejemplo, la industria papelera.

El mercado potencial de uso de estas nuevas emulsiones solo en España es enorme. Así, según datos del Ministerio de Transporte, Movilidad y Agenda Urbana (2018), solo la red de carreteras interurbanas de titularidad de los ayuntamientos tenía a finales de 2018 una longitud de 361.517 km. Son precisamente este tipo de vías secundarias, en las cuales las mezclas en frío presentan su mayor potencial de aplicación.

A nivel comercial, existe un derivado de la celulosa que se puede utilizar como agente emulgente de emulsiones bituminosas. Se trata de la carboximetilcelulosa de sodio (CMC) (Hou et al., 2019). Pero hasta la fecha no se han encontrado investigaciones relativas al empleo de nanocelulosa en emulsiones de este tipo.

2. MATERIALES Y MÉTODOS

2.1 Áridos

Como árido natural se ha utilizado una corneana, obtenida de la cantera de Astariz (Ourense), en la Comunidad Autónoma de Galicia. Sus principales propiedades pueden verse en la tabla 1.

Propiedad	Corneana
Índice de lajas (FI) según la norma UNE-EN 933-3	24 %
Partículas trituradas según la norma UNE-EN 933-5	100 %
Equivalente de arena (SE) según la norma UNE-EN 933-8 (0/2 mm)	61 %
Coeficiente de Los Ángeles (LA) según la norma UNE-EN 1097-2	14,2 %

Tabla 1 – Propiedades de los áridos

2.2 Nanocelulosa

En la presente investigación se han utilizado dos tipos diferentes de nanocelulosa: nanofibras de celulosa (NFC) y nanocristales de celulosa (CNC). Las propiedades de ambos tipos de nanocelulosa se incluyen en la tabla 2.

Propiedad	NFC	CNC
Densidad aparente	-	0,7 g/cm^3
Área superficial específica	-	400 m^2/g
Gramo de peso molecular	-	14.700 - 27.850
Tamaño de partícula	-	1-50 µm
Contenido de humedad	-	4 - 6 %
Densidad de cristalito	-	1,5 g/cm^3
pH(dispersión en agua)	-	6 - 7
Fuerza iónica	-	230 - 270 mol/kg
Viscosidad en agua (2%)	>20.000 mPas	-
Conductividad (2%)	<500 µS/cm	-
pH (2% en agua)	5 - 7	-
Capacidad de retención de agua	≥ 70 gH_2O/g	-

Tabla 2 – Propiedades de la nanocelulosa facilitadas por el suministrador

2.3 Agente emulgente comercial

Se han utilizado tres emulgentes comerciales de referencia: el Polybit QP-30 (de rotura lenta), el Polybit QPE-L (de rotura lenta) y el Prebit 100L (de rotura rápida). El primero está constituido por un polímero orgánico con grupos amino y propiedades tensoactivas con una dosificación recomendada entre el 2,5% y el 4,0%. El segundo está constituido por un copolímero orgánico con grupos amino y propiedades tensoactivas, con una dosificación recomendada de entre 0,8% y 1,2%. El tercero es un emulgente catiónico, líquido a 25ºC.

2.4 Betún

Para la fabricación de las emulsiones con nanocelulosa se ha utilizado un betún B160/220.

2.5 Emulsión bituminosa de control

Como emulsión de control se ha seleccionado una emulsión comercial C60B5 GE. Presenta un 59,8% de betún obtenido por destilación según la norma UNE-EN 1431. Su índice de rotura obtenido siguiendo la norma UNE-EN 13075-1 fue de 214, por lo que se trata de una emulsión de rotura lenta.

2.6 Fabricación de emulsiones bituminosas mediante molino coloidal

Con el fin de fabricar las emulsiones con sustitución parcial del agente emulgente químico comercial por nanocelulosa, se ha utilizado un molino coloidal emulsionador (Figura 1).

Fig. 1 – Molino coloidal utilizado

El procedimiento de fabricación utilizado se resume a continuación:

- Se calienta el B160/220 a 120ºC y se pesa la cantidad requerida.
- Se procede a constituir la fase dispersante: se pesa la cantidad de agua y emulgente requeridos y se mezclan a 60ºC con un agitador magnético. Finalmente, se ajusta su pH mediante la adición de HCl, hasta obtener un pH inferior a 7.
- Se acondiciona el molino coloidal a 80ºC.
- Una vez se tiene todo aclimatado a la temperatura de trabajo se introduce la fase dispersante en el molino coloidal, que trabaja a 3.000 rpm. Posteriormente se añade el betún paulatinamente de manera que el grosor del flujo no supere los 6 mm.
- Se abre la válvula de salida del molino para que fluya la emulsión bituminosa por el molino coloidal.

2.5.1 Ensayos de envuelta

El agua de envuelta es necesaria para la correcta dispersión de la emulsión durante la fase de mezclado de la mezclas bituminosa. Para determinar el contenido de agua de envuelta, se siguió la norma NLT-145. Se llevaron a cabo tanteos con diferentes contenidos de agua de envuelta. En concreto se probó con un 0%, 1%, 2% y 3% de agua de envuelta sobre el peso del árido seco. Además, para la totalidad de los contenidos de agua se analizaron dos contenidos de ligante residual: un 2,5% y un 3%. Para todos los casos se utilizó una mezcladora mecánica y una cantidad de árido de unos 500 gramos. El tiempo total de mezclado fue de 2 minutos: 1 minuto mezclando el agua de envuelta con el árido y, a continuación, 1 minuto mezclando la emulsión. Visualmente se determinó el contenido de agua más adecuado, como aquel que permite alcanzar un mejor recubrimiento de los áridos para ambos contenidos de ligante residual.

3. RESULTADOS Y DISCUSIÓN

3.1 Emulsión bituminosa de control

Como se aprecia en la figura 2, el agua de envuelta necesaria para la emulsión de control C60B5, se estimó en un 3%.

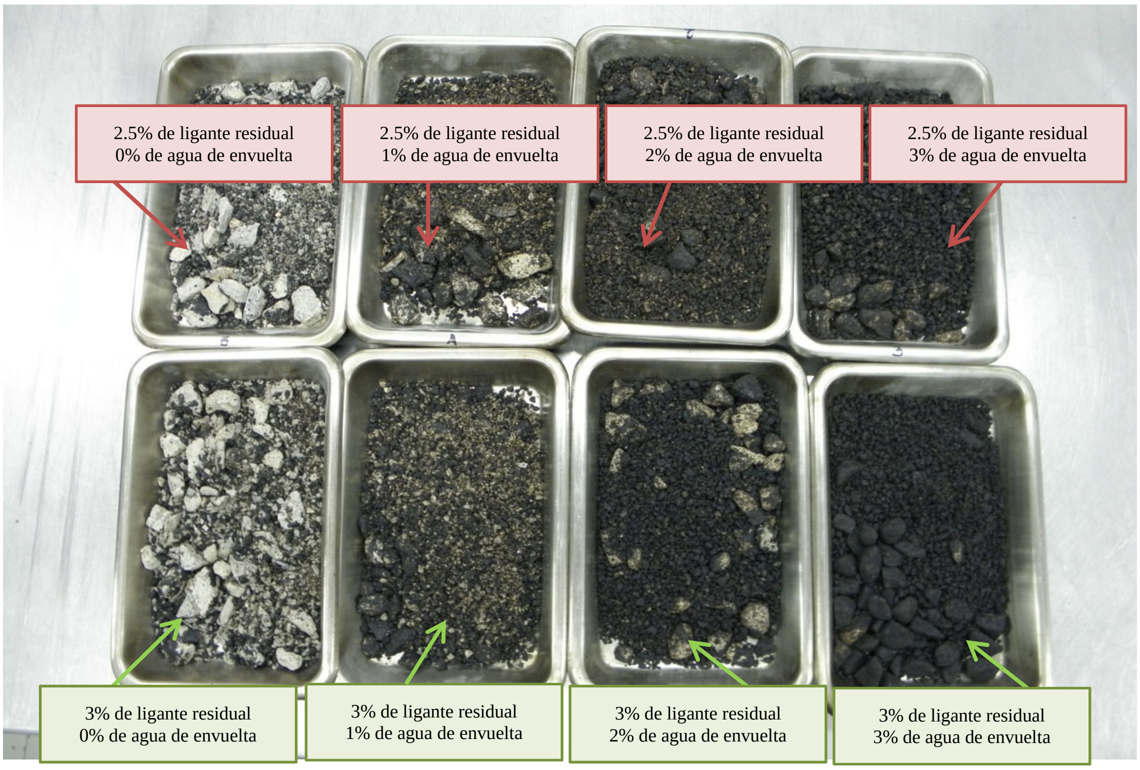

Fig. 2 – Análisis del agua de envuelta de la emulsión de control C60B5.

3.2 Emulsión con nanocelulosa

En laboratorio se hicieron diversas pruebas de fabricación con el molino coloidal de emulsiones tipo C60B5 utilizando los dos tipos de nanocelulosa (NFC y CNC) como sustitutos parciales del agente emulgente comercial. Durante la fabricación de las mismas se obtuvieron diferentes complicaciones. La primera de ellas es que, inicialmente, la emulsión obtenida al utilizar CNC como agente emulgente, resulta de naturaleza aniónica, cuando el producto buscado era una emulsión catiónica, más versátil para todo tipo de áridos y climatologías. Ese problema se intentó solucionar mediante la utilización de CNF y de otras nanocelulosas cationizadas. El segundo problema encontrado fue que realizar una sustitución total y elevada de emulgente comercial por nanocelulosa daba lugar a emulsiones con elevadas viscosidades, que llegaban a atascar el molino coloidal, lo cual hacía inviable su fabricación a escala de laboratorio. Para solventar este inconveniente se redujo el porcentaje de sustitución del emulgente comercial. Con todo ello, de entre todas las emulsiones fabricadas, finalmente llegó a analizarse la envuelta de un total de 8 emulsiones bituminosas con nanocelulosa:

- eNanocel-01: 0,4 % de CNC
- eNanocel-02: 1,2 % de CNC
- eNanocel-03: 0,8 % de CNC cationizada con Glycidyltrimethylammonium choride (GTMAC)
- eNanocel-04: 1 % de CNC cationizada con Glycidyltrimethylammonium choride (GTMAC)
- eNanocel-05: 0,4 % cationizada en origen.
- eNanocel-06: 0,4 % de CNC y 2 % de Polybit QP-30
- eNanocel-07: 0,6 % de CNC y 1 % de Polybit QP-30
- eNanocel-08: 0,6 % de CNC y 0,35% de Prebit 100L

En la figura 3 se incluyen los resultados de la emulsión bituminosa con nanocelulosa que aportó mejores resultados de envuelta: eNanocel-07. Como puede apreciarse, el 3% sigue siendo el contenido de agua de envuelta más adecuado. Además, los resultados arrojados por esta emulsión, son similares a los obtenidos para la emulsión de control.

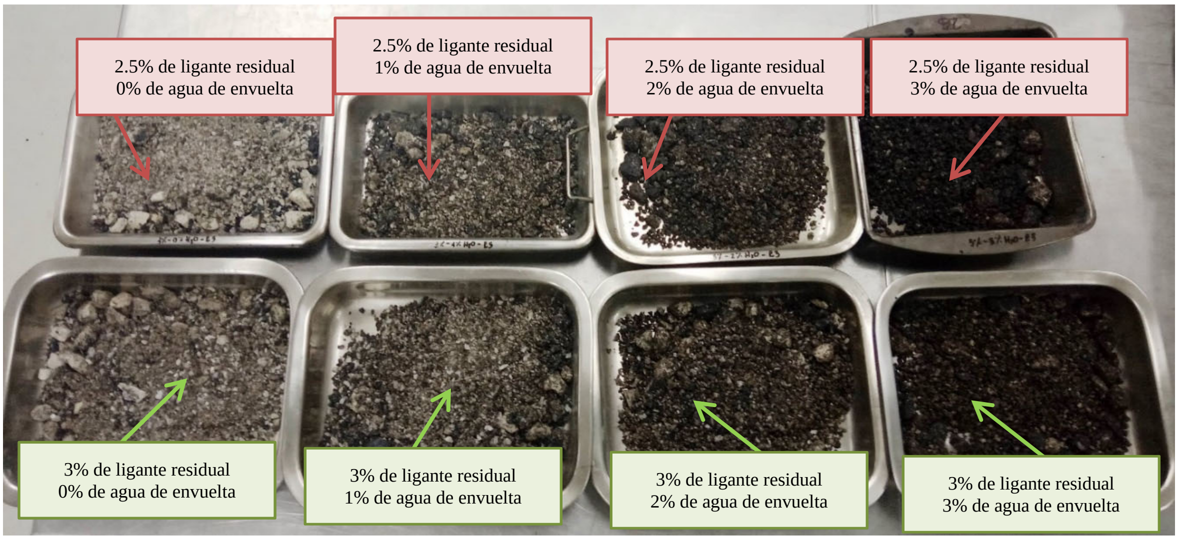

Fig. 3 – Análisis del agua de envuelta de la emulsión eNanocel-07.

Sin embargo, es preciso destacar que, como puede apreciarse en la figura 4, en la emulsión con nanocelulosa se obtuvo una gran cantidad de sedimento. Por ello, aunque los resultados obtenidos son alentadores, se hace preciso profundizar aún más en el análisis de esta nueva emulsión bituminosa. Particularmente mediante el análisis de sensibilidad al agua de mezclas en frío fabricadas con la nueva emulsión con nanocelulosa, así como el estudio de su rigidez y deformación permanente.

Fig. 4 – Sedimentos dejados por la emulsión eNanocel-07.

4. CONCLUSIONES

La dificultad de fabricar emulsiones bituminosas catiónicas de tipo C60B5 utilizando nanocelulosa como agente emulgente, ha quedado claramente patente con el análisis preliminar de laboratorio realizado para la presente investigación.
Sin embargo, tras una compleja investigación de laboratorio, se ha conseguido obtener hasta un total de 8 emulsiones con nanocelulosa como sustituto parcial del agente emulgente.

La que mejores resultados obtuvo en el presente análisis preliminar se dosificó con un 0,6 % de CNC y un 1 % de Polybit QP-30. Esta nueva emulsión arrojó resultados similares a la emulsión C60B5 de control en cuanto a agua de envuelta. Así, se estimó que un 3% de agua de envuelta es el contenido más adecuado.

La presencia de sedimentos apreciables a simple vista en la emulsión con nanocelulosa hace que sea necesario profundizar en el estudio de la misma antes de poder obtener una conclusión clara sobre su funcionamiento. En este sentido, se hace especialmente necesario analizar la sensibilidad al agua, rigidez y resistencia a la deformación permanente, de mezclas en frío fabricadas con esta nueva emulsión y comparar los resultados con los obtenidos para la emulsión de control.

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REVISION OF THE SPANISH QUALITY CONTROL PROCEDURE FOR ROFILLS AND RANDOM FILLINGS

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ABSTRACT

Infrastructure quality control must be done through an adequate control process, which must be well planned, programmed and executed. It implies the revision of the specific control procedures as part of the general objective of continuous improvement. It must be applied to the construction of quarries with stone materials, called rockfills for large sizes or random fillings for intermediate products. There continues to be a problem in terms of compacting control methods in the execution of these diggings, with little practical development of new techniques when the spread is of good – quality material an aspect that must be revised in order to ensure the quality of the final result extended and compacted. The current procedures for Quality Control in rock compaction have limited operability. For example, the granulometric analysis with macro-pits ($4m^3$) it is have done with heavy fractions, being a destructive testing. The average density control by nuclear methods has high heterogeneity, low performance and low thickness tested. The topographic measurement settlement is the most accurate, but it is a poorly referenced method. For the wheel impression test, the required values do not impose any limitation.

This research studies the application use to granites, slates and granitic alteration soils stabilized using cement. The necessary field and laboratory works were developed in order to elaborate new test procedures for a proposed compaction control in rocks. The compaction control procedures revised were wheel impression test, topographic settlement and plate load test (PLT). Doing simple regression on SPSS, in which any predictor outcome variable (dependent) should be placed (independent). An analysis of variance ANOVA shows the sums of squares and the degrees of freedom associated with each: is significant at $p < 0,05$. There is less than 0,5% chance that an F Levene – ratio this large would happen if the null hypothesis were true.

1. INTRODUCTION

Infrastructure quality control must be done through an adequate control process, which must be well planned, programmed and executed. It implies the revision of the specific control procedures as part of the general objective of continuous improvement.

The classical sense of road geotechnics implies that stone materials, with a high maximum size, were rejected. This meant that high quality materials were underused. Today, there is a less restrictive trend towards the use of materials to achieve the highest environmental efficiency. There is a need to review the quality control compaction at rockfills and random fills. Optimization of the compaction control means a reduction of the inspection times, adapting the quality to the high construction performance shown in figure 1.

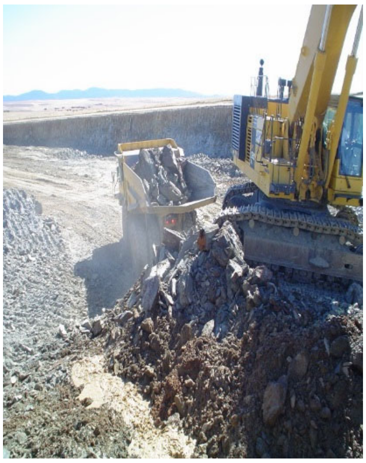

Figure 1. Rock diggings with high construction performance

This research is applied to the construction of quarries with stone materials, called rockfills for large sizes or random fills for intermediate products. With a high variety of rocks, this study has been particularized to granites rockfills, figure 2, and slates in random fillings.

Figure 2. Granitic rock excavation associated to rockfill

2. STATE OF THE ART

For Teijón-López-Zuazo et al. (2020), grading with pits, weighing different rock fractions presents a limited operability. The control of topographic settlements defined in the General Specifications for Roads and Bridges Works, PG-3 (2002), presents reference values and thresholds that are not very practical. The wheel impression test, UNE 103 407 (2005), usually complies. The plate load test, UNE 103 808 (2006), is only representative for plate load sizes five times the maximum of the aggregate.

There are limitations in the nuclear density methods UNE 103 900 (2013) due to the high particle sizes, the layer thicknesses to be tested, greater than 30cm, and the lack of reference in the Proctor test UNE 103 501 (1994). So, there continues to be a problem in terms of compacting control methods in the execution of rockfills and random fills, figure 3, with little practical development of new techniques when the spread is of good – quality material an aspect that must be revised in order to ensure the quality of the final result.

Figure 3. Execution of random fill

The French Standard includes in a more detailed way the use of rocky materials. Thus, the technical guide "Construction of embankments and esplanades" GTR (2003), published by the LPC (Laboratoire Central des Ponts et Chaussées), classifies within the group R_6 magmatic and metamorphic rocks (granites, andesites, gneisses, metamorphic schists and slates, etc.). The classification is made conforming to the values of resistance to fragmentation UNE-EN 1097-2 (2010), resistance to wear (micro-Deval) UNE-EN 1097-1 (2011) and dynamic fragmentation test, XP P 18-574 (1990). Sopeña (2007), with experimental sections, considers that the topographic settlement is the most important test in stone materials. It obtains graphically the number of passes from which the deformation ends, that is, the pass with which the stabilization of the settlements is reached, figure 4.

Figure 4. Topographic settlement control after roller pass

An example of other control techniques is the compactometer, Rahman et al (2012), which is used on the vibration equipment itself. These are the rollers with intelligent compaction (IC rollers). They have an accelerometer in the transducer and a measurer in the dashboard.

As a curiosity, as an example of the great possibilities of developing other techniques, space exploration has developed procedures to estimate soil density by remotely controlled drone raking from Earth. Gertsch et al. (2013) have deduced the density of the lunar soil raked with the raking force.

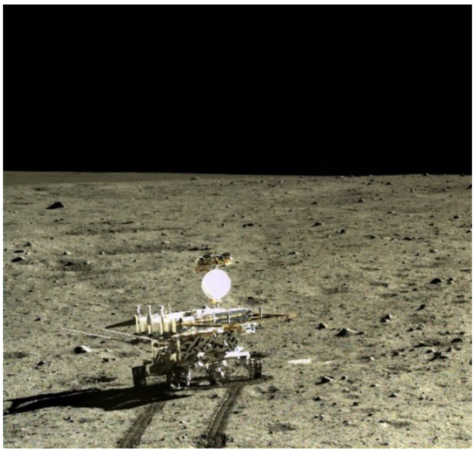

Figure 5. Lunar exploration (NASA)

Scale models with JSC-1a (artificial lunar regolite), have provided relationships between the density of the soil or regolite rock, the shale and the scarifiers of the ship.

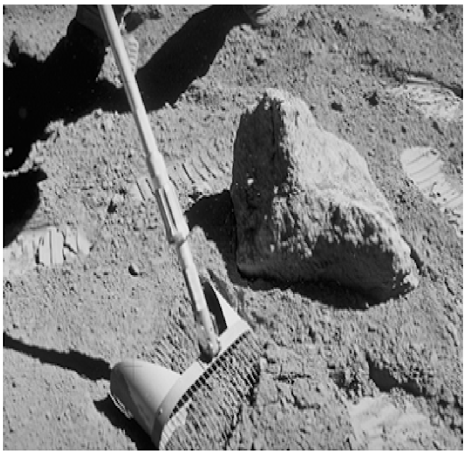

Figure 6. Apollo 16 photograph (NASA)

3. MATERIALS

The tests were carried out as part of the Quality Assurance Plan for the A-66 motorway on the Cáceres (N) - Aldea Cano section attached to the Ministry of Public Works, where were used granites, slates and slate alluvial materials. Table 2 provides a summary, including examples of the tests that were conducted on the slate alluvial material. The last row showing average values.

Ref.	# 100.0	# 20.0	# 2.0	#0.40	#0.08	LL	LP	IP	d (g/cm^3)	H (%)	CBR
CC-007	100.00	62.00	28.00	22.00	18.70	33.00	23.00	9.00	2.11	9.60	5.00
I-0933/04	100.00	68.00	33.00	20.00	17.10	39.00	28.00	10.00	2.08	7.20	21.00
I-0948/04	100.00	83.00	45.00	28.00	19.70	34.00	25.00	9.00	2.16	6.60	19.00
I-0932/04	100.00	70.00	52.00	26.00	20.30	35.00	24.00	11.00	2.08	7.90	14.00
I-0947/04	100.00	70.00	46.00	32.00	26.20	36.00	28.00	9.00	2.08	8.50	11.00
CC-018	100.00	37.00	15.00	10.00	7.80	32.00	24.00	9.00	2.13	7.80	11.00
CC-024	100.00	100.00	54.00	44.00	40.70	37.00	24.00	13.00	1.98	13.00	7.00
I-1018/04	100.00	72.00	43.00	30.00	20.50	27.00	22.00	5.00	2.12	6.90	25.00
Averages	100.00	70.25	39.50	26.50	21.38	34.13	24.75	9.38	2.09	8.44	14.13

Table 1. Examples of physical parameters for slate alluvial material identification

4. METHODOLOGY

Thus, the necessary field and laboratory works are developed in order to elaborate new test procedures for a proposed compaction control in rocks. Compaction control procedures revised: wheel impression test (figure 7), topographic settlement, plate load test.

Figure 7. Wheel impression test: passing over the alignment pegs

The revision to the wheel impression test (UNE 103 407) implies modifying several aspects, such as the marking with plaster by levelling picks, figure 8, going from 10 points aligned at 1 meter to 2 rows of 5 points spaced 10 meters. This means an increase in the test length from 9 to 40 meters. It also moves from initial leveling over land to over pikes. Instead of taking readings on a wheelbase, the two truck tracks are measured, figure 9.

Figure 8. Wheel impression test: leveling over pikes

Figure 9. Schematic diagram of wheel impression test

Another revised test is the topographic settlement control, as shown figure 10. A measuring reference has been changed from the first roller pass to the penultimate one.

According to results in experimental sections, the criterion of settlement between the first and last pass of less than 1% has not been accepted (for a thickness of 1m, admissible settlement 10 mm). It has been proposed as a measurement criterion the settlement between the penultimate and last pass of the compacting roller, which in case of rockfills, should be less than 5mm. The measuring system has been changed from being undefined to having levelling picks distributed in 2 rows of 5 points spaced 10 m.

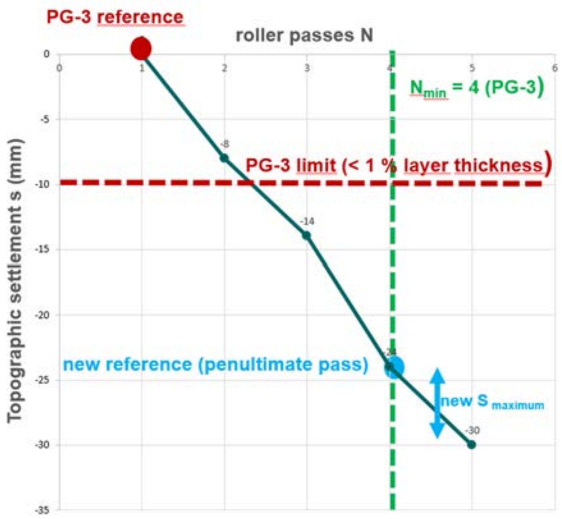

Figure 10. Revised topographic settlement test

According to the PG-3, the PLT test is representative when the plate diameter is at least 5 times the maximum size. This would result plates of 4300 and 2000 mm when the biggest standard size is 762 mm, figure 11. Traditionally the 300mm plate has been used, which gives positive results independently of the compaction conditions. It is more correct to use the 762 mm, which corresponds to the limit of manageability. It is proposed to review by size, using the Ø 762 mm plate in stone fillings and the Ø 600 mm plate in random fillings.

Figure 11. standard load plates (300, 600 and 762mm)

The PG-3 recommends not to use nuclear tests except when correlated with the sand method, although this test is also not representative for stone materials, figure 12. The determination "in situ" of density of soil by the sand method (UNE 103 503) is performed on soils with a maximum size of less than 5 cm and in a 15 x 20 cm sand hole when the maximum size is bigger than 30 cm. The Proctor test rejects the 20.0 UNE sizes, substituting them with fine particles: therefore, it is not representative for stone materials.

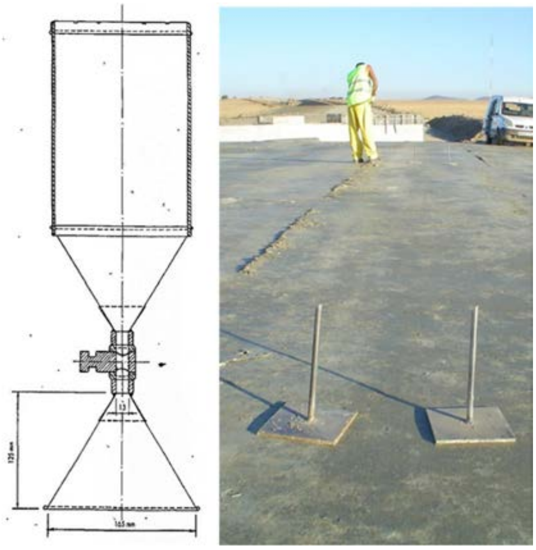

Figure 12. Sand method (UNE 103 503) and nuclear method for low depths

In PG-3, grain sizes are determined by pits, in the case of rockfills with a minimum volume of 4 m3 and a minimum surface area of 4 m2. In random fills, a minimum volume of 1 m3 and a minimum surface area of 1 m2 are required. These inspections are considered without practical use. Thus, the weighing of different fractions of rocks presents limited operativity. In addition, they are destructive tests, with minimum surfaces of 4 or 1 m2 of great difficulty of repair like located fillings. They also pose problems of safety at work, due to instability within the tasting walls.

This complex characterization is required on three processes: bench, spread and fill. PG-3 proposes to carry out a test section on stone materials and to establish a procedural control.

The revised procedure consists of fixing, from the test section results, the control parameters of the compacted layer.

5. RESULTS

The big number of compaction lots processed (450) made it necessary to classify them by material types: granites in rockfills and slates in random fillings. Finally, they have been subdivided by their use in core or crown. The general quality control specifications, that have been satisfactorily applied to the quality control, are shown in the table 2.

material	zone	N	GC (%)	h (mm)	s (mm)	PLT Ø (mm)	Ev_1 (MPa)	Ev_2 (MPa)	k
granite	core	5	---	≤ 4	≤ 5	762	≥ 50	---	< 3.2
	crown	5	98	≤ 3	≤ 5	762	---	≥ 120	< 3.6
slate	core	4	95	≤ 4	≤ 4	600	≥ 30	---	< 3.0
	crown	4	98	≤ 3	≤ 4	600	---	≥ 120	< 3.6

--- not applied

Table 2. General specifications

The variables have been entered into the IBM SPSS Statistics calculation program. An analysis of variance ANOVA shows the sums of squares and the degrees of freedom associated with each: is significant at p < 0,05. There is less than 0,5% chance that an F Levene – ratio this large would happen if the null hypothesis were true. A multitude of non-linear models have been analysed, although finally all the adjustments have been linear because no curve has been found that has significantly improved the adjustments.

As shown in table 3, an optimisation of the compaction control system has been achieved in rockfills and in random fillings, obtaining a reduction in the control time and a higher production rate.

material	zone	nuclear methods	wheel impression test	topographic settlement	PLT Ø(600mm)	PLT Ø(762mm)
granite	core			■		■
	crown	■		■		■
slate	core	■			■	
	crown	■			■	

■ significative test

Table 3. Optimisation of the compaction control system

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STUDY ON THE CONSERVATION OF BITUMINOUS MIXES IN HIGH MOUNTAIN ROADS AND COASTAL ZONES

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ABSTRACT

The main objective of road conservation is to maintain the characteristics of the platform elements to ensure that vehicle mobility is carried out comfortably and safely. The orographic conditions of Spain, with a large length of high mountain roads and others at sea level; and winter weather events, with low temperatures, wind, water, ice, snow,…, which cause deposits of particles, filler, soils, small metals, or sea salt on the pavement surface, can be dangerous in the circulation of vehicles.

One of the traditional methods for maintaining wheel-pavement adhesion is to apply flux products, mainly salt (sodium chloride, NaCl) and calcium chloride (Cl_2Ca), solidly or humidified (salt brine). This chemical fluxes have the property of preventing the formation of ice as antifreeze, or facilitating their melting if it has already formed.

This research studies the influence of salt in the surface layer of pavement made of hot mix asphalt with conventional binder. The effect of the salt is analyzed under three different conditions: immerse the specimens in salt water; add salt as aggregate in the manufacture of the mix; and submerging the natural aggregate in water with several amounts of salt, dry it and then manufactured the mixture with it. The mechanical parameters of the mixture have been analyzed in the laboratory: density, air voids, adhesion, indirect tensile strength and plastic deformation. To do this, Marshall test, Water Sensitivity Test (ITSR) and Wheel Tracking Test have been performed.

The properties of hot mix asphalt do not decrease significantly when it is manufactured of salt added as aggregate, neither when it is submerged in salt water. The bituminous mixture offers negative results when it is manufactured with natural aggregate submerged in water with salt previously, because the adhesion between the aggregate and the binder is low.

1. INTRODUCTION

The conservation of roads is defined by actions aiming at restoring the initial properties of the road, homogenizing the quality of the pavements, correcting construction mistakes and adapting pavements to new traffic loads, getting a comfortable and safe circulation.

Some conservation activities are intended for the maintenance of the road in the winter season, avoiding or eliminating the presence of snow or ice on the road surface, because they have direct influence on the circulation of vehicles. In other places, such as roads in port and coastal areas, actions are performed that protect or reduce the damage of the pavement by aggressive elements (seawater, soils, chemical elements, wastes, oils,..).

However, the construction and conservation of highways implies an environmental impact, mainly with the consumption of natural materials, or the modification of others, to improve the mechanic properties and durability of the pavements (Organisation for Economic Co-operation and Development 1997). This implies in a large investment in winter road viability. For example, in the winter road viability campaign 2015-2016, Spain's Ministry had 1334 snowplow machines, 240,877 tons of fluxes, mainly salt, and 36 emergency car parks on the State Road Network, which cost more than 65 million of euros (ACEX 2017).

Fluxes are products, natural or not, that have the property of preventing the formation of ice, lowering the freezing point of the water to temperatures below 0ºC, or melting it in case it is already formed. The most commonly used materials in road winter viability are sodium chloride (NaCl) and calcium chloride ($CaCl_2$), in solid form or in brine form (water with a dissolved salt concentration greater than 5 %). Magnesium chloride ($MgCl_2$) is also used, but less than the previous ones. In other infrastructures, such as ports and airports it is common to use acetates (calcium acetate – magnesium and potassium acetate) and urea, less aggressive with this type of roads, but its cost is higher.

When salt is spread over the surface of the icy or snowy pavement, the salt dissolves in the layer of water that covers the icy surface, but without incorporating into the ice. The effect is that the freezing temperature of the solution decreases by increasing with the amount of salt. However, this decrease stops from a certain concentration. There is a concentration called “eutectic”, from which the addition of salt does not decrease any more the freezing temperature. If this amount of flux is exceeded, the freezing temperature of the solution starts to rise again until it reaches 0ºC. In conservation activities the salt extends as brine; with a sodium chloride (NaCa) concentration of approximately 23.1%, in order to achieve an eutectic concentration, so that the road surface will not freeze, or it may melt ice if it already exists, up to a temperature of -21.1ºC. Below this temperature, the effect of the de-ice will be lost. In theory, the de-ice effect occurs up to the eutectic temperature, but it really is before, because there is an increase in time for salt to act, even depending on humidity (García 2010).

The reaction with salt is endothermic, needing an external supply of heat to be able to dissolve the salt in water. This heat is generated from the elements in contact with flux, pavement and air. If the existing temperatures are -5ºC, it may be necessary to apply a ratio of calcium chloride (approximately one third), which functions as exothermic agent, generating heat to dissolve the salt better. If the temperature is below -15ºC, sodium chloride loses its fluxing effect. Salt acts as a flux because it is hygroscopic, and reacts with humidity and atmospheric temperature from relative humidity of 75%. When a film of water is formed on the surface of the ice or snow layer, there is a contact with the salt and a heat transfer to the outside, resulting in a cooling of salt and water, theoretically until the temperature of this solution reaches the corresponding value of the saturated solution (-21.1ºC). The initial heat that melts the snow, allows the absorption of the cold of the salt, generating a heat of the condensation that is released, generating the defrosting process (ACEX 2017). When salt dissolves in water the sodium (positive) and chlorine (negative) ions are floating, and one attracts hydrogen and the other to oxygen, breaking the hydrogen bonds of water. The problem is that the brine absorbs humidity, dissolving more and more, forming a saturated solution, and therefore decreases its antifreeze capacity, favoring new layers of ice. Therefore, it is often necessary to extend new layers of brine.

There are also studies on the behavior that bituminous mixtures have when they are in contact with de-icing salt. A direct effect of salt on the surface of the road, is that it stiffens the bituminous mixture, decreasing the penetration of bitumen. When salt ions dissolve in water, sodium ion (Na+) is poorly reactive in bitumen, while chlorine ion (Cl^-) reacts with sulfur ions (S^-) that bind the different carbon chains of binders , so that ion (Cl^-) is introduced into these carbon bonds, rigidizing them and weakening bitumen, decreasing adhesiveness between bitumen and aggregate. Hassan et al. (2012) studied the mechanical properties of the bituminous mixes affected by different types of de-icing agents and freeze-thaw cycles. For the specimens submerged in salt water, observed an increase in indirect tensile strength respect the specimens submerged in distilled water for 25 and 50 freeze-thaw cycles. Giuliani (2012) or Zheng et al. (2015) studied different types of additives added to the asphalt mixture as aggregate, to avoid the formation of ice in the roadways, composed basically of salt (NaCl and $CaCl_2$).

Others studies are not based on the deicing salt due to winter road processes. Seawater is a salt water with a salt concentration of approximately 3.5%. Seawater freezing temperatures are lower than distilled water, and in coastal areas, salt can modify the mechanical properties of the bituminous layers of roads near the coast. Feng et al. (2010) studied the effect of the salt in asphalt mixtures with some specimens submerged in seawater and have remained under freeze-thaw cycles. They simulated it by adding salt to the bitumen and subjecting the specimens to freeze-thaw cycles. They concluded, for all mixes studied (AM-16, OGFC-19 and AC-16), a decrease in the indirect tensile strength ratio, more evident in the AM mixture and less in the AC mixture.

The purpose of this study is to evaluate the mechanical properties of asphalt concrete mixtures that have been submerged in saltwater, manufactured with salt (salt added as aggregate or as anti-icing additive), and manufactured with aggregates that had been submerged in salt water. The tests carried out have been density, air voids, indirect tensile strength (ITS), water sensitivity test (ITSR) and wheel tracking test.

2. MATERIALS

2.1 Aggregate

The aggregate used is ophite. Some properties of aggregate are:

- Density = 2.92 gr/cm^3.
- Los Angeles Abrasion Test (UNE-EN 1097-2: 2010) = 16.0%.
- Water Absorption (UNE-EN 1097-6: 2014) = 1.0%.
- Flakiness Index (UNE-EN 933-3: 2012) = 9.0%.

2.1 Binder

For this study, a conventional B 50/70 bitumen has been used for the bituminous mixes. Some properties are:

- Penetration (25ºC; 100g, 5s) (UNE-EN 1426:2015) = 65.0 dmm.
- Softening Point (UNE-EN 1427:2015) = 47.2ºC.
- Frass Breaking Point (UNE-EN 12593:2015) = -9.0ºC.

2.3. Salt and seawater

The density of salt used is 2.165 g/cm^3. Its content of filler (under 0.063 mm) is 6.6%.

The seawater used comes from the Bay of Santander (Spain) near the Maritime Museum of the Cantabrian Sea. This was filtered by a 50 µm sieve. It has a salt concentration of 3.5%, completely dissolved.

2.4. Asphalt concrete

The bituminous mix analyzed is AC-16 Surf B 50/70 D. It is normally used in the surface layer of the pavements. The composition for the mix is in Table 1.

Passing rate (%)									Asphalt s/m (%)
Sieve size (mm)	22.00	16.00	8.00	4.00	2.00	0.50	0.25	0.063	
	100.0	95.0	71.5	51.5	38.5	21.5	15.5	6.0	5.0

Table 1 – Composition of asphalt concrete (AC-16 Surf B 50/70 D)

The manufacture of the asphalt concrete is done in a mixer with vertical shaft and planetary rotation. First, the aggregate is introduced in it and the bitumen are added. The binder content is 5.0% s/m, by weight of the mixture. They are mixed for one minute. After, the filler is added and mixing continues for 3 minutes more.

Marshall samples were used to calculate the air voids of the mix (UNE-EN 12697-34:2013) and the water sensitivity test (UNE-EN 12697-12:2009), while for the wheel tracking test (UNE-EN 12697-22:2008) slabs of 50 mm were manufactured.

3. METHODOLOGY

3.1 Salt treatments

The effect of the salt in the asphalt concrete is studied in three different ways.

3.1.1. Specimens submerged in salt water

In this case, specimens of asphalt concrete are submerged in water with different concentrations of salt. The salt is completely dissolved.

The amount of salt by weight of water are based in the percentage of salt in seawater (3.5%), and two different contents (5.0% and 10.0%). The quantity, the temperature and time that the specimens are submerged in water varies according to the test conditions.

The series of specimens are:

- Series 0: Reference. They are submerged in distilled water and 0.0% of salt by weight of water.
- Series 11: They are submerged in seawater with 3.5% of salt by weight of water.
- Series 12: They are submerged in distilled water with 5.0% of salt added by weight of water.
- Series 13: They are submerged in distilled water with 10.0% of salt added by weight of water.

3.1.2. Salt added to the mixture as aggregate

In this case, salt is added into the mixer when aggregates and binder are being mixed. Salt is a new aggregate and it is not a substitute for any initial aggregate (Giuliani et al., 2012, or Zheng et al., 2015). When the mixture is being manufactured, salt does not dissolve in the binder.

The series of specimens are:

- Series 0: Reference. 0% of salt by weight of binder.
- Series 21: 5.0% of salt by weight of binder.

- Series 22: 10.0% of salt by weight of binder.
- Series 23: 38.0% of salt by weight of binder.
- Series 24: 95.0% of salt by weight of binder.

3.1.3. Aggregate saturated in salt water

The aggregate is submerged for 72 hours at 20 °C in water with different salt concentrations. It is enough time to saturate the aggregate. After, the aggregate is dried at 60°C for 24 hours. Then, the particles are heated to obtain the mixing temperature. The amount of salt by weight of water to saturate the surface of the particles are based in the concentration of salt in seawater (3.5%), and two different contents (2.0% and 5.0%).

The series of specimens are:

- Series 0: Reference. Aggregate is not submerged in water with salt.
- Series 31: Aggregate is submerged in water with 2.0% of salt by weight of water.
- Series 32: Aggregate is submerged in water with 3.5% of salt by weight of water.
- Series 33: Aggregate is submerged in water with 5.0% of salt by weight of water.

3.2 Laboratory tests

3.2.1. Density and air voids

Density and air voids percentage of the bituminous mix are obtained according to the Marshall Test (UNE-EN 12697-34, 2013).

Fig. 1 - Marshall Test

The specimens of asphalt concrete are compacted by 75 blows per side (Figure 1). The diameter of the specimens is 101.6 mm and the height is 63.5 mm height. The test is carried out with four specimens for each series.

3.2.2. Water Sensitivity Test (ITSR)

This test calculates the Indirect Tensile Strength Ratio (ITSR), to evaluate the adhesion between aggregate and binder, according to the procedure “Method A” of the UNE-EN 12697-12 standard (2009). The resistance to traction of the specimens kept dry (ITSd) and wet (ITSw) was obtained (Figure 2). The Indirect Tensile Strength Ratio (ITSR) was calculated by dividing (ITSw) between (ITSd). In Spain, the Spanish Standard requires an Indirect Tensile Strength Ratio of at least 85% for mixtures for the surface layer, tested at 15ºC (PG-3, 2008).

Fig. 2 - Indirect Tensile Strength Test

The dimensions of the specimens are the same than Marshall Test. They are compacted with 50 blows per side, as it is established by PG-3 (2008). Each group of samples was separated into two groups. One of the groups was kept for three days in a room at 20ºC and the other was submerged in water at 40ºC for three days after a vacuum treatment for 40 minutes. After three days, the mixes were put into a room at 15ºC for two hours prior to the test. Then, an indirect tensile strength test was performed on both groups of specimens, according to UNER-EN 12697-23 (2004), using a universal static machine.

3.2.3. Wheel tracking test

This test evaluates the plastic deformation of the mixture when a moving vertical load is applied on the surface of the specimens. This test was done for cases in which the ITSR result in the sensibility water test was closest to 85%, according to the Spanish Standard. The test is carried out in accordance with the standard UNE-EN 12697-22:2008, “Procedure B in air” and “Procedure B in water”, compacted by roller compactor (UNE-

EN 12697-33:2006+A1, 2007). The dimensions of the specimens are 410.0 mm length, by 260.0 mm width, by 50.0mm height (Figure 3). Two specimens of each series have been tested. In Spain, the Spanish Standard requires a Wheel Track Slope (WTS) in air, at 60ºC, between 0.07 - 0.10 mm/103 cycles depending on the heavy vehicles categories.

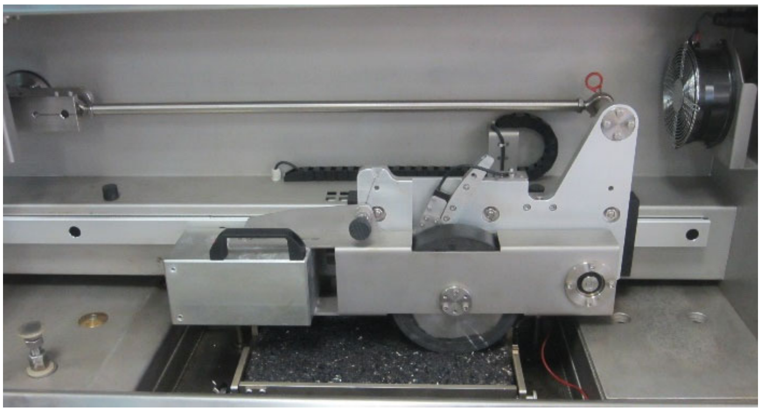

Fig. 3 - Wheel tracking Test

4. RESULTS

4.1. Density and air voids

The results of densities and air voids percentage obtained for AC-16 Surf B 50/70 D are shown in Table2.

Series		Air Voids (%)	Density (gr/cm^3)
Reference	A	6.1	2.51
Specimens submerged in salt water	11	6.1	2.51
	12	6.0	2.51
	13	6.4	2.50
Salt added as aggregate	21	6.0	2.51
	22	6.7	2.49
	23	6.6	2.49
	24	7.3	2.45
Aggregate saturated in salt water	31	6.5	2.50
	32	8.2	2.46
	33	6.4	2.50

Table 2 – Density and air voids content

The specimens submerged in seawater (series 11) or submerged in salt water with similar salt concentration than seawater obtained equals results than reference series A. Series 13, specimens submerged in salt water, with 10.0% of salt added by weight of distilled water, resulted with higher air voids content, and therefore, lower density.

For the second series, some differences appear when salt is added as aggregate to the bituminous mixture. When the salt particle content increases, the density of the mix decreases, and therefore, the air voids content increases. This happens when the salt modifies the particle size of all aggregates. Also, the density of the salt is lower than the density of the aggregate. The salt is added but it does not fill voids. Salt produces an increase in the total volume of the specimen and the air void volume increases.

For the third series, when only the aggregate has been saturated in salt water, small differences were observed. For a concentration of 3.5% of salt in water, the percentage of air voids is higher than the reference mixture; but the aggregate covered by salt does not modify the particle size of the mixture.

4.2. Indirect Tensile Strength and Water Sensitivity Test

The values of ITS and ITSR are in Table3.

Series		ITSd (kN)	ITSw (kN)	ITSR (%)
Reference	A	1687	1610	95
Specimens submerged in salt water	11	1687	1575	93
	12	1687	1636	97
	13	1687	1590	92
Salt added as aggregate	21	1595	1559	97
	22	1477	1493	101
	23	1625	1471	90
	24	1468	1432	98
Aggregate saturated in salt water	31	1595	1299	81
	32	1369	1040	76
	33	1544	1156	75

Table 3 – ITS and ITSR

For the first series, there is not significant variation between the specimens submerged in salt water and series A. The results of Indirect Tensile Strength Ratio fulfill the specifications of the Spanish standard, clearly above 85%.

For the second series, in which the salt is added as aggregate, the results of all ITS for dry and wet specimens are lower than ITS for the reference series. Anyway, the values of the all ITSR are very good and similar to the reference series, fulfilling the specifications of the Spanish standard. It could be caused by the fact that the asphalt concrete has more quantity of aggregates by the salt added to the mixer. The density of salt and its size are lower than the density and particle size of the ophitic aggregates, but filler/binder ratio of the bituminous mix is higher when salt is added. So, the Indirect Tensile Strength for wet specimens does not decrease as much as in dry specimens. In the case of a 10.0% of salt added by weight of binder the ITSR is greater than 100%.

The results for the specimens in which the aggregate is saturated in salt water are very low, and the ITSR values are below 85%. The Indirect Tensile Strength for wet specimens decreases significantly. In this case, the adhesiveness between aggregate and binder is affected by the salt that envelops the particles of the aggregate.

4.3. Wheel Tracking Test

For this test, one case of each salt treatment was selected in which the ITSR result in the sensibility water test was closest to 85%, according to the Spanish Standard. The test was carried out in air at 60ºC, and in wet.

The results of wheel track slope at 10000 cycles (WTS) and rut depth (RD) are presented in Table4.

Series		WTS (mm/10^3 cycles)		RD (mm)	
		In Air	In Water	In Air	In Water
Reference	A	0.08	0.07	3.2	4.0
Specimens submerged in salt water	13	0.08	0.05	3.2	2.3
Salt added as aggregate	23	0.07	0.07	3.2	3.7
Aggregate saturated in salt water	31	0.07	0.07	3.0	3.0

Table 4 – Wheel track slope and rut depth

All the values obtained are similar than series A, and wheel track slope comply the Spanish Standard for all heavy traffic categories. Salt does not affect the plastic deformation of the mixture.

5. CONCLUSIONS

The mechanical properties of a bituminous mixture AC-16 Surf B 50/70 D are not affected by salt dissolved in water with amounts similar to the concentration of salt in seawater, in high mountain and coastal roads.

When the asphalt concrete is submerged in salt water, density, percentage of air voids, adhesiveness between aggregate and binder, and plastic deformation resistance is maintained in the same conditions as the same mixture under non-aggressive environmental conditions.

The mechanical behavior of the bituminous mixture when the salt is added to the mix as aggregate is the best of all the treatments analyzed. The best results have been obtained with 10.0% of salt added by weight of binder. The density decreases by increasing the added salt, and filler/binder ratio is higher. Water does not worsen the characteristics of concrete asphalt when salt is added as aggregate.

The worst results have been obtained when the aggregate is previously saturated in salt water, especially for the water sensitivity. The salt creates a film around the surface of the aggregate particles, decreasing the adhesiveness.

No treatment affects the resistance to plastic deformations.

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TÉCNICAS DE APRENDIZAJE AUTOMÁTICO PARA LA PREDICCIÓN DE INTERVENCIONES DE MANTENIMIENTO EN INFRAESTRUCTURAS LINEALES DE CARRETERA

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RESUMEN

Las técnicas de mantenimiento predictivo persiguen disminuir la aparición de fallos imprevistos, y la ejecución de las intervenciones correctivas necesarias que deben llevarse a cabo con anterioridad a la aparición de los fallos.

Esta comunicación presenta una metodología, que permite automatizar la predicción de alertas de mantenimiento en infraestructuras lineales de transporte, aplicada al caso de una red de carreteras. Combina información cuantitativa del estado del activo junto con datos de las intervenciones de mantenimiento operativos e históricos, haciendo uso de técnicas de analítica de datos y modelos de aprendizaje automático.

Una vez los modelos se encuentran entrenados, se infiere el estado del activo en el escenario futuro de interés, y las tareas de mantenimiento necesarias para evitar una degradación posterior o desajustes de las condiciones de seguridad y/o confortabilidad. La metodología genera una lista priorizada correspondiente a las alertas generadas por todos los activos de la infraestructura monitorizada.

La parte científica de esta comunicación presenta: i) el análisis de la información mínima necesaria para obtener predicciones de alertas, y de las intervenciones de mantenimiento más probables asociadas a ellas en redes de carreteras; ii) el diagrama de flujo esquemático del conjunto de herramientas desarrollado para predecir alertas de mantenimiento; iii) el procedimiento metodológico utilizado, para activar alertas y predecir las intervenciones más probables, necesario para resolver estas alertas; iv) la metodología para determinar la fiabilidad y el nivel de severidad de alertas frente a falsos positivos y negativos.

La parte empírica del artículo recoge la descripción y resultados de un caso piloto de red de carreteras.

Finalmente, se extraen conclusiones sobre el enfoque del procedimiento propuesto y la capacidad predictiva alcanzada.

1. INTRODUCCIÓN

El mantenimiento predictivo de las infraestructuras de transporte lineales ha despertado un interés considerable en las dos últimas décadas. La importancia de impulsar el desarrollo de herramientas de predicción fiables, a fin de maximizar la disponibilidad de las redes de carreteras y ferrocarriles, y optimizar los recursos dedicados a mantenerlas en servicio, es de suma importancia socioeconómica. Actualmente, desde la faceta gerencial, varios códigos profesionales de administración de activos lineales (e.g. Bentley Exor, Bentley Optram, HDM-4, INFOR EAM, PAVER, PMS Core) incluyen aplicaciones que brindan algún tipo de capacidades predictivas sobre alertas y operaciones de mantenimiento, que facilitan ciertos niveles de predicción; aunque se echa en falta mayores esfuerzos y avances hasta su completa automatización y universalización.

En el ámbito del desarrollo de las técnicas de predicción del estado de activos, se produjo un gran salto en los años 1940-60 con la introducción del concepto de fiabilidad y el uso de técnicas estadísticas y de optimización (Dekker, 1996), que dio lugar al cuerpo de conocimiento del *Mantenimiento Centrado en la Fiabilidad* (Moubray, 1998), una de las herramientas más utilizadas en la actualidad. Un segundo salto hacia delante aparece, en la década de los años 80, con la analítica de datos computacional, que permite inferir modelos de estimación de la evolución del estado de activos y componentes (e.g. inteligencia artificial, sistemas expertos). Esto da lugar a la estructuración en un novedoso corpus científico (e.g. aprendizaje automático: ML) entre los años 1980 y 2000 y su más reciente popularización (e.g. minería de datos) ha suscitado un gran interés por predecir el estado de las infraestructuras lineales de transporte con el fin de establecer programas de planificación de las intervenciones y tareas de mantenimiento, de acuerdo con los recursos disponibles y el mínimo impacto en el funcionamiento de la infraestructura.

La detección de alertas de mantenimiento se basa, por lo general, en la inspección del estado de los activos mediante la visualización/auscultación/medición de las características explicativas del activo involucrado. La evolución de estas características, estimadas de manera cuantitativa o cualitativa, utilizando técnicas de proyección (e.g. regresión) o cualitativas (e.g. experiencia), y la verificación cruzada con umbrales y límites (definidos por estándares técnicos prescritos por la administración/regulador de la infraestructura correspondiente), ha sido la principal herramienta para prever los posible fallos o deficiencias en el funcionamiento de los activos.

Estos umbrales se basan en el conocimiento acumulado adquirido durante un período prolongado de tiempo, en relación con la adecuación del estado de los activos analizados, y responden a una envolvente conservadora que garantiza la seguridad, integridad y correcto funcionamiento del activo como parte del sistema en el que se integra. Con el fin de mejorar la capacidad "predictiva" de este procedimiento, se han considerado nuevas y adicionales características explicativas, unitarias o combinadas, que se han ido progresivamente incorporando, durante el pasado, a la lista de índices a monitorizar y medir. Sin embargo, la gran diversidad de factores que afectan a un determinado activo, en relación con su estado, hace poco probable que se prevea el caso ideal en el que cualquier estado/condición pueda explicarse de manera integral utilizando un conjunto fijo de características medibles y, como consecuencia adicional, obtener una estimación fiable de la evolución de su integridad u operatividad. Esta falta de determinismo se solventa, parcialmente, con el conocimiento histórico recogido por el equipo de mantenimiento.

Durante décadas, la construcción de modelos deterministas o probabilísticos basados en características explicativas apriorísticas (i.e. modelos empíricos-mecanicistas) ha sido la tendencia más acusada (e.g. Lytton, 1987; NCHRP, 2004; AASHTO, 2008; Mubaraki, 2010). En la actualidad, los desarrollos se han enfocado en sustituir esa forma de proceder por el modelado basado en datos, haciendo uso de técnicas de minería de datos y aprendizaje automático (e.g. Quinlan 1986; Schwartz 1993; TRB 1999; Dick et al.2003; Podofillini et al.2006; Iqbal 2010; Podder 2010; Witten et al.2011; Karlaftis et al.2015; Plati et al.2015), y apoyándose en la creciente disponibilidad de datos capturados de las actividades y campañas de auscultación/monitorizado. Estas técnicas inteligentes (i.e. automáticas y de minería) han promovido el concepto de aprender de los datos, facilitando la extracción de patrones y tendencias al "dejar que los datos hablen por sí mismos". El uso de estas técnicas, complementadas con la información histórica contenida en el repositorio de órdenes de trabajo, permite una rápida mejora de las predicciones.

En el ámbito de las infraestructuras de carreteras, desde la década de los 90s, la tendencia se ha enfocado en la predicción de la evolución del estado de determinados componentes usando técnicas ML y analítica de datos; tal es el caso de la predicción de los índices asociados al pavimento, (Attoh-Okine, 1994; Bosurgi & Trifiro, 2005; Gong et al., 2018), o al estado global de éste (Eldin & Senouci, 1995; Salini et al., 2015; Sollazzo at al., 2017). En relación con la estimación de las intervenciones de mantenimiento ha habido importantes avances (Hanna et al., 1993; Taha & Hanna, 1995; Alsugair & Al-Qudrah, 1998; Domitrovic et al., 2018; Roberts et al., 2021); referenciadas por diversas publicaciones sobre el estado del arte en esta temática (TRB, 1999; Flintsch & Chen, 2004; Ismail et al., 2009; Ceylan et al., 2014; Abambres & Ferreira; 2020; Karimzadeh & Shoghli, 2020).

Esta comunicación presenta un enfoque metodológico para la estimación y activación de alertas asociadas a activos de infraestructuras lineales de carreteras relativas a intervenciones de mantenimiento, sean correctivas o predictivas. Su objetivo final es disponer de un sistema de información basado en un sistema experto que respalda y automatiza la gestión de la infraestructura desde la auscultación hasta el mantenimiento utilizando un enfoque modular. Se basa en: i) un sistema de gestión de los datos asociados a las variables explicativas de los activos implicados; ii) un conjunto de herramientas de analítica de datos (i.e. cuantificación del estado de los activos, gestión de alertas) y un sistema de apoyo a la toma de decisiones que recibe los resultados de estas herramientas y optimiza las intervenciones de mantenimiento. Esta comunicación presenta avances en el marco metodológico y analítico, y se avala con resultados obtenidos en un caso piloto (Infralert, 2016, 2017; Morales et al, 2017, 2018, 2020; Reyes, 2018). Las alertas estimadas se evalúan, de acuerdo con la información que brinda el sistema de toma de decisiones, en base a la evolución del estado de los activos de interés, reflejado por sus variables explicativas (e.g. características físicas endógenas, variables exógenas), y la base de datos de intervenciones históricas. Los resultados inferidos proporcionan las alertas etiquetadas con un determinado nivel de severidad y una clasificación de todas las alertas en una lista jerárquica de intervenciones junto con sus probabilidades de incidencia. El objetivo final es facilitar la gestión de todas las intervenciones activas y previstas, optimizando las operaciones de mantenimiento.

2. INFORMACION RELEVANTE PARA EL PROCESO DE PREDICCIÓN

En el enfoque propuesto, las alertas se infieren correlacionando los valores estimados (proyectados) de las características explicativas ($X_{i1},\dots,X_{in}$) del estado del activo (A_i), en un escenario futuro de interés para el mantenimiento, con la información almacenada en el repositorio histórico de mantenimiento (RHM). En este proceso están involucradas dos fuentes de datos principales diferentes: i) mediciones realizadas en la infraestructura en la que se incluyen los valores de las características relevantes; ii) datos de mantenimiento histórico que almacena, al menos: a) cada una de las intervenciones realizada (incluyendo información cronológica/tipológica); b) cuantificación/valoración de las variables de estado/explicativas previas a la intervención. Esto hace que la activación de alertas se base no solo en la comparativa de los valores estimados de las características explicativas con sus umbrales preestablecidos, sino también en el uso de la información no explícita oculta en estas fuentes de datos, lo que puede explicar la intervención necesaria realizada en casos pasados. Este repositorio también puede contener información registrada, con respecto a la evaluación subjetiva, del estado del activo inspeccionado por el equipo de mantenimiento previo a la intervención realizada (e.g. la evaluación subjetiva de cada característica explicativa individual del activo [$SX_{i1},\dots, SX_{in}$], una característica explicativa combinada [CX_i] y/o una valoración global del estado del activo [G_i]).

Además, existen otras características (variables endógenas y exógenas) que afectan a la evolución del estado del activo. Éstas completan el conjunto de características explicativas a tener en cuenta en el enfoque de intervención predictiva (e.g. flujo de tráfico, categoría de la infraestructura).

3. PROCESO METODOLÓGICO

El marco general propuesto se esboza en la Figura 1 donde se muestran diferentes módulos (que incorporan técnicas, metodologías, algoritmos y modelos) y sus interacciones, entradas y salidas. El enfoque tiene como objetivo estimar y priorizar las alertas de mantenimiento y predecir las intervenciones necesarias. En particular, se consideran dos tipos de alertas en la metodología propuesta: i) las desencadenadas por la desviación de los indicadores asociados a la calidad/estado de un activo establecido por la normativa vigente (e.g. europea, administración/gestor de la infraestructura), y ii) los índices cuantitativos que se infieren al correlacionar la información registrada de intervenciones históricas.

El Módulo AM1 (*Pre-alerts base on limits*) se encarga de generar pre-alertas basadas en límites, desde el punto de vista de aquellas características que superan sus umbrales asociados, utilizando como datos de entrada los valores pronosticados de las características explicativas del activo. El objetivo de este módulo es comparar el valor de cada característica prevista con el umbral correspondiente (según los parámetros de diseño/calidad/seguridad) para cuantificar el estado del activo. Como resultados, se proporcionan las siguientes salidas: i) Pre-alertas (*Warnings*) que indican que una característica específica excede su umbral prescrito, y ii) niveles de severidad técnica (*Technical Severity Level* TSL) de las pre-alertas estimadas. El TSL es un valor objetivo que se utiliza para priorizar las pre-alertas (e.g. en función de un criterio de distancia entre el valor de las características y los umbrales). El módulo AM2 se encarga de predecir alertas basadas en órdenes de trabajo (WO), desde el punto de vista de requerir una acción de mantenimiento (Sí/No); también estima las operaciones de mantenimiento necesarias más probables. Para lograr esto, el módulo incorpora dos submódulos funcionales diferentes. El primero (AM21) está específicamente dedicado a activar alertas atendiendo a la necesidad de mantenimiento (Sí/No) y su correspondiente nivel de severidad técnica global (*Global Technical Severity Level* GTSL) cuantificada en términos de todas las características previstas consideradas en su conjunto. El GTSL se infiere en función de todos los TSL de las características explicativas correspondientes $X = \{X_1, X_2, \ldots X_n\}$, previamente normalizadas (referidas a la misma escala) y ponderadas por valores preestablecidos α_i a cada característica individual X_i (sujeto a restricciones de ponderación unitaria $\alpha_1 + \alpha_2 + \ldots + \alpha_n = 1$). Aquí, las alertas son activadas por el estimador contenido en el primer bloque (*Alert Estimator*), que ha sido previamente entrenado con la información adecuada mediante un procesamiento de aprendizaje automático. El segundo submódulo (*Maintenance interventions* AM22) tiene como cometido la estimación de la tipología de intervenciones de mantenimiento más probables (ver Sección 3.2).

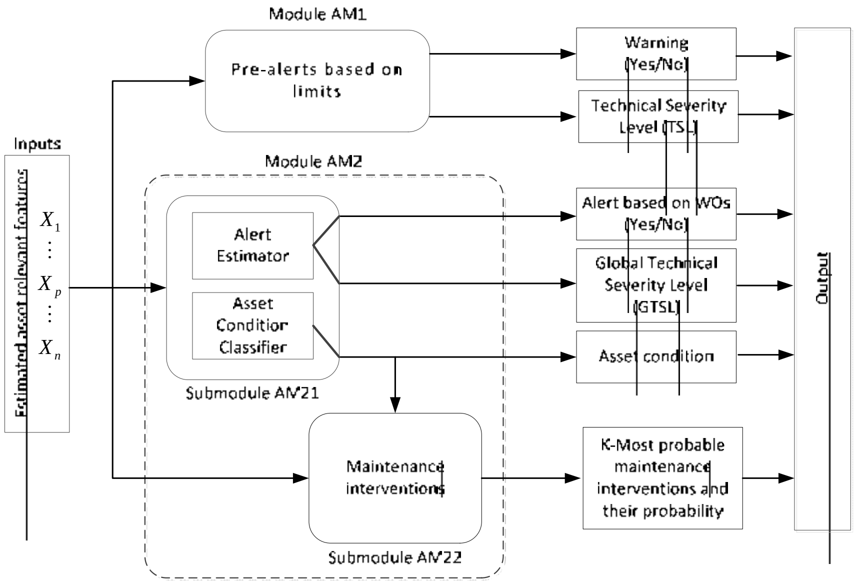

Figura 1. Marco metodológico

3.1 Proceso de aprendizaje y predicción de alertas

La metodología de aprendizaje, representado en la Figura 2, consiste en una clasificación automática basado en variables binarias (1-0: Sí/No). Se ha considerado un conjunto de cuatro modelos de clasificación binaria automática (i.e. árbol de decisión DT, red neuronal artificial ANN, vecinos más próximos KNN-K, máquina de vector soporte SVM).

De entre los cuatro modelos que se ensayan queda seleccionado el que proporciona las mejores capacidades predictivas. El submódulo AM21 también proporciona una salida opcional utilizando un segundo bloque (*Subjective asset condition* en la Figura 2), que "aprende" del conocimiento del RHM, con el propósito final de predecir una evaluación subjetiva del estado del activo (a partir del conjunto de características pronosticadas).

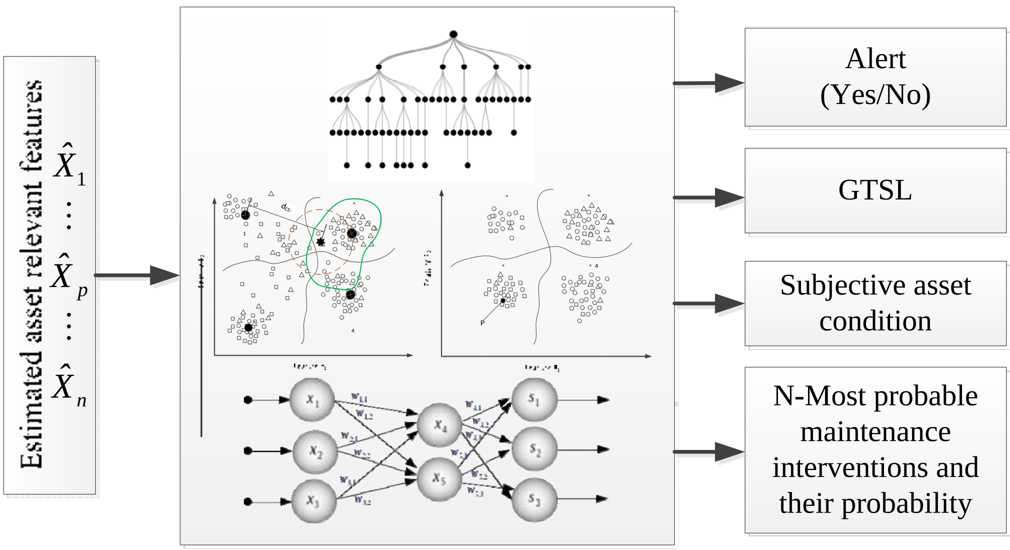

Figura 2. Esquema del proceso de aprendizaje y predicción

3.2 Proceso de predicción de tipo de intervenciones de mantenimiento

El segundo submódulo (AM22), Figura 1, tiene como objetivo determinar el conjunto de las k-intervenciones de mantenimiento más probables que deben realizarse, así como sus correspondientes probabilidades de incidencia, mediante un procedimiento de aprendizaje basado en datos de la base histórica de intervenciones. Para estimar el tipo de intervención más probable, en un activo específico, de acuerdo con el conocimiento contenido en la base histórica, se debe iniciar un proceso correlacionando los valores estimados de las características explicativas relevantes ($\hat{X}$) y el estado subjetivo pronosticado ($S\hat{X}, C\hat{X}, \hat{G}$) proporcionado por el submódulo AM21; este proceso hace uso de muestras de activos similares reportadas en el repositorio histórico; las predicciones del tipo de intervención se basan en un esquema de aprendizaje automático no supervisado que utiliza técnicas de agrupamiento y k-vecinos. Como resultado, el módulo AM2 proporciona: i) alertas activadas que identifican aquellos activos donde se requiere mantenimiento; ii) nivel de severidad técnica global (GTSL) de esos activos; iii) K-intervenciones previstas más probables asociadas a cada activo y alerta activada; y iv) probabilidades de incidencia de las intervenciones más probables.

4. REGLAS DE AUTOAPRENDIZAJE AUTOMÁTICO

Dado que el enfoque se basa en técnicas de aprendizaje automático, se encuentran definidas un conjunto de reglas de autoaprendizaje para mejorar las capacidades predictivas. Esta sección se centra en la metodología utilizada para discernir las predicciones de “falsos positivos” y “falsos negativos”, de acuerdo con las siguientes reglas:

- Un falso positivo surge cuando una estimación (derivada de los modelos) indica que se ha alcanzado un estado determinado, cuando no es así. Este caso se considera como una "falsa alarma", valorándose como caso positivo erróneo.
- Un falso negativo aparece cuando una estimación indica que no se ha detectado ninguna alerta (i.e. el estado previsto del activo es correcto), mientras que posteriormente tuvo que realizarse una intervención de mantenimiento correctivo; por lo que el pronóstico de fallos era erróneo.

La Figura 3 esboza una descripción del modo de proceder que debe seguir el equipo de mantenimiento cuando se comunica una alerta activada; incluyendo la información necesaria a registrar en la base de datos. Esto puede tener una causa "correctiva" o "predictiva". El caso de intervención preventiva no se tiene en cuenta en este documento, ya que sigue un plan predefinido y con reglas específicas. De acuerdo con esto, todos los datos registrados tienen asociado un campo de marca cronológica para identificar el instante en que se tomó cualquier decisión/acción (cuando la alerta se considera como “no atendida”, “atendida” o “intervenida”).

Los casos falsos pueden surgir cuando las estimaciones incorrectas se deben a: i) predicción incorrecta de una característica, ii) predicción incorrecta para solicitar mantenimiento (Sí/No), iii) predicción incorrecta del tipo de operación de mantenimiento requerido. En los siguientes párrafos se presenta una descripción gráfica de los casos.

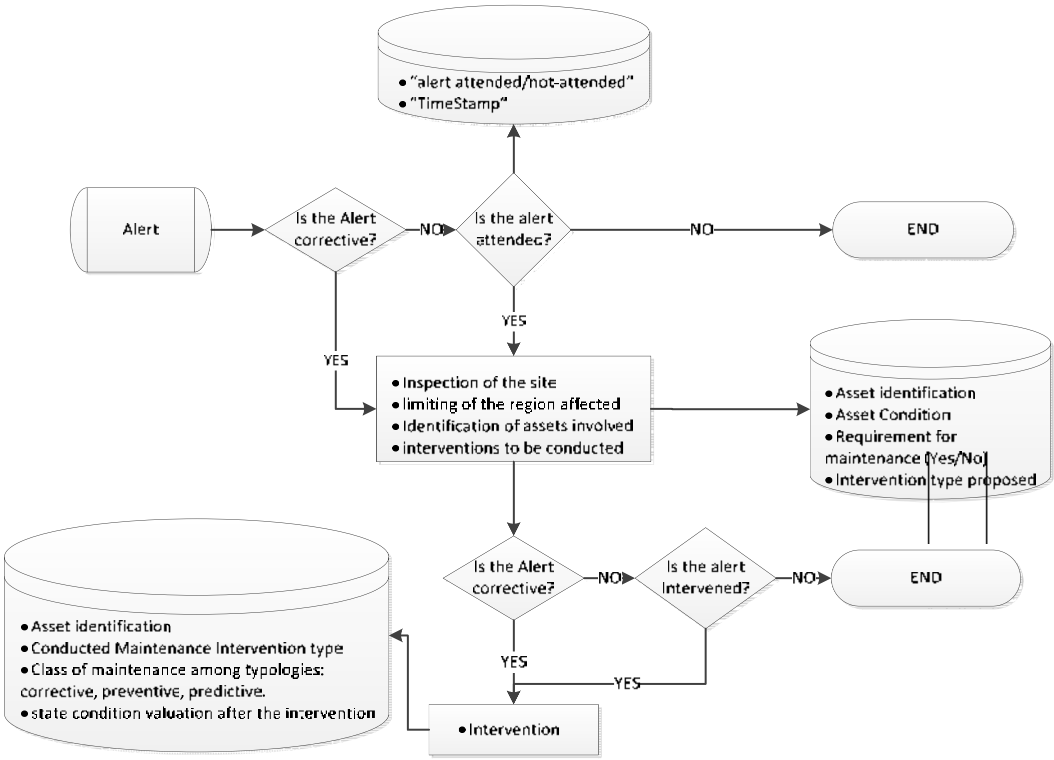

Figura 3. Diagrama de flujo del procedimiento de verificación y activación de alertas

4.1 Predicción incorrecta de una característica

Se analizan por separado dos posibles casos, falso positivo y falso negativo:

- i) Falso positivo. Tiene lugar cuando la alerta se activa por el valor esperado de una característica (individual, combinada, o multiplicidad de características), debido a la predicción incorrecta de los valores de las características. El procedimiento de alerta activada, puesto en marcha por el Equipo Gestor del Mantenimiento (EGM), finaliza con la evaluación de todos los activos implicados en la alerta y con el registro de información sobre el estado de dichos activos. La nueva información enriquecerá la base de datos (RHM) correspondiente al estado de los activos involucrados. El procedimiento de aprendizaje automático aprenderá de la información enriquecida de la base de datos, mejorando la tasa de éxito de acuerdo con la calidad de la información capturada en más ejecuciones de predicción.
- ii) Falso negativo. Surge cuando el valor esperado de las características (única, combinada o multiplicidad de características) está por debajo del valor que tendrán y también cae por debajo del umbral TSL. En este caso, el procedimiento de activación-de-alerta no se activa y no se predice ninguna alerta. Eventualmente, puede aparecer una advertencia correctiva y activarse el procedimiento de activación-de-alertas, que registrará la información identificada en la Figura 3.

4.2 Predicción incorrecta de incidencia de mantenimiento

Al igual que en el caso anterior, se analizan los casos de falso positivo y falso negativo:

- i) Falso positivo. Esto ocurre cuando el submódulo AM21 predice la necesidad de mantenimiento y se activa una alerta. Este caso sigue un patrón similar al caso (i) de la sección 4.1. El procedimiento de ML se mejorará de acuerdo con el enriquecimiento de la base de datos.
- ii) Falso negativo. Esto ocurre cuando el submódulo AM21 no detecta la necesidad de mantenimiento y no se activa ninguna alerta. Este caso sigue un patrón similar al caso (ii) de la sección 4.1.

4.3 Predicción incorrecta del tipo de mantenimiento

En este caso, se supone que la solicitud de mantenimiento se estima correctamente como positiva, de lo contrario el procedimiento vuelve a la sección 4.2. Solo es posible la predicción general de "tipo falso de mantenimiento ":

- Tipo falso. La alerta se ha activado debido a una solicitud de mantenimiento (submódulo AM21) y se proporciona un tipo de intervención de mantenimiento estimado. El EGM activa el procedimiento de *Alerta-activada* y el equipo de intervención de mantenimiento evalúa los activos implicados. El equipo detecta que el tipo de mantenimiento estimado no corresponde al tipo previsto, y que se ha realizado una predicción incorrecta del tipo de mantenimiento por parte del submódulo AM22. Se continúa el procedimiento de *Alerta-activada*, actuando de acuerdo con las acciones especificadas. La información capturada por este procedimiento (que refleja todos los presentados en la Figura 3) se registra en la base de datos RHM, lo que enriquece la información almacenada. Las estimaciones posteriores de los algoritmos ML se verán beneficiadas por la nueva base de datos enriquecida.

5. CASO PILOTO

Para el caso piloto se ha elegido una subred de carreteras de la zona centro de Portugal, con una extensión de 620 km, gestionada por *Infraestruturas de Portugal*. La información disponible consta de dos bases de datos: 1) la primera corresponde a los resultados de diferentes campañas de medición en las que se obtienen características representativas del estado de la vía; 2) la segunda recopila las intervenciones históricas de mantenimiento realizadas en la red en las últimas cuatro décadas. Al correlacionar ambas bases de datos se infieren las entradas y los objetivos para los modelos de aprendizaje automático. Sin embargo, los datos registrados se han filtrado previamente para extraer la información relevante que utiliza el sistema antes de activar toda la metodología predictiva de mantenimiento.

Con la información disponible para el caso piloto, los modelos se han implementado computacionalmente usando las técnicas de árboles de decisión (DT), k-vecinos más próximos (KNN), máquinas de vectores soporte (SVM) y redes neuronales artificiales

(ANN). Para comprobar la precisión de esos modelos, el conjunto de datos de los últimos años se ha dividido en tres subconjuntos: a) datos de entrenamiento y testeo, b) datos para predicción, c) datos de las operaciones de mantenimiento reales llevadas a cabo en los tramos usados para la predicción. El primer subconjunto se ha utilizado como base de datos para detectar la técnica de aprendizaje automática más adaptada a la naturaleza de los datos e información disponibles, manteniendo ésta fuera del conjunto de datos utilizados para predicción. El segundo subconjunto de información se ha focalizado en los datos existentes de las variables explicativas de los tramos (no incluidos en el conjunto de entrenamiento y testeo), para los que se conocía las operaciones de mantenimiento que se habían llevado a cabo (pero que no era información disponible utilizada para las predicciones) correspondiendo a un subconjunto de tramos de la red piloto. El tercer subconjunto corresponde a los datos de las operaciones de mantenimiento reales, entre los años 2012 a 2016, llevadas a cabo en los tramos del subconjunto anterior (b) con la finalidad de contrastación de la bondad/divergencia de las predicciones estimadas. La evaluación del rendimiento de los modelos se realizó mediante el uso de una matriz de confusión, basada en el recuento de los registros de prueba predichos correcta e incorrectamente. En esas matrices aparecen el tipo de mantenimiento real (M) y el predicho a tendiendo a los tipos de intervenciones, recogidos en la Tabla 1. La clase T0 está asociada a no-alerta, y el resto de las clases pertenecen a diferentes alertas de mantenimiento.

M	Alerta	Descripción
T0	No	No se requiere mantenimiento
T1	Si	No actuar
T2	Si	Microaglomerado, Recubrimiento-tratamiento de superficie
T3	Si	Capa fina mezcla caliente de asfalto (grosor ≤ 5 cm)
T3.1	Si	Fresado y extendido de capa fina de mezcla en caliente de asfalto (grosor ≥ 5 cm)
T4	Si	Capa gruesa de mezcla en caliente de asfalto (grosor > 5 cm) combinada con o sin fresado

Tabla 1- Descripción de los tipos de mantenimiento

Las curvas de aprendizaje de los modelos seleccionados se muestran en la Figura 4, donde se representan un total de cuatro gráficos; el eje horizontal (x) representa diferentes tamaños de conjuntos de entrenamiento, el eje vertical (y) el error obtenido. Las dos líneas gruesas representan el valor promedio de los conjuntos de entrenamiento y prueba; las líneas finas representan los percentiles 20 y 80 de los conjuntos de entrenamiento y prueba, proporcionado una cuantificación de la variación de las predicciones.

A medida que aumenta el tamaño del conjunto de entrenamiento, las líneas convergen hacia una asíntota que representa la cantidad de error irreducible en los datos. El error de la predicción del conjunto de entrenamiento en el modelo de k-vecinos más cercanos es siempre del 0%. Esto se debe al hecho de que la predicción de un registro se calcula a partir de una vecindad en la que se incluye el registro. El modelo DT presenta el error más bajo. Los modelos SVM, ANN y KNN arrojaron resultados similares; ninguno de ellos redujo el error promedio del conjunto de prueba por debajo del 5%. Solo el modelo DT alcanzó un error promedio por debajo del 5% utilizando un tamaño de conjunto de entrenamiento más elevado (375 registros).

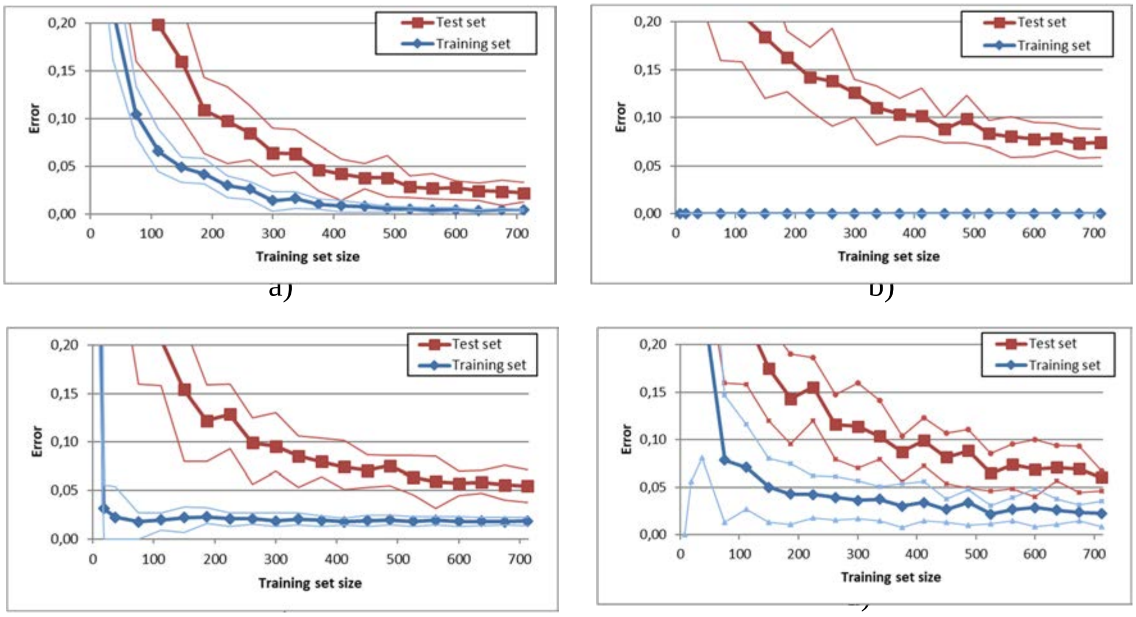

Figura 4. Curvas de aprendizaje: a) árbol de decisión, b) modelos de k-vecinos más cercanos, c) máquina de vectores soporte y d) modelos de redes neuronales artificiales.

Es importante subrayar que los resultados corresponden a un caso de datos numerosos. En la práctica real, la base de datos de mantenimiento histórico proporciona un conjunto de muestra válido limitado debido a múltiples causas: i) el número de intervenciones que se registran con descripción detallada no suele ser alto; ii) la información almacenada carece de coherencia cronológica (las intervenciones reales no se describan con el mismo rigor a lo largo del tiempo); iii) se cuantifican insuficientes características físicas explicativas. Por ello es importante que los modelos seleccionados logren un error de conjunto de prueba promedio bajo, con un número limitado de registros. En este caso, el modelo DT resulta ser la mejor opción.

La Figura 5 muestra la matriz de confusión para el modelo DT donde las columnas corresponden a la clase conocida (clase especificada por la orden de trabajo) y las filas a las predicciones inferidas por el modelo (clase de salida).

Los elementos diagonales muestran el número de clasificaciones correctas alcanzadas para cada clase; los elementos fuera de la diagonal muestran los errores cometidos por las predicciones del modelo. Cada celda contiene la misma información como porcentaje del tamaño total del conjunto de prueba. En la última fila y columna, estos gráficos presentan las medidas de rendimiento derivadas de la matriz de confusión: la precisión (ACC), recuperación o tasa de verdaderos positivos (TPR) y precisión o valor predictivo positivo (PPV), que se muestran en color verde; así como los respectivos índices complementarios: tasa de error (ERR), tasa de falsos negativos (FNR) y tasa de descubrimiento de falsos (FDR), mostrados en color rojo.

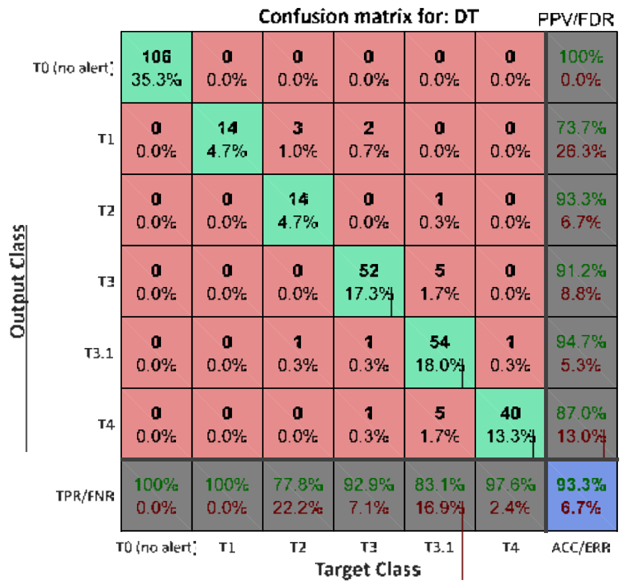

Figura 5. Matriz de Confusión (modelo DT).

5.1 Resultados

En la Figura 6 se extracta una selección de los resultados obtenidos tras aplicar las metodologías presentadas al conjunto de tramos de carreteras no incluidas en el proceso de elección y aprendizaje del modelo de predicción. La predicción del estado general de cada tramo se cuantifica numéricamente a través de la variable explicativa global (GTSL) y cualitativamente por el color de la celda. El penúltimo conjunto de columnas (*Estimated alert per year*) identifica los tramos en los que se predice (aconseja) la necesidad de realizar intervenciones de mantenimiento. El último conjunto de columnas (*Intervention by year*) señala los tramos en los que realmente se llevaron a cabo labores de mantenimiento. Los tipos de intervenciones de mantenimiento más recomendados, propuesto por el algoritmo de predicción, se identifican por el color asignado al tramo de carretera en el mapa de la Figura 7.

Road id			Global Technical Severity Level (GTSL) by year					Estimated alert by year					Intervention by year			
idSection	netClass	Section	GTSL_2012	GTSL_2013	GTSL_2014	GTSL_2015	GTSL_2016	2012	2013	2014	2015	2016	2012	2013	2014	2015
218174	2521	0	0,358	0,353	0,285	0,307	0,398	--	--	--	--	--		Maintened		
218174	2521	0,5	0,367	0,645	0,287	0,32	0,342	--	--	--	--	--		Maintened		
218174	2521	1	0,596	0,688	0,318	0,436	0,429	--	Alert	--	--	--		Maintened		
218174	2521	1,5	0,737	0,653	0,448	0,656	0,601	Alert	Alert	--	--	--		Maintened		
218174	2521	2	0,477	0,475	0,279	0,37	0,445	--	--	--	--	--		Maintened		
218174	2521	2,5	1,144	1,052	0,187	0,212	0,227	Alert	Alert	--	--	--		Maintened		
218174	2521	3	1,078	1,247	0,204	0,228	0,231	Alert	Alert	--	--	--		Maintened		
218174	2521	3,5	0,801	1,051	0,268	0,346	0,407	Alert	Alert	--	--	--		Maintened		
218174	2521	4	0,563	0,757	0,194	0,21	0,231	Alert	Alert	--	--	--		Maintened		
218174	2521	4,5	0,338	0,585	0,157	0,174	0,187	--	Alert	--	--	--		Maintened		
218174	2521	5	0,498	0,532	0,195	0,219	0,293	--	--	--	--	--		Maintened		
218174	2521	5,5	0,969	0,56	0,169	0,188	0,2	Alert	--	--	--	--		Maintened		
218174	2521	6	0,505	0,328	0,219	0,233	0,332	--	--	--	--	--		Maintened		
218174	2521	6,5	0,377	0,288	0,208	0,224	0,232	--	--	--	--	--		Maintened		
218174	2521	7	0,779	0,642	0,248	0,263	0,277	Alert	Alert	--	--	--		Maintened		
218174	2521	7,5	0,481	0,925	0,718	1,044	1,056	--	Alert	Alert	Alert	Alert				
218174	2521	8	0,313	0,979	0,804	1,024	0,862	--	Alert	Alert	Alert	Alert				

Figura 6. Resultados de GTSL y Alertas del tramo 218174, segmentado en subsecciones de 500 metros, predicciones para el período de tiempo 2012-2016.

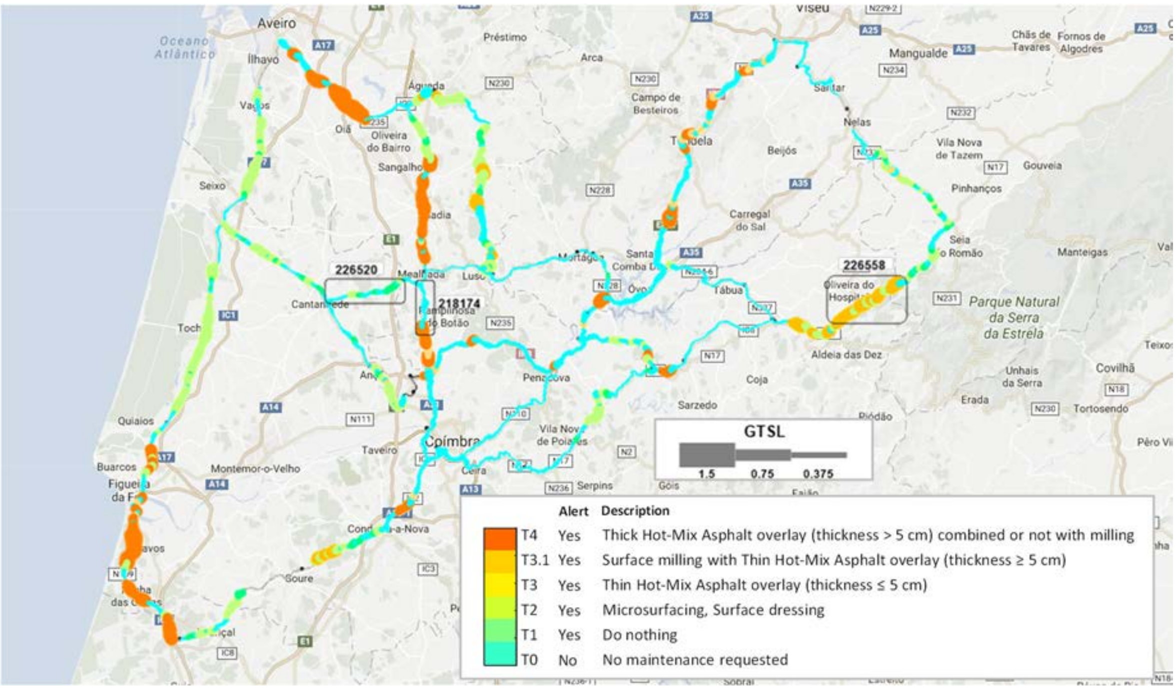

Figura 7. Estimación de la tipología de operaciones de mantenimiento en la red del caso piloto.

6. CONCLUSIONES

Se ha desarrollado una metodología, basada en un conjunto de varias técnicas, de aprendizaje automático supervisado y no supervisado para la predicción de alertas y de las operaciones de mantenimiento requeridas más probables. La aplicación práctica se ha llevado a cabo en una red de carreteras con una dilatada base de datos históricos. Los resultados obtenidos se fundamentan en la elección óptima de los mejores modelos predictivos basados en a) órdenes de trabajo de intervenciones contenidas en la base de datos histórica, b) características de los activos, c) y auscultaciones de medición.

Los principales resultados alcanzados son: i) el tipo de intervención estimado para cada tramo de carretera y la probabilidad de incidencia, ii) una lista ordenada de alertas estimadas según el nivel de gravedad técnica. Cada conjunto de predicciones se refiere a escenarios identificados por fecha. Los resultados evidencian que el marco metodológico proporciona buenas capacidades predictivas.

El trabajo presentado es parte de la generación de una herramienta inteligente de apoyo a la decisión con el objetivo de inferir planes de mantenimiento, basados en la generación de pronósticos de alerta y la selección óptima de operaciones en cuanto a las intervenciones más críticas a realizar. Estas últimas constituyen la información más relevante para avanzar en un sistema de ayuda a la planificación del mantenimiento de infraestructuras lineales de transporte a nivel operativo, táctico y estratégico, bajo un marco de sistema experto.

Las metodologías y resultados aquí presentados distan de ser exhaustivos y concluyentes, y se encuentran abiertos en varias líneas de investigación paralelas: a) sensibilidad a la calidad de la descripción de la intervención en el repositorio histórico con respecto a las fechas de las intervenciones, b) importancia de la descripción detallada/vaga del estado del activo previo a la intervención y, por último y de mayor relevancia a nivel de fiabilidad, c) el enriquecimiento de las bases de datos bajo el esquema procedural de verificación y activación de alertas.

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LA INFRAESTRUCTURA DEL TRANSPORTE ROMANO COMO PATRIMONIO CULTURAL

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RESUMEN

El creciente interés por acercar el patrimonio cultural a la sociedad ha impulsado la investigación en el ámbito del transporte durante la época romana. Su objetivo es conocer la organización territorial, las características del comercio y su influencia en la economía y la sociedad a través del tiempo y el impacto de las decisiones políticas en las infraestructuras y el desarrollo económico de los territorios.

Estos estudios se apoyan en los mapas confeccionados a partir de los emplazamientos de las ciudades y calzadas históricas. De tal modo que la precisión de sus resultados depende de la fiabilidad de tales cartografías históricas. Sin embargo, todavía persisten un notable número de ciudades y vías romanas sin localizar o cuyas identificaciones actuales no son seguras.

En el presente trabajo, se detallan las dificultades inherentes a la identificación de las calzadas romanas, así como las herramientas de las que se dispone para ello. Además, se describe uno de los métodos para localizar rutas antiguas conflictivas en su identificación junto con un caso de estudio. Como resultado, se puede observar la importancia de las estrategias para la reconstrucción de los trazados de las rutas antiguas y la identificación de las ciudades en los estudios de movilidad en el mundo antiguo.

1. INTRODUCCIÓN

El creciente interés por acercar el patrimonio cultural a la sociedad ha impulsado diferentes proyectos de investigación en el ámbito del transporte durante la época romana.

Un ejemplo es el proyecto ORBIS (2012) de la Universidad de Stanford que ha desarrollado un modelo que permite al usuario calcular los costes y tiempos asociados a las rutas durante la época imperial. Por su parte, el proyecto Mercator-e desarrollado por De Soto (2016) está enmarcado dentro de los siguientes objetivos del Programa Horizon 2020: rutas de movilidad transeuropeas y patrimonio cultural en Europa. En él se establecen estudios de conectividad y funcionalidad de la red de transporte romana en la península ibérica. De esta forma se pueden conocer la organización territorial, las características del comercio y su influencia en la economía y la sociedad a través del tiempo.

Estos estudios se basan en las fuentes de cartografía histórica. Sin embargo, todavía persisten un notable número de ciudades y vías romanas sin localizar. En algunas ocasiones existen diferentes propuestas de ubicación para un mismo itinerario o ciudad romana.

Las herramientas que se han utilizado para la determinación de los trazados han sido fundamentalmente fuentes geográficas antiguas, menciones de autores clásicos y medievales y las aportaciones de la arqueología y la epigrafía. Dentro de las primeras, las principales son: el Itinerario de Antonino, el Anónimo de Ravenna, la Cosmografía de Ptolomeo, la Tabla de Peutenger y los Vasos de Vicarello. En el caso de *Hispania*, últimamente han cobrado valor las Tablas de Barro de Astorga, desde que Fernández, Morillo y Gil (2012) demostraran su autenticidad por medio de pruebas de termoluminiscencia. En cuanto a las fuentes históricas, las menciones que los historiadores clásicos hacen sobre las ciudades, junto con la literatura medieval aportan una información cualitativa que puede servir para confirmar las localizaciones. Finalmente, los recursos arqueológicos y epigráficos, aunque escasos, suponen un elemento de comparación esencial para dar validez a las teorías propuestas. En la actualidad, el desarrollo de los Sistemas de Información Geográfica (GIS) está constituyendo un soporte para la arqueología. De este modo, Verbrugghe, De Clercq y Van Eetvelde (2017) mediante técnicas como el Light Detection and Ranging (LIDAR) y la de la Ruta del Menor Coste han realizado la reconstrucción de trazados de calzadas romanas en Bélgica.

Las dificultades para la identificación de las rutas están basadas en la imprecisión de algunos de los trazados citados en las fuentes junto con la carencia de evidencias epigráficas y arqueológicas suficientes de las ciudades y calzadas.

Uno de los precursores en el estudio del trazado de las calzadas romanas en *Hispania* fue Saavedra (1862), quien presentó un mapa en el que están la localizadas todas las *viae* de la Península Ibérica citadas en el Itinerario de Antonino. Blázquez (1892) propuso otros trazados para el mismo basándose en el análisis de las distancias del Itinerario y su adaptación al plano. Por su parte, Margary (1955) fue un pionero en el estudio de las vías romanas en *Britannia* con diferentes contribuciones como el descubrimiento de una nueva calzada y un sistema de numeración para las mismas.

Más recientemente y en el caso de *Hispania* resaltan los trabajos de Roldán (1966) y Moreno Gallo (2017). Éste último ha revolucionado el concepto que se tiene sobre la estructura y composición de las calzadas romanas interurbanas. Mediante un extenso estudio científico demuestra que aquellas están pavimentadas con material tipo zahorra, frente a la generalizada idea de pavimentos con grandes bloques de piedra. De tal manera que el uso de grandes bloques de piedra para el pavimento corresponde a calzadas urbanas.

Además ha realizado un estudio sobre las vías romanas en Castilla y León. En él se han complementado los recursos toponímicos, epigráficos e históricos con arqueología aérea y reconocimientos terrestres para confeccionar un mapa de calzadas romanas dentro de la citada Comunidad. Los trazados de algunas *viae* difieren sobre las propuestas de anteriores autores. Un nuevo trazado para una de estas vías, la Vía Aquitana, ha sido precisado por López-Zamanillo (2018) a su paso por la ciudad de Burgos mediante un estudio de la literatura medieval y trabajo de campo en la propia ciudad.

En casos especialmente conflictivos se debe recurrir a singulares metodologías como las propuestas por Verhaggen (2014) o Romera y Pérez-Acebo (2020). La segunda es interesante para el caso de trazados en valles con ríos sinuosos donde es difícil recurrir a alineaciones rectas entre estaciones. La última es adecuada en situaciones donde en el itinerario analizado existe un número consecutivo importante de estaciones o *mansiones* desconocidas.

En el presente trabajo se analiza un caso crítico de estudio mediante el método de Romera y Pérez-Acebo (2020). De esta forma se puede observar la importancia de las estrategias para la reconstrucción de los trazados de las infraestructuras de transporte terrestre romanas.

2. METODOLOGÍA

En este trabajo se va a hacer uso del método de Romera y Pérez-Acebo (2020) para la reconstrucción del trazado de las vías. El método consta de cuatro fases: determinación del dominio geográfico, correlación entre las coordenadas ptolemaicas y las de un sistema de referencia actual, obtención de la distribución de probabilidad espacial de las estaciones cuyo emplazamiento se desconoce y reconstrucción del trazado a partir de esas ubicaciones.

2.1 Definición del dominio geográfico

Como primer paso del método se deben definir los límites del dominio geográfico de la calzada objeto de estudio. Para ello, son de ayuda los trazados de vías paralelas a la calzada de estudio cuyo trazado sea conocido, además de límites geográficos como líneas de costa o divisiones territoriales si se sabe que la vía pertenece a una provincia romana en concreto.

2.2 Correlación entre las coordenadas del sistema de referencia WGS 84 y las coordenadas ptolemaicas

El planteamiento es localizar algunas de las *mansiones* por las que circula la ruta para reconstruir su trazado. Para ello, se deben obtener previamente unas regresiones lineales simples entre las coordenadas de Ptolomeo de localizaciones en la provincia romana por la que transcurre la vía y sus coordenadas correspondientes en el sistema de referencia actual WGS 84. Es determinante el hecho de que esos emplazamientos estén uniformemente repartidos geográficamente y que su ubicación en la actualidad no presente discusión.

2.3 Distribución de probabilidad espacial

Si los errores asociados a las regresiones lineales siguen una distribución normal, se puede utilizar la distribución normal bivariante como distribución de probabilidad de localización. Tras la citada comprobación, se establecen las distribuciones de probabilidad correspondientes a las localizaciones de las ciudades de emplazamiento desconocido por las que discurre la vía de estudio. A continuación, se utilizan esas distribuciones para valorar la viabilidad de cada una de las propuestas de localización para dichas ciudades. Si existen diferencias de probabilidad significantes entre las diferentes propuestas, se opta por aquella opción mejor localizada geográficamente.

2.4 Reconstrucción del trazado

Se hace pasar el trazado por las ciudades cuyo emplazamiento se ha estimado en base a su mayor probabilidad.

3.APLICACIÓN A LA VIA AB ASTURICA PER CANTABRIAM CAESARAUGUSTAM

Se ha optado por este caso de estudio por ser la vía más conflictiva del Itinerario de Antonino, debido a un gran número de estaciones consecutivas sin localizar en su tramo inicial. Existen propuestas diferentes para el trazado de la misma establecidas por distintos autores. En la Tabla 1 se detalla el itinerario correspondiente al primer tramo de la *via ab Asturica per Cantabriam Caesaraugustam*. Junto al nombre original de la vía se ha añadido entre paréntesis la numeración de Blázquez. Para simplificar la denominación de las *viae*, en lo sucesivo se va a utilizar dicha numeración. Para las mansiones identificadas se ha indicado entre paréntesis el nombre de la localización actual. A continuación del nombre de cada mansión, salvo en el caso de la primera de cada tramo, se muestran las distancias medidas en *milia passuum* (1.480 m), con respecto a la mansión anterior. Cuando figura más de un valor es porque los valores de los diferentes códices de los que se han obtenido esas distancias no coinciden.

***Ab Asturica per Cantabriam Caesaraugustam* (Camino 27)**
Asturica (Astorga)
Brigeco: 40
Intercatia: 20
Tela: 22
Pintiam: 24
Raudam (Roa): 11
Cluniam (Peñalba del Castro): 26, 16

Tabla 1 –*Ab Asturica per Cantabriam Caesaraugustam* según el Itinerario de Antonino

Se opta por proceder a la localización de la estación intermedia de *Intercatia* para la reconstrucción del trazado, por ser la *mansio* de la que más información se dispone y que condiciona claramente la trayectoria de la calzada. En efecto, tenemos sus coordenadas ptolemaicas, inscripciones epigráficas con su gentilicio y es citada por Apiano y Polibio. Para establecer las distribuciones de probabilidad correspondiente a la localización de *Intercatia*, se han obtenido previamente unas regresiones lineales simples entre las coordenadas de Ptolomeo de localizaciones en la Península Ibérica y sus coordenadas WGS 84. Dado que se busca una ubicación en *Hispania*, se decidió restringir las localizaciones únicamente a la Península Ibérica, seleccionándose 48 localizaciones incluidas en la *Cosmographia* de Ptolomeo.

Puesto que los errores asociados a las regresiones lineales siguen una distribución normal, se puede utilizar la distribución normal bivariante como distribución de probabilidad.

Entonces, se establecen las distribuciones de probabilidad correspondientes a la localización de la ciudad de emplazamiento desconocido, con objeto de valorar la viabilidad de cada una de las propuestas de localización para dicha ciudad. En la Figura 1 aparece representada dentro de los límites administrativos de las provincias que pertenecen al área de estudio la elipse correspondiente al error standard correspondiente a la localización de *Intercatia*. Los límites superior e inferior del dominio de localización de la vía 27 y de *Intercatia* están definidos por las vías 32 y 24, respectivamente, por ser dos calzadas adyacentes de trazado paralelo a la considerada y cuya trayectoria no es tan confusa. En dicha figura se representan mediante círculos las propuestas de emplazamiento para la ciudad considerada realizadas por diferentes autores. Como se puede ver en la Figura 1, la única posibilidad que entra dentro de la región correspondiente al error standard es Paredes de Nava. Por lo tanto, se opta por esta opción por ser la mejor localizada geográficamente.

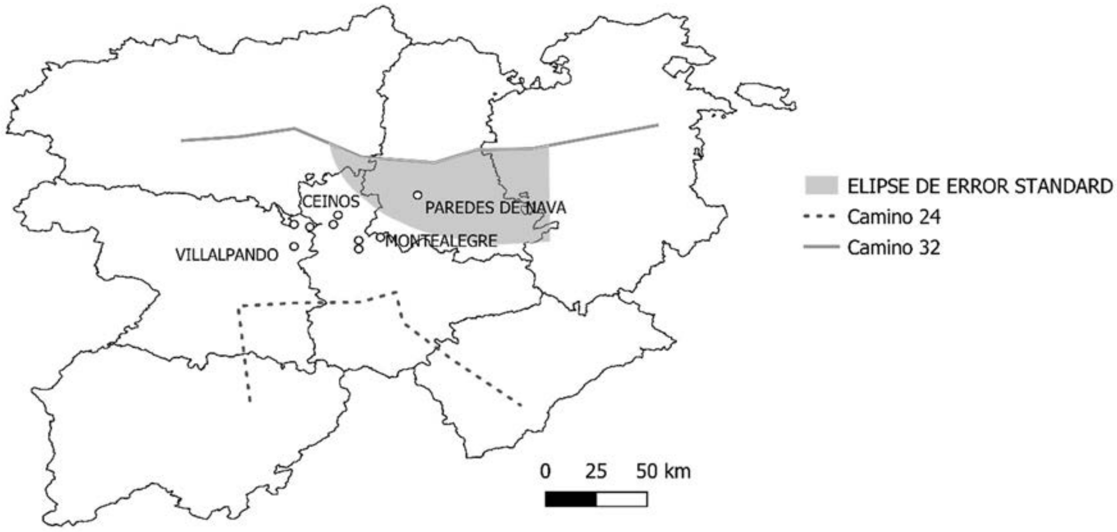

Fig. 1 – Elipse de error standard y localizaciones propuestas para *Intercatia*

En la Figura 2 se hace pasar el trazado de la vía estudiada por Paredes de Nava flanqueando el antiguo Mar de Campos por el norte antes de vadear el Carrión por Palencia. En realidad, no es necesaria una gran modificación del trazado propuesto por Saavedra para hacerlo pasar por esta ciudad. Se representan además las soluciones propuestas por Blázquez (1892) y Wattenberg.

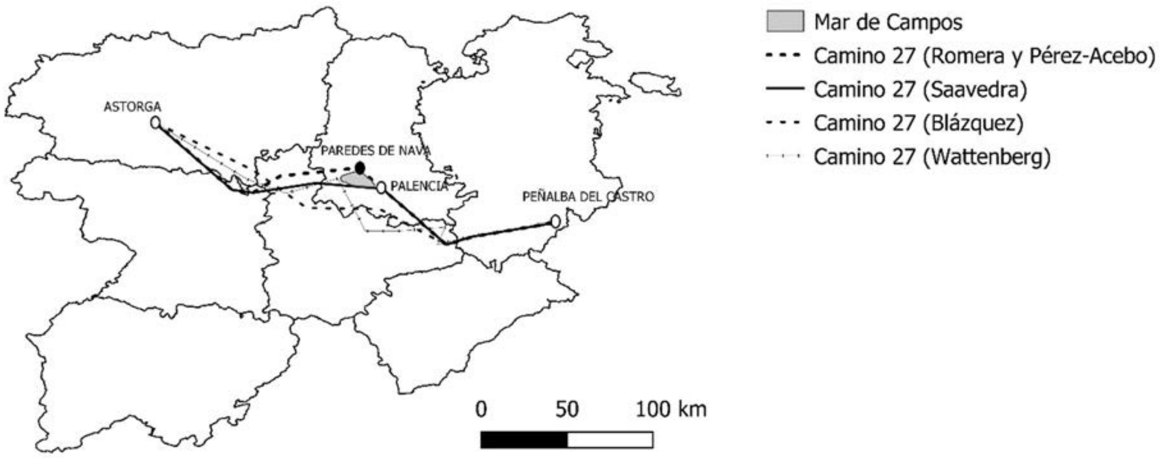

Fig. 2 – Trazados sugeridos para la vía 27 entre *Asturica* y *Clunia*

4. CONCLUSIONES

Los estudios sobre movilidad y transporte del mundo antiguo se apoyan en los mapas confeccionados a partir de los emplazamientos de las ciudades y calzadas históricas. De tal modo que la precisión de sus resultados depende de la fiabilidad de tales cartografías históricas. Sin embargo, todavía persisten un notable número de ciudades y vías romanas sin localizar.

En ocasiones, además existen propuestas geográficas muy dispersas para un mismo emplazamiento.

Teniendo en cuenta las dificultades inherentes a la identificación de las calzadas romanas, se describe uno de los métodos para localizar rutas antiguas especialmente conflictivas en su identificación junto con un caso de estudio.

Para el uso del planteamiento realizado en este trabajo es necesario que las opciones propuestas estén dispersas geográficamente, de lo contrario los valores de probabilidad serían similares debido a la dispersión de las coordenadas de la *Cosmographia*.

Como resultado, se puede observar la importancia de las estrategias para la reconstrucción de los trazados de las rutas antiguas y la identificación de las ciudades en los estudios de movilidad en el mundo antiguo y en el conocimiento sobre los elementos del patrimonio.

AGRADECIMIENTOS

Este trabajo ha sido posible gracias al apoyo de la Universidad del País Vasco UPV/EHU (PPGA20/26). Del mismo modo, queremos agradecer la ayuda al Grupo de Investigación del Gobierno Vasco IT1314-19.

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COOL PAVEMENTS FOR CLIMATE CHANGE ADAPTATION

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ABSTRACT

In the framework of road infrastructures, CHM has led a study that investigates construction products in order to combat the heat that is accumulated and released by urban surfaces, such as asphalt, especially in summer, seeking to minimize the "island of urban heat".

This project is the result of having developed reflective pavements (cool pavements) than have passed through the first phase at the laboratory level, manufacturing on an industrial scale and their small-scale testing to ensure proper implementation, as well as their implementation by means of a large-scale demonstrator, operating on 24.000 m^2 of pavement in the city of Murcia (LIFE HEATLAND).

This mixture has a series of benefits with respect to conventional mixtures, leading to an improvement in the urban environment and quality of life of the citizens of the implantation environment and which are mainly:

- Saving energy in air conditioning and in the consumption of public lighting.
- Saving energy consumption and raw materials.
- Improves air quality.
- Improves noise pollution.
- Improves comfort and health of pedestrians.
- Economic and environmental benefits.

To date, the demonstrator has been monitored and the following conclusions have been obtained, validating this type of pavement as a mechanism to reduce the urban heat island effect:

- Initial luminance of reflective pavement 2.5 cd / m^2 under the lamppost, 150% higher than in the conventional asphalt street.
- Solar reflectance is almost four times higher than conventional asphalt.

- Average surface temperature for reflective pavement of 7-11 ºC lower than conventional.
- Asphalted areas where tire rubber has been deposited as a result of the rolling of vehicles are heated 1-3 ºC more than clean areas.
- Environmental noise level of the area: 3 dB (A) lower.

1. MAIN INFORMATION

1.1 Introduction

Research project developed by CHM Obras e Infraestructuras, S.A., with the collaboration of CTCON, within in framework of the REPARA 2.0 project, supported by co-financed by Centre for the development of Industrial Technology (CDTI) and European Regional Development Fund (ERDF).

At first, we are going to explain what the cool pavements are and how they help to reduce the climate change. So now we are going to define key concepts which are the following.

The development of the innovative asphalt pavement with high solar reflectance arises in order to mitigate the effects of climate change and, specifically, due to the global warming that is taking place on our planet according to the latest anomaly data determined by NASA, with annual anomalous average temperature variations of between 1-2 ºC, while in summer periods this range of temperature variation is between 1-4 ºC at the national level.

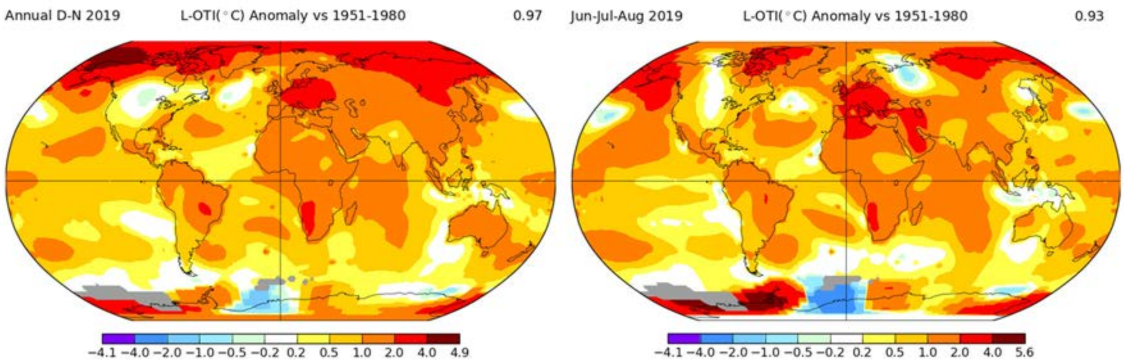

Fig. 1 – Average variation climate (2019), about Surface temperature, and variation of June-August 2019. NASA, Goddard Institute for Studies

The actions which have contributed to this climate change it is found in the last 50 years the population has start to live in urban areas instead of rural areas. See Fig. 2.

This fact has caused the proliferation of big urban zones where it is produce the phenomenon known as “Urban heat island”.

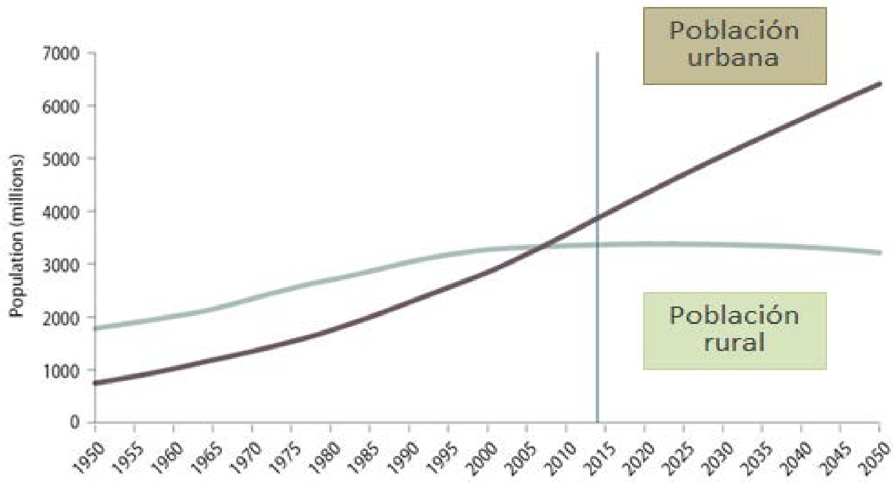

Fig. 2 – Source: data from World Bank about the basis of the Urban Perspective of the United Nations

1.2 Urban heat island (UHI)

It is the effect when an area, which has been created by the human, get a temperature hotter than the around area without modify.

This temperature difference can be seen in the following graph "referential temperature urban profile compared to rural areas", where it can be seen between urban centers and surrounding areas such as the countryside, without modifications by humans, it is got temperatures differences between 3ºC and 4ºC. See Fig. 3.

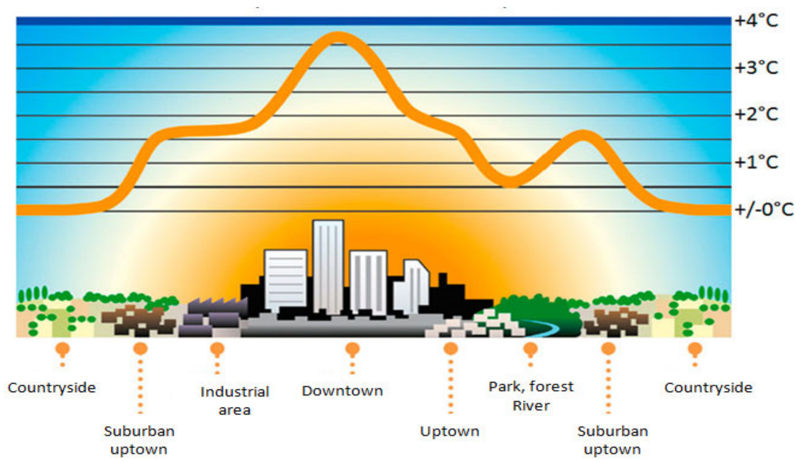

Fig. 3 – Referential temperature urban profile compared rural areas. Source: Saint-Gobain PPC. Translate, own development

Therefore, it is obtained one of the actions which cause the urban heat island effect is to change areas with vegetables materials by other materials, such as concrete or asphalt, among others.

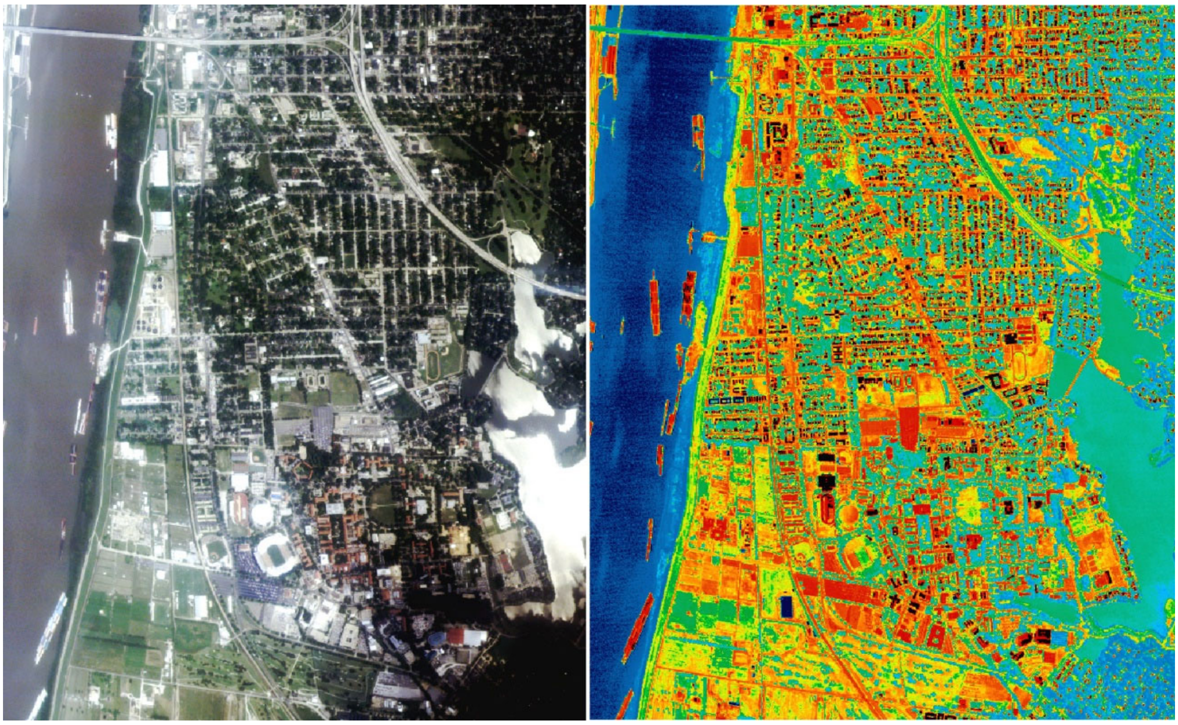

Fig. 4 – Thermography, Baton Rouge city, USA. NASA

From this and after the consulted bibliography, it has been estimated the general distribution of surfaces is identified with the distribution of the following diagram, in which the majority areas modified in the cities are constituted by pavements in general. It is had the pavements constituted around 39% of the modified surfaces in a city and these are capable of absorbing and storing energy in the form of heat, which is notoriously contributing to the aforementioned urban heat island effect. See Fig. 5.

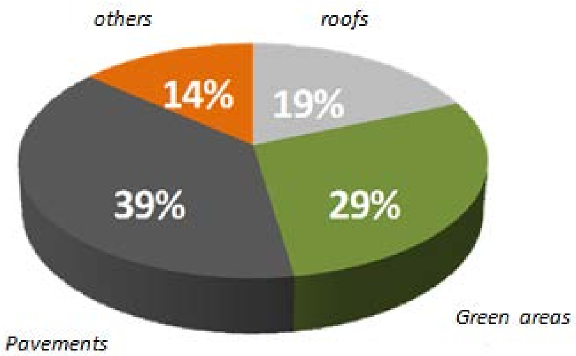

Fig. 5 – Surface distribution in urban areas.

Conventional pavements are able of absorbing up of the 90% of the incident solar energy that means they have a low solar reflectance.

1.3 Solar reflectance

It is the relation between reflected solar energy and incident solar energy. See Fig. 6.

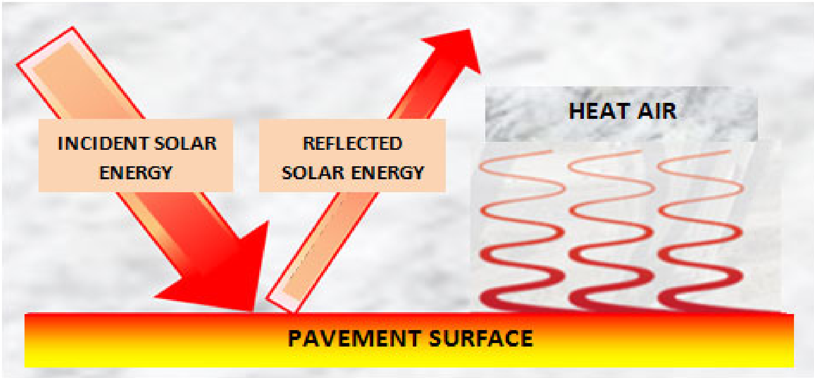

Fig. 6 – Solar reflectance. Source: own development

That the reason why, conventional pavements contribute to urban heat island effect by the following mechanism:

- Solar energy hits the pavements surface.
- Part of that energy is reflected, approximately 10%.
- The rest of the energy is absorbed as heat by the pavement, around 90%, which causes the surface to heat up, reaching surface temperature of up to 70ºC. This means, especially at night, there is a flow of hot air (convection) which increases the ambient temperature and increase the urban heat effect.

This effect gives a great Energy demand and due to the poor ventilation in the cities with respect to the existing one in the field, it is produce an overheating of urban areas.

On the other hand, solar radiation which is a thermal radiation defined as a set of electromagnetic radiation emitted by the sun which in form of waves propagates in the form of waves with lengths between 150 and 400 nanometers (nm). The radiation which reaches the Earth oscillated between 300 and 2500 nm, the rest is rejected by the atmosphere. This wavelength range it divided in three electromagnetic spectra: UV spectrum: wavelength range between 280 – 400 nm; VIS spectrum: wavelength range between 400 – 700nm; IR spectrum: wavelength range between 700 – 2500nm.

The magnitude which measures the solar radiation is called irradiance and its units are W/m2, each wavelength will have a determinate irradiance. The standard distribution of the irradiance is definite by the ASTM standard G173-03-AM 1.5G, where it is quantified the energy power which affects the Earth layer in each one of the three spectrums (UV, VIS and IR).

These values are measure at sea level, 20ºC temperature and with a determined inclination of the sun (37ºC) to the terrestrial surface. If all irradiances values of all wavelength are added, the total radiation which arrive to the Earth will be 963,8 W/m². With these incident solar results and measuring the reflected energy, one can know the reflectance percentage of a surface. See Fig. 7.

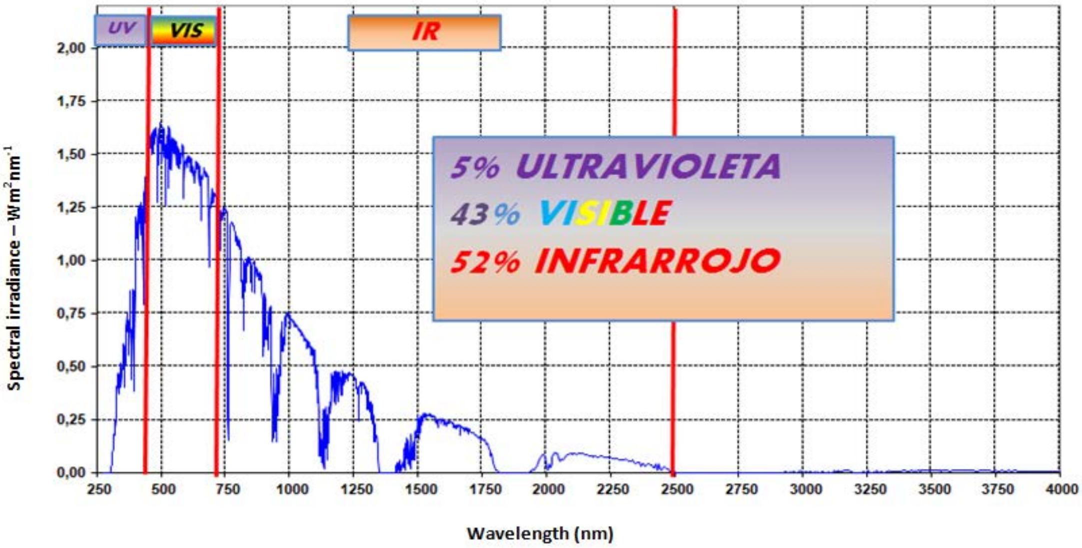

Fig. 7 – Graphic representation of solar spectrum AM 1,5 G-ASTM G173-03.

It can see, approximately the 5% of the energy which affects the Earth's surface corresponds to the ultraviolet spectrum (UV), the 43% to the visible spectrum and 52% to the infrared (IR).

The reflectance value range to zero (for surface without reflectance) from one (for surface with total reflectance). The result may give as a percentage. The absorbance is an inverse concept of reflectance. See Fig. 8.

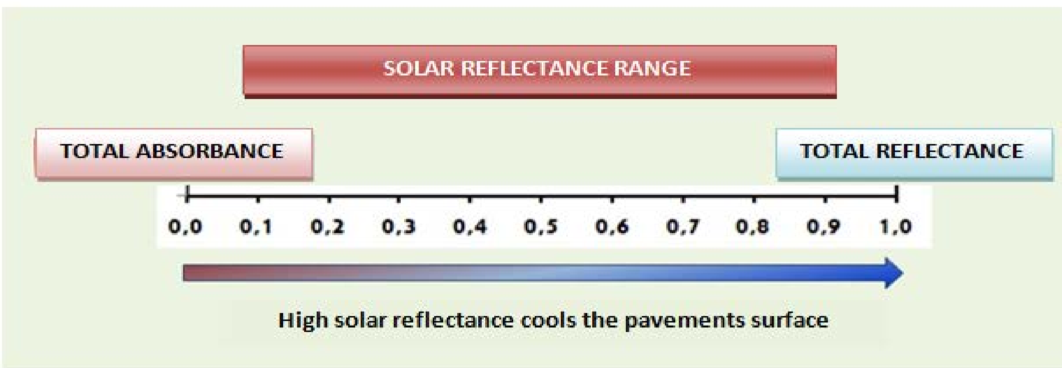

Fig. 8 – Solar reflectance range. Source: own development.

The solar spectrum is composed of UV, VIS and IR, it can determine within the total solar reflectance, the reflected part in the ultraviolet spectrum (UVR), the visible- VISR spectrum and the infrared-IR.

2. MATERIALS AND METHODS

These reflected pavements are able to reduce the surface heating, especially in cities, as a consequence the ambient temperature, so this gets a great importance in summer periods. See Fig. 9.

Fig. 9 – Cool Pavement. Source: own development

According to the LEED v4-ND Certification system sponsored by the US Green Building Council for the Development of Residential Areas, in the chapter GIB CREDIT: HEAT ISLAND REDUCTION, it is selected the measures which the horizontal surfaces of the pavements have to adopt to minimize the heat island effect in the cities.

In particular, pavements are considered reflective when the initial reflectance index is equal or greater than 33% and the reflectance index at three years is equal or greater than 28%. Therefore, based on the definition of the reflectance index, the higher the solar energy reflected, the higher the reflectance index and the lower the solar energy or the heat absorbed by the pavement surface, resulting in less heating of the ambient air, so a lower ambient temperature.

2.1 Measurement methods of solar – SR reflectance on opaque surfaces

In the process of designing the reflective pavements, two test methods have been used to measure the reflectances of the entire solar spectrum in the materials and mixtures developed. One uses a UV-VIS-IR spectrophotometer that measures reflectances in laboratory samples and in the other a pyranometer is used to measure the solar reflectances on surfaces of already constructed pavements.

2.1.1 Spectrophotometer UV-VIS-IR:

To measure the solar reflectance from flat surface it is used a UV-VIS-IR spectrophotometer with integration sphere according to ASTM E 903-12 standard. It is the ideal method for small laboratory samples, 5 x 5 cm in size. It does not serve to measure reflectances on field surfaces. The measurement range is between 300 and 2500 nm of wavelength.

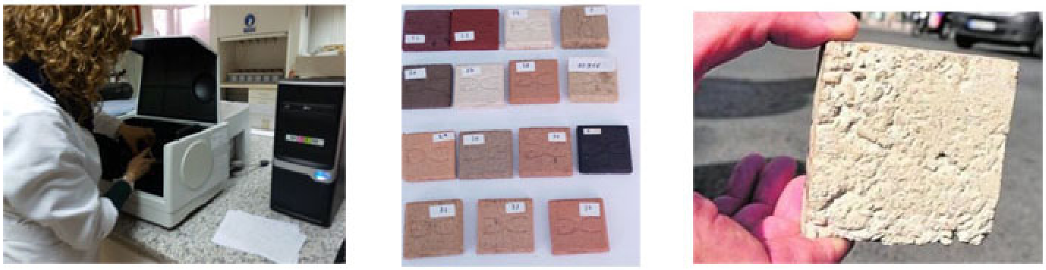

Fig. 10 – Spectrophotometer and simples used

This method of measurement allowed the characterization of the raw materials to use for establish the composition and final dosage of the asphalt pavements developed, according to the criteria of the LEED certification system mentioned above.

2.1.2 Pyranometer:

The solar reflectance is calculated from the measurement of the intensity of the solar radiation, incident and reflected by a surface, with the ASTM E1918 standard (ASTM 2006). Large areas are needed, such as circles with at least four meters in diameter and squares with four lateral meters and a low slope. It measures both the incident energy and the reflected energy in W / m².

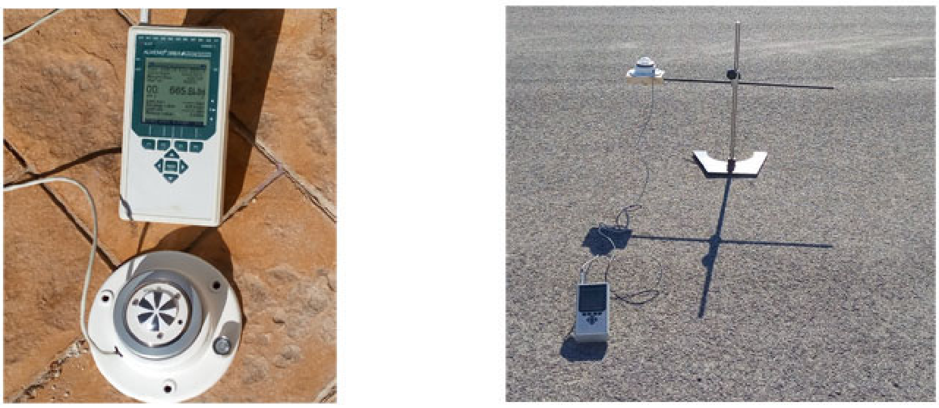

Fig. 11 – Pyranometer and field measurement

According to the defined reflective mixture, tests have been made with their corresponding measurement, which it has been obtained that initially the reflectance index is 40% compared to 7% of a conventional mixture.

Therefore, based on the initial value obtained, initially this mixture is considered reflective and it is expected that it can contribute to mitigate the urban heat island effect.

2.2 Behavior

Regarding, the variation of temperature itself, both superficial and internal, the following figure shows a reference sample of conventional mixture and another of reflective mixture, which the temperature inside of both with respect to the surface temperature varies around 3-4ºC, of which the behavior of both is similar and the data obtained are comparable.

The surface and interior temperature of the reflective mixture differs 8-10°C with respect to the conventional mixture. This temperature difference does not depend on the ambient temperature but depends on the radiation which reaches the exposed surface.

With this, the reflective mixture, when subjected to a lower temperature, will have a longer life than the conventional mixture.

In addition, the reflective mixture has been subjected to the regulatory tests in Spanish regulations (granulometry, density, hollow%, water sensitivity, Marshall deformation, rolling resistance - track test, etc.) and it is concluded that it meets the regulatory requirements, like conventional asphalt pavements.

2.3 Benefits

According to North American studies, in particular, the one realized by the investigating group Heat Island Group of the National Laboratory of Energy Lawrence Berkeley (LBNL), for pavements with reflectance index superior to 40%, the benefits are the following:

- Energy savings: in lighting system -Public light- and air conditioning system -air conditioner-.
- Natural improvement: air quality.
- Improvement quality of life: comfort and pedestrian.

It is expected a temperature reduction on surface between 10-12ºC respect to conventional mixture, probably it will be a temperature reduction of 1-2ºC so it will save 0.5KW/m2 in air conditioner, as a consequence a reduction in energy demand.

In addition, the decrease in ambient temperature causes the slowdown of photochemical reactions and, consequently, the formation of "smog" by the 5% decrease in tropospheric ozone due to tropospheric ozone in abundant quantities is considered a pollutant of the atmosphere.

Respect to change of the hue of the reflective mixtures with respect to the conventional ones, it would suppose a saving of 30% in public lighting due to the need of less power in the luminaries, which translates in a saving of energy consumption, together with the above, leads to lower levels of CO2, NOx and VOCs to cover the energy demand.

On the other hand, with the solar reflectance measurement methodology, the total solar reflectance value is obtained in %. You can also obtain the % of the reflectance of the three spectra (UV-VIS-IR) separately, this possibility of calculation is very important for the design criteria of the reflective asphalt mixtures. We look for pavements with high reflectance in the visible and infrared, and low reflectance in the UV (this will avoid any inconvenience to the users of the pavements), for this we will take into account the color and physical-chemical characteristics of the components of the mixtures.

From this, it wanted to check if the clear tone of the reflective pavement could be harmful to health due to the level of reflectance. To do this, a comparison was made of the reflectance values for the wavelengths of each spectrum in other surfaces which are harmful to health such as snow, and another with conventional pavements which are not.

It is known the ultraviolet-UV electromagnetic spectrum is harmful to health; the following figure determines the solar reflectance values and shows that the UV wavelength behavior of the reflective asphalt pavement is more similar to conventional asphalt pavement, far from the reflectance of a surface harmful to health such as snow. See Fig. 12.

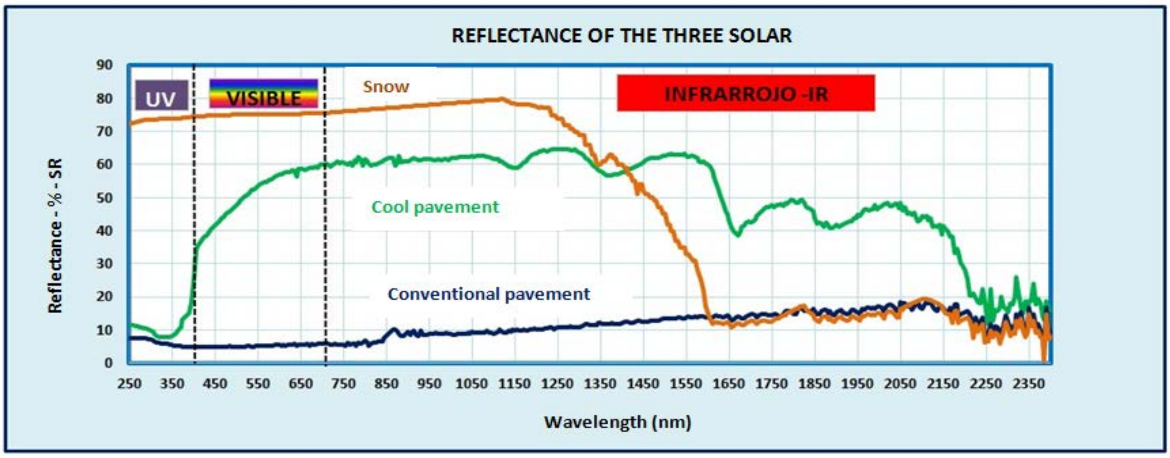

Fig. 12 – Graphic representation of the reflectance of the three solar spectra on snow surfaces, reflective and conventional asphalt pavements.

Therefore, from the design system of obtaining reflectance of the pavements separately, low reflectance of the ultraviolet-UV spectrum can be achieved, which will allow to circulate through the reflective pavements reducing the need to use sunglasses or sunscreen, in contrast to what occurs in other surfaces such as snow, due to its high reflectance of the ultraviolet-UV spectrum and that the mixture developed so far meets the expectations of being a reflective asphalt pavement that may contribute to the mitigation of change climate.

3. RESULTS

The developed technology has been studying by CHM, with CTCON collaboration, with REPARA 2.0 project. Also, a prototype LIFE HEATLAND project with the European support of the LIFE program whose general objective until 2020 is to group forces to contribute to sustainable development achieve the objectives and goals of the European 2020 Strategy and the strategies and plans of the European Union on the environment and climate. The following results are:

- 24.000 m2 of the cool pavement installed. The pavement albedo is expected to be increase from the 0.05 for conventional asphalts to 0.46 for the new technology.
- Four metering towers built-up and data acquisition system correctly working.
- Quantitative and qualitative demonstration of the effectiveness of the innovative pavement to mitigate the UHI effect. Throughout the test program, about 1.5 million data will be obtained: metering towers will register, every 30 minutes, 24 hours/day and during 2 years, the following parameters: pavement surface temperature, air temperature (at 0.5, 1.5 and 4 m height), moisture, wind speed, solar irradiance, air ozone, illumination level and noise; together with thermography, existing and new pavement samples analysis and other related information.
- To actually mitigate the UHI effect in the implementation area. It is expected to reach an air temperature decrease of 1.5ºC and a surface pavement temperature decrease of 10ºC. Energy savings of 7% for refrigeration devices and 5% for street lighting are expected.
- A mathematical model to predict the effect of the innovative pavement implementation in other urban areas.
- Quantitative demonstration of the economical balance of the new technology and its feasibility.

Fig. 13 – Work area. Demonstrator.

Fig. 14 – Monitoring tower

Fig. 15 – Location – monitoring tower.

Fig. 16 – Demonstration results about innovation pavement.

Fig. 17 – Crosswalk. Intersection between pavements.

Fig. 18 – Thermometer. Surface temperatura difference dirty-clean 4,7 ºC, conventional-cool pavement clean 13,1 ºC (14/06/2020 - 15.30 a.m.).

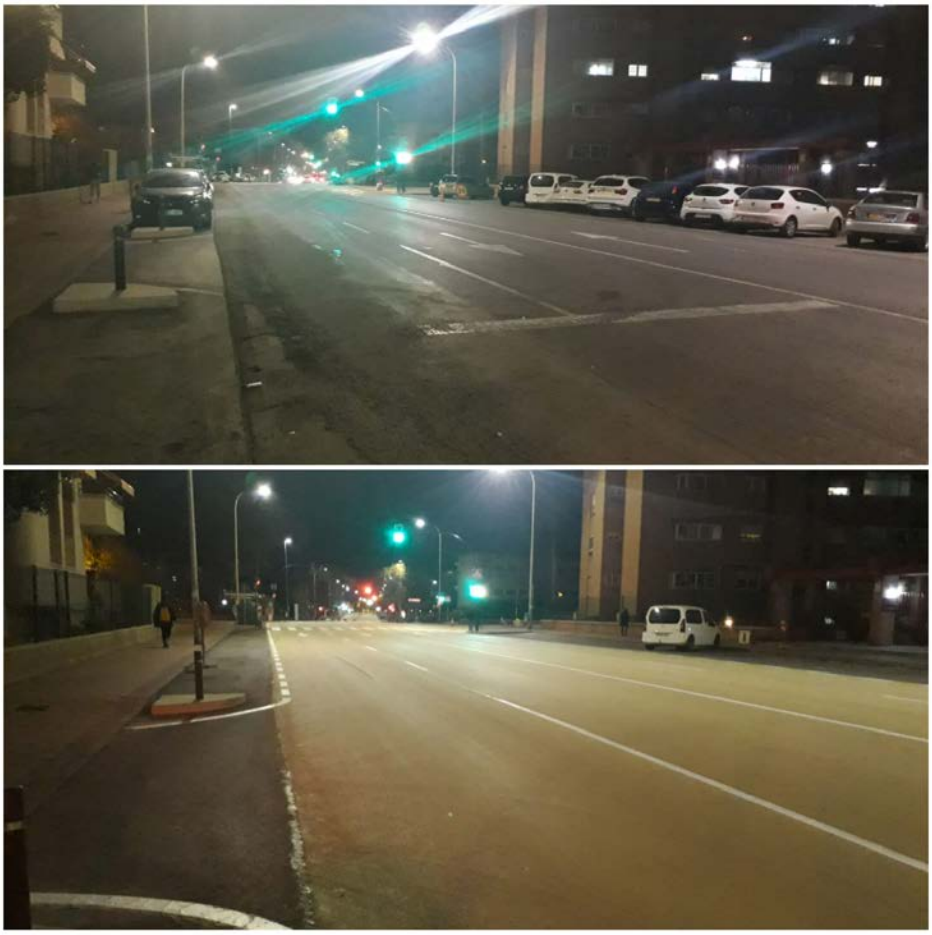

Fig. 19 – Night results, before and after cool pavement.

4. CONCLUSIONS

Until today, the demonstrator has been monitored and the following conclusions have been obtained, validating this type of pavement as a mechanism to reducing the urban heat island effect:

- Initial luminance of reflective pavement 2.5cd / m2 under the lamppost, 150% higher than the conventional asphalt street.
- Solar reflectance of 30%, almost four times higher than that of conventional asphalt.
- Average surface temperature with reflective pavement 7-11ºC lower than that of the conventional pavement surface
- Areas of the asphalt where rubber has been deposited from the tires as a result of the rolling of vehicles are heated 1-3ºC more than the clean areas.
- Lower environmental lower noise level of the area: 3 dB (A).

Fig. 20 – Demonstrator results.

4.1 Innovation

- National Patent (Spain): P201830642
- Patent Cooperation Treaty: PCT/ES2019/070432
- European Patent: 19827481.3 – PCT/ES2019/070432

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- XIV Congreso de Ingeniería del Transporte (CIT 2021).

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- www.chm.es
- http://www.proyectorepara.com/
- https://heatlandlife.eu/

ANALYSIS OF ROCK MASS CLASSIFICATIONS FOR SAFER INFRASTRUCTURES

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ABSTRACT

In the construction of land transport infrastructures such as roads, highways, or railways, one of the factors that determine their design most is the characteristics of the terrain through which they run. Additionally, tunnels have become one of the most adopted solutions to reduce environmental impact. The characteristics of the rock mass are a key point to decide the layout of the tunnel and its construction method. However, the rock masses are discontinuous, anisotropic, and heterogeneous media, so their classification and knowledge are needed for a safer design of these infrastructures.

The rock mass is not an industrial material with “pre-established” properties and behaviours, but rather a natural material that needs to be analyzed, understood, and standardized. The need to understand the behaviour of the rock mass has led throughout modern history to the use of different standards, which lead to the development of geomechanical classifications, with the aim of establishing a common language that translates the very advanced geological language in the macro and microgeological behaviour, which is needed for applications in civil engineering. In the last decades of the 20th century, and in the present 21st, the efforts in the process of understanding the intact rock and the rock mass has been constantly increasing because a better understanding of the rock mass behaviour implies a better result in reached in projects involving affection to rock masses. This paper briefly reviews the history of rock mass classifications, their implications in rock mechanics and their applicability in the definition of behaviours as a function of natural conditions and human action, as well as their direct implication in some fields of the transport infrastructures management with regard to hazard and risk assessment.

1. INTRODUCTION

The construction of infrastructures generates physical and geometrical changes of the ground in which they are integrated. It is necessary to have an explicit knowledge of the behaviour of the ground, as it will usually modify the natural equilibrium of the ground, which is constantly changing due to physical and geological processes.

The understanding of the micro and macro geological context is needed for its consideration in design processes. Therefore, the relationship between geological and engineering disciplines is required for proper design, construction and use. This article highlights the importance of the interpretation of the rock masses in which infrastructures are developed, from the point of view of design, construction and operation management.

The implication of Rock Mass Classifications (RMC) in the assessment of the safety and durability of infrastructures is addressed in this article through different risk and hazard indices, together with cases of infrastructure application and management.

2. GEOLOGY AND ROCK ENGINEERING

The geological model on which an infrastructure is built must encompass both the microscopic scale of the materials and their macroscopic scale and their geological evolution. Civil, mining and rock engineering intensively analyse the behaviour of industrial materials, and this same understanding should be transferred to natural materials such as soils and rocks, since, due to natural or anthropic processes, changes in their behaviour and, consequently, their action on infrastructures are imposed to them. For this reason, the relationship between engineering projects must be complemented with precise geological models. Civil and mining engineering have been designing structures on rock masses for centuries, using the principles of rock mechanics and engineering (Hoek, 2007).

The rock mass encompasses both the scale effect of the material that make it up, as well as its intrinsic characteristics as an isotropic material, and the singularities that make it anisotropic.

2.1 Geology in the engineering context

An understanding of the geological environment is required for proper design of excavations and foundations in infrastructures, whether tunnels, slopes or structures. Often, misconceptions are made in order to save costs and time in the development of projects, starting from extensive borehole investigation in the area under study, without taking into account the geological environment and its evolution in which the small-scale investigations are integrated (Hoek and Bray, 1977; 1989).

The geological setting, its configuration and state, has direct implications on the rock mechanics design with aspects such as: tectonic stresses, metamorphic processes, history of overburden and erosion discharges, as well as the modelling of the terrain by them, cooling processes of igneous material, sediment desiccation, etc (Palmstrom and Stille, 2015).

The influence of geological factors on rock mechanics, starting from the problem of mechanics of materials, has to do with the material sensu stricto and the forces that are imposed to it (Hudson and Harrison, 2000). From these basic principles of mechanics, basic forces and stresses are imposed to the rock mass, to which are added the physical actions of exogenous agents such as water and air and the action of these over time. It is well known that all the natural actions to which the rock mass has been exposed (rock intact + discontinuities) are processes of geological origin.

2.2 Rock mass units

The rock mass conceptually consists of two elementary units (Figure 1). Based on the geological conditions of the environment, the so-called intact rock and discontinuities are the main units defining the rock mass. In addition to these fundamental units, there are singularities of geological and hydrological origin, such as faults, karst, saturation, etc.

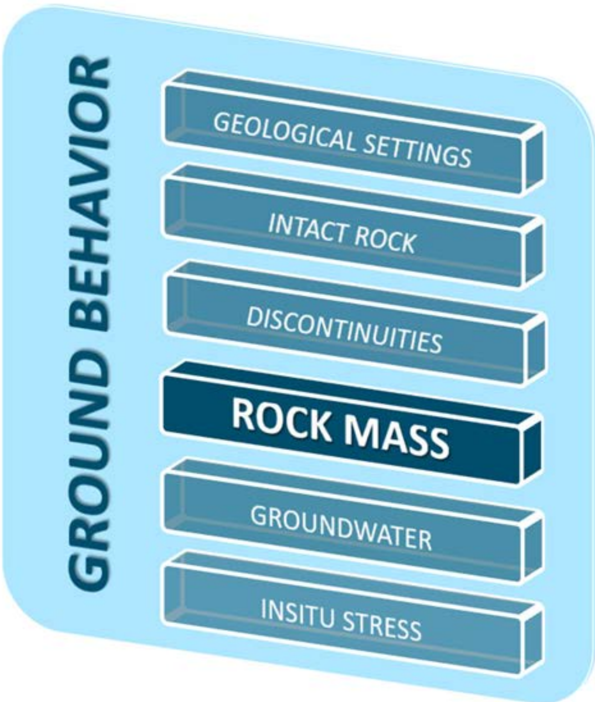

Fig. 1 - Ground behaviour and fundamental units

Homogeneous, isotropic material consisting of mineral aggregates, which can be crystals with or without preferred orientation or ammorphic masses, is called intact rock (Wittke, 2014). The aggregate of crystals and the matrix in which they are embedded, i.e. the mineral skeleton, exhibit mechanical properties that are used in rock engineering.

In various scientific publications, the rock mass is defined as a heterogeneous material consisting of fragments and blocks of rock of different sizes, intact or altered, with their defects, separated by a series of discontinuities, such as joints, faults, bedding planes, etc., which also vary in composition in space and time (Bieniawski, 1989; Potvin et al. 2012; Palmström 1996; Hoek and Brown 1980).

From the point of view of the fundamental units of the rock mass, intact rock and discontinuities, geological compression is essential, since the genesis of the material, its composition and physical-chemical properties, and consequently its mechanical properties, depend on the geological processes that the material has undergone throughout its geological history.

Likewise, within the geological history, the succession of tectonic processes generates stresses in the materials creating folding, compressional/distensive structures (faults). The physical/chemical changes (geomorphological/metamorphism) determine the structure and behaviour of the materials, as well as the topography modelled by the geological history. The evolution of the rock mass and its spatial distribution, episodes of kinematic instability and dissolution processes occur. These processes generate the natural conditions for the evolution of the relief, to which anthropic modelling must be added.

The singularities that characterize the rock mass, defined as the set of planes of weakness that interrupt the cohesion of the intact rock, are named with terms such as discontinuity, fracture, joint, lithoclase, with a common meaning in the specific literature.

2.3 Rock mechanics and Civil Engineering Project

Rock mechanics plays a fundamental role on the feasibility of a civil engineering project developed in a rocky environment. The principles and applications of rock mechanics are nowadays encompassed in what is known as Rock Engineering (Hoek, 2007). As mentioned above, Rock Engineering is closely related to the geological context, its interpretation and adaptation to engineering needs.

Mainly, but not only, solutions for infrastructure projects based on tunnels have been the ones that impose a lesser impact on the environment. At the same time, tunnel design for civil engineering projects has increased continuously during the last 70 years. Rock engineering requires well-structured development processes (Figure 2), always starting from a geological basis and how it conditions the success of the project.

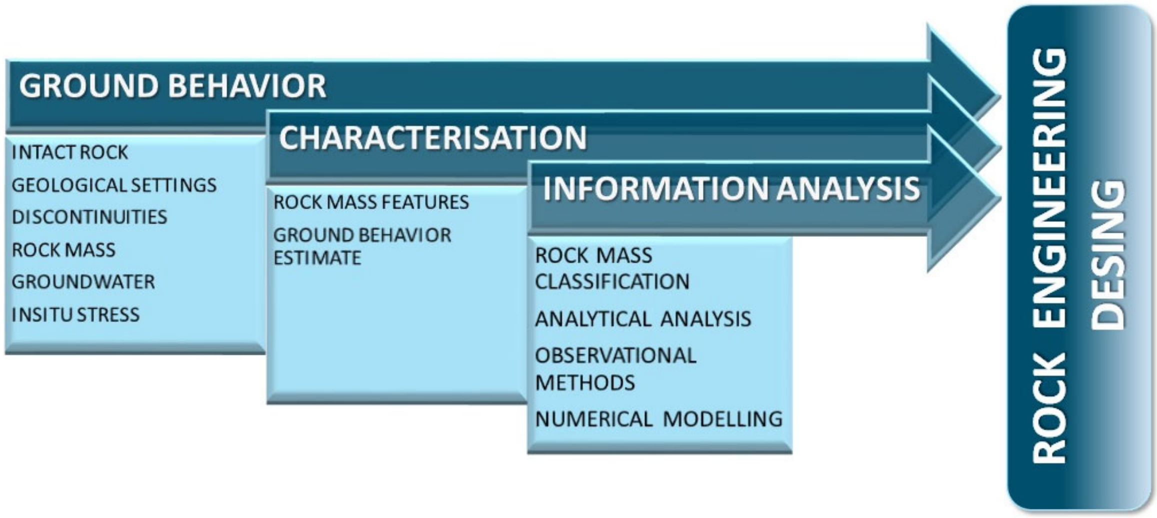

Fig. 2 - Rock mass units and Rock engineering relationship (based on Palmstrom, 2015)

With the structure of the basic processes required in a Rock and Civil Engineering project, the appropriate tools must be used to evaluate and develop the final design approach with the following items:

- Rock engineering processes (Figure 2)
- Feasibility
- Risk Management
- Estimation of time and cost of the project

From the Rock Engineering point of view, the geological context, its application to the design principles and the use of the needed tools for it, aims at achieving a design with the safety factors imposed by the standards, as well as the evaluation of the risks and costs necessary to carry out the design.

In both slope stability and foundations the processes have to be governed by the principles of Rock Engineering, but the design and construction of tunnels involves constant verification of the initial conditions during construction, as the uncertainty of material changes and investigation intensity may not be appropriate. Both geological and investigation uncertainty have a direct implication on the risk and costs of tunnel construction.

3. ROCK MASS CLASSIFICATIONS

3.1 Philosophy

Taxonomy is the science that deals with classifications, starting from theoretical aspects that involve foundations, principles, procedures and rules (Singh and Goel, 1999).

Throughout modern history, the rock mass has been the target of analysis, understanding and generation of indexes or languages to describe its quality or performance from an engineering point of view, but above all its stability and safety under modifications of its natural original state.

The rigour of the studies that lead to each RMC, as well as the simplification in the description of their nature and state summarised in different categories and/or parameters, make Rock Mass Classifications (RMC) a powerful tool that is easy to understand as well as widely used in different fields and stages of an engineering project. However, the application of RMC has to be exhaustive in its determination so that it can be assumed with guarantees as the basis of empirical design.

3.2 State of art

The development of geomechanical classifications began mainly to provide a tool for the construction of tunnels and mines. Later evolution led to their use also in the design of slope stability and bearing capacity of foundations.
Since first rock mass classifications appeared, the basic idea has been to reflect both aspects: the intact rock and the conditions and characteristics of the discontinuities that separate the rock into blocks, fragments or masses, thus making up the rock mass. Therefore, historically, an attempt has been made to categorize the basic aspects of an isotropic and homogeneous material from the matrix scale to the anisotropy and discontinuities that form the rock mass, depending on the scale assessed.

Thus, it is verified that the rock mass must be described as a discontinuous, anisotropic and heterogeneous material. Table 1 details the most common geomechanical classifications, with some others of minor relevance or use in rock mechanics projects (Cosar, 2004; Fernandez-Gutierrez, et al. 2017).

Rock Mass Classification	**Author**	**Application Areas**
Protodyakonov	Protodyakonov (1907)	Tunneling
Rock Load	Terzaghi (1946)	Tunneling and steel support
Stand-up time	Lauffer (1958)	Tunneling
Rock Quality Design (RQD)	Patton (1967)	Core logging and tunneling
Rock Structure Rating (RSR)	Wickham et al. (1972)	Tunneling
Rock Mass Rating (RMR)	Bieniawski (1973, 1989, 2014)	Tunnels, mines, slopes and foundations
Rock Mass Quality (Q index)	Barton et al. (1974, 2002)	Tunneling, mining, foundations
Strength-Block size	Franklin (1975)	Tunneling
Basic geotechnical classification	ISRM (1981)	General

Rock Mass Classification	Author	Application Areas
Rock Mass Strength (RMS)	Stille et al. (1982)	General
Slope Mass Rating (SMR)	Romana et al. (1985)	Slopes stability and support
Modified Rock Mass Rating (M-RMR)	Ünal and Özkan (1990)	Mining
Slope Mass Rating (SMR)	Romana et al. (1985)	Slopes stability and support
Rock Mass Index (RMi)	Palmström (1996)	Tunneling
Rock Condition Rating (RCR) and Rock Mass Number (N)	Goel et al. (1996)	Tunneling
Geological Strength Index (GSI)	Hoek et al. (1997, 2013) Cai et al. (2004)	All underground excavations
Rock Mass Quality Index	Aydan et al. (2014)	Rock mass properties
Rock Mass Quality Slope (Q Slope)	Barton and Bar (2017)	Slopes, cliffs

Table 1 – Compilation of Geomechanical Classifications

Most of geomechanical classifications, as shown in Table 1, were proposed to help engineers during design of tunneling and mining supports. Taking advantage of the development of these indices, the fields of applicability of RMCs, such as slope and foundation stability and the estimation of rock mass properties, have been extended.

Talking about the origin of the classifications, the one that has gained more relevance throughout history has been RQD (Deere and Patton, 1971) due to its integration in other indexes and its applicability in tunnels, slopes. It also allows the possibility of its estimation in any rock outcrop.

Historically, the most widely used classifications, mainly for the design of tunnels, are: RMR, Q index, GSI, and RMi. These RMCs have been listed in order of relevance in terms of their use in projects.

3.3 Description and relationships

The relationships between the most relevant geomechanical classifications will be shown below, based on the parameters that are considered or evaluated in each one of them. The formulations of each classification are also summarised.

3.3.1 Rock Mass Rating (RMR)

The Rock Mass Rating, RMR, was initially proposed by Bieniawski (1974; 1975; 1976; 1979; 1989). It is an index that evaluates the competence of the rock mass based on 6 parameters:

- R_1: Intact rock strength.
- R_2: Rock quality designation (RQD).
- R_3: Joins Spacing (J_s).
- R_4: Joints conditions (J_c).
  - $R_{4.1}$: Persistence
  - $R_{4.2}$: Aperture
  - $R_{4.3}$: Roughness
  - $R_{4.4}$: Joint weathering
- R_5: Groundwater Condition
- R_6: Discontinuities orientation correction.

Equation (1), established by Bieniawski (1974; 1989; 2000), is based on the arithmetic sum of the parameters participating on the classification. Since 2000, there are trends involving the parameters R_2 and R_3 (R_{2-3}) (Bieniawski, 2011) in order to determine the joint/meter scores from 40 to 0 for jointless masses (0 joints/meter) to extremely jointed rock masses or sugar cubes (50 joints/meter), shown in Equation (2).

$$RMR_{c(73-89)} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \quad (1)$$

$$RMR_{c(89)} = R_1 + R_{2-3} + R_4 + R_5 + R_6 \quad (2)$$

The characterization without the water effect (R_5) and the correction for the orientation of the discontinuities with respect to the construction element (tunnel, slope, and foundation) is called RMR_b (basic), shown in Equation (3).

$$RMR_b = R_1 + R_2 + R_3 + R_4 \quad (3)$$

In 2014, the relation of the original 6 parameters is updated to Equation (4) and renamed RMR_{14} (Celada et al. 2014) using 3 factors, named F_0 (which is approximately R_6, according to 1974-1989's classification), F_e (excavation method adjustment) and F_s (stress-strain associated with tunnel face behaviour).

$$RMR_{14} = (RMR_b + F_0) \times F_s \times F_e \quad (4)$$

The rock mass is classified into 5 classes according to standardised methodology scores.

3.3.2 Rock Mass Quality (Q index)

The Quality Index, developed by Barton and co-workers in 1974 (Barton et al. 1974) and in later years (Barton et al. 1976;, 1977; 1980), also uses 6 parameters to estimate rock mass behaviour:

- Rock Quality Design (RQD).
- Joint set number (*J_n*).
- Joint roughness (*J_r*).
- Joint alteration number (*J_a*).
- Joint reduction number (*J_w*)
- Stress Reduction Factor (*SRF*).

Equation (5) defined by the author, is divided into 3 ratios, each one being indicative of three very important concepts in Rock Mechanics.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad (5)$$

Where some parameters are grouped:

- Block Volume = *RQD*/*J_n*
- Shear strength = *J_r*/*J_a*
- Active Stress = *J_w*/*SRF*

In 2002, in order to establish correlations with other ground parameters the original author (Barton, 2002) presented the modified index, *Q_c*, which relates the simple compressive strength of intact rock (σ_c) to the Q index, reducing the quality of the rock mass for values of Q < 100, Equation (6).

$$Q_c = \sigma_c \times \left(\frac{Q}{100}\right) \quad (6)$$

The rock mass is classified into 9 classes or categories, which according to Grimstad et al. (2004) are recommended for tunnel support technologies.

3.3.3 Geological Strength Index (GSI)

Geological Strength Index (GSI), was developed in 1995 by Hoek et al. (1995). This qualitative observational index originally related the structure of the rock mass according to the degree of fracturing and its volumetric arrangement, together with the state of the rock mass itself in its surface (Sanchez et al. 2017).

This index is constantly being reviewed and updated by different authors. An example of this, is the calibration of Cai and Kaiser (Cai et al. 2004) shown in Figure 3 which includes the relation to the joints condition. Russo (2007) also includes to this the *jC* parameter of RMi, which is based on quantitative parameters. Both are included in classification abacuses.

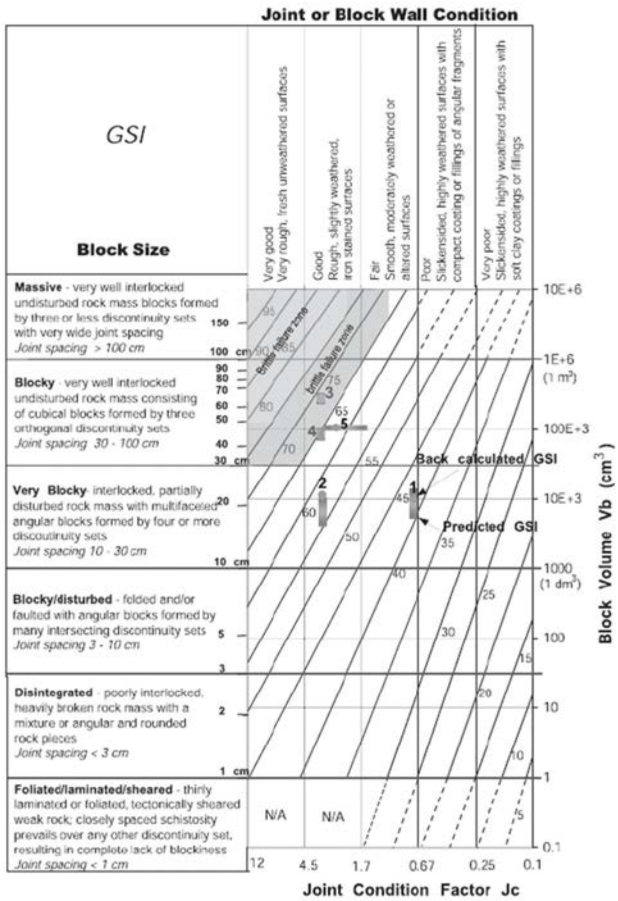

Fig. 3 - Hoek's chart for the determination of the GSI modified by Cai, Kaiser et al. (2004)

Hoek et al. (2013) related the joint condition ($JCond_{RMR89}$) of RMR_{89} (3), Equation (7) and the parameters defining the shear strength of the joints (J_r and J_a), according to Q system, Equation (8), so that the GSI value and its classification can be obtained based on the most common geomechanical characterisations.

$$GSI = \left(1{,}5 * JCond_{RMR_{89}}\right) + \frac{RQD}{2} \tag{7}$$

$$GSI = \frac{52\frac{Jr}{Ja}}{\left(1+\frac{Jr}{Ja}\right)} + \frac{RQD}{2} \tag{8}$$

Based on the graph, the rock mass is classified into 6 block size ranges and 5 rock mass states, related to each other by the score obtained.

3.3.4 Rock Mass Index (RMi)

Rock Mass Index (RMi) was developed by Pälmstrom in Oslo (Norway) in 1995 (Palmström, 1995) taking into account the main parameters of the rock mass and intact rock. This classification relates the uniaxial compressive strength of intact rock to the shear strength properties of the joints that divide the rock into blocks.

Relationships are differentiated for jointed rocks, Equation (9), and massive rocks, Equation (10).

$$RMi = \sigma_c * JP = \sigma_c * \sqrt{jC} \times {V_b}^D \quad (9)$$

$$RMi = \sigma_c * f_\sigma = \sigma_c * \left(\frac{0{,}05}{Db}\right)^{0{,}2} \quad (10)$$

Where σ_c is the uniaxial simple compressive strength of the intact rock, *JP* is the joint index that defines the conditions of persistence, aperture and roughness of the joints, V_b and D_b are the parameters defining the volumetric and surface geometry respectively. *D* is a correction parameter for the joint condition *jC*. f_σ is the massivity factor of the rock mass.

3.3.5 Relationships and Correlations

As has been briefly described, each RMC considers a different relationship between the fundamental units of the rock mass, such as the intact rock and the discontinuities that divide it, being these two main concepts the ones that are common to all classifications.

In Figure 4, it is schematically shown which parameters of the geomechanical characterisation of the rock mass are evaluated by each RMC, as well as the relationship with the geological and geomechanical models that have to integrate the rock mechanics designs and their relationship with civil engineering projects. Some classifications developed for tunnel support, such as RMi, include factors such as the number of joint families and the orientation in relation to underground excavation, water affection or stress state, for the estimation of the recommended support, but not in the geomechanical classification sensu stricto.

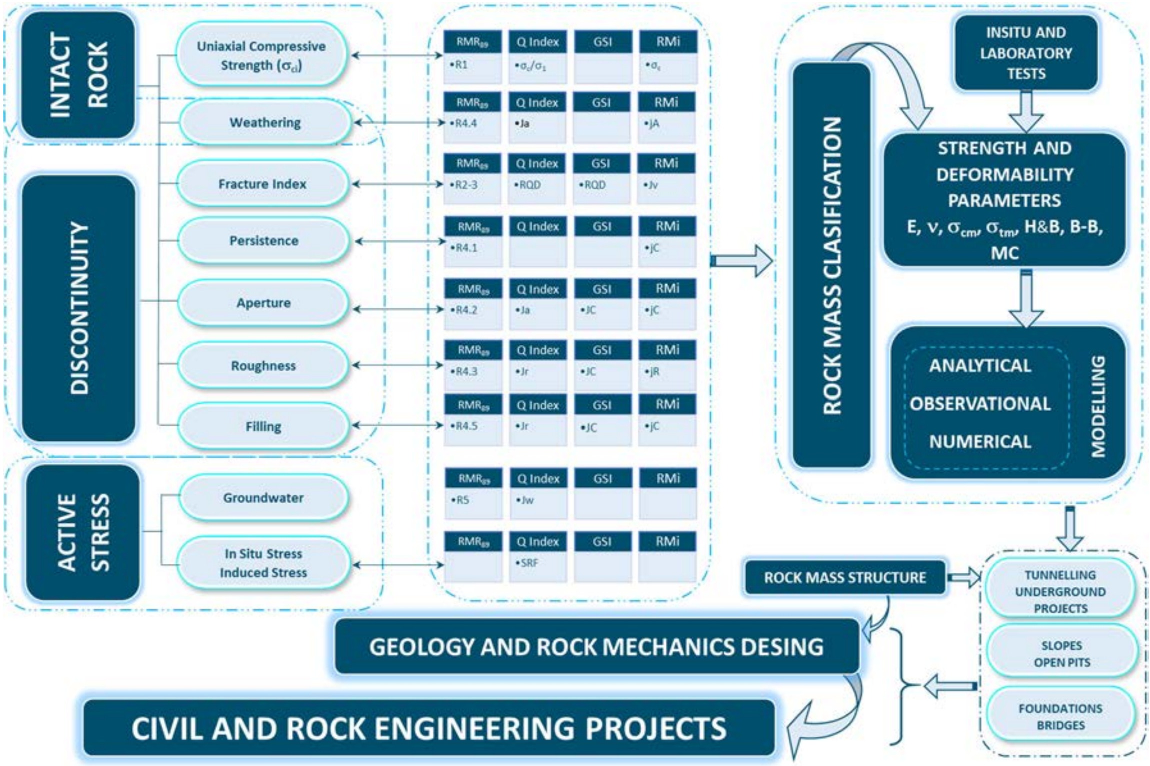

Fig. 4 - Rock Mass Classifications and Civil Engineering Projects

On the other hand, RMCs have been studied to propose a great number of correlations, mainly between RMR and Q and between RMR and GSI. There is a large number of authors and correlations between various geomechanical systems or indices in the specific literature. In this article we show graphically some correlations, obtained for specific lithologies, since it is considered by the authors, that in the field of correlations, lithologies of similar sedimentary and tectonic environments, show better fitting than general correlations for any type of lithology (Sánchez et al. 2016; Fernandez-Gutierrez et al. 2017). Figure 5 shows the correlations between RMR and Q, both generally, as well as the one developed by Fernandez-Gutierrez et al. (2017), which analyzes the relationship for fine-grained sedimentary rock formations.

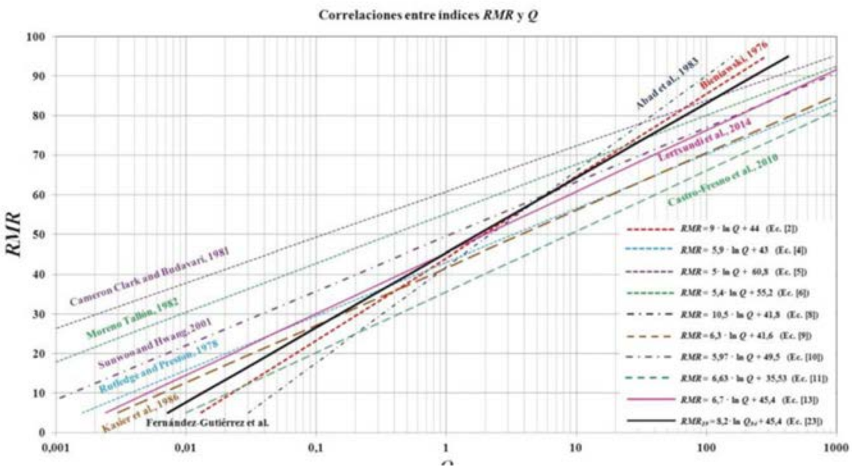

Fig. 5 - RMR-Q correlations (Fernández-Gutiérrez et al. 2017)

Figure 6 shows the comparison of correlations between RMR and GSI for different lithologies in Andean environments (Sánchez et al. 2016) compared to the original one proposed by Hoek (Hoek 1995).

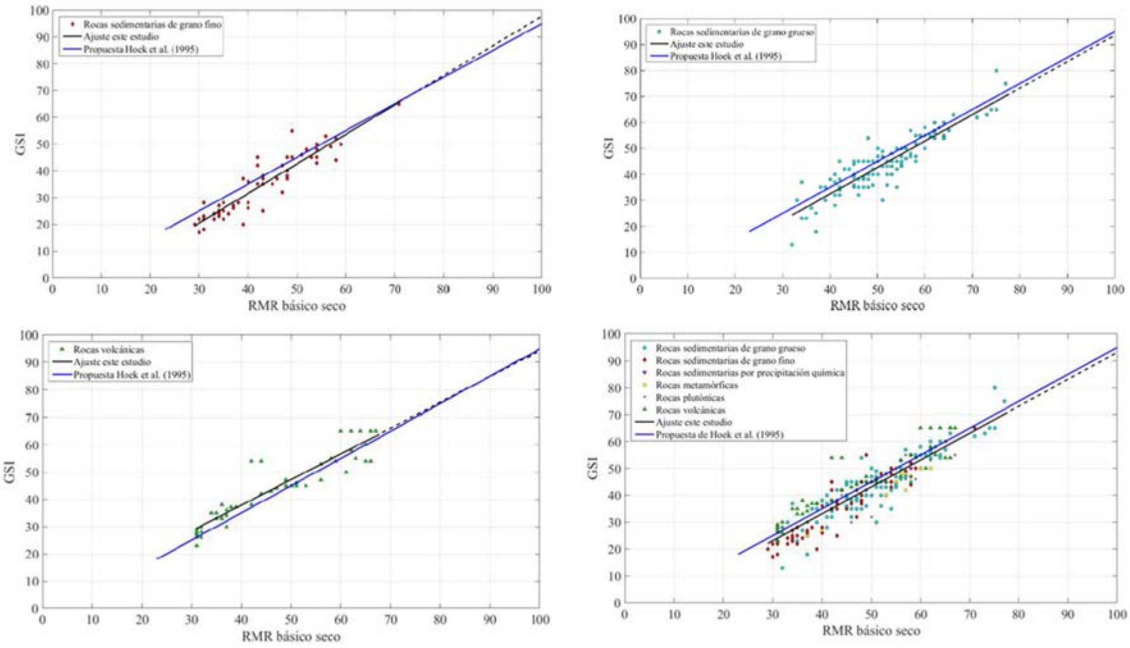

Fig. 6 - RMR-GSI correlations in Andean environments (Sanchez et al. 2016)

4. ROCK MASS CLASSIFICATIONS FOR SAFER INFRAESTRUCTURES

As shown so far, the relationship of geology with geomechanical characterization and design plays a very important role in the final designs of a civil engineering project. Therefore, a bad design, either due to the lack of budget, lack of importance given to the role of rock mechanics, or lack of expert judgement, has serious implications in relation to the safety, risks, durability and final costs of an infrastructure.

In the specific literature, there are numerous cases of the relationship between design costs and construction costs due to causes usually referred to as geological. Some of these causes may be difficult to detect, but many others are due to a lack of rigour in the design.

Figure 7 (Palmstron et al. 2015) shows the sequence of an underground excavation project and the influence of a good design (rock mechanics and engineering) over the final costs, compared with a bad design where the final cost is increased. It can be seen how the costs and time during the construction and operation phases can be very high when proper management of design fails.

Generally, an infrastructure project is designed under the regulations of each country, the Eurocode 7 and the specifications of each infrastructure owner.

A rigorous approach should impose that each design of slopes, walls, foundations, embankments and tunnels had to be verified during construction according a Factor of Safety requirement, comparing this with the design.

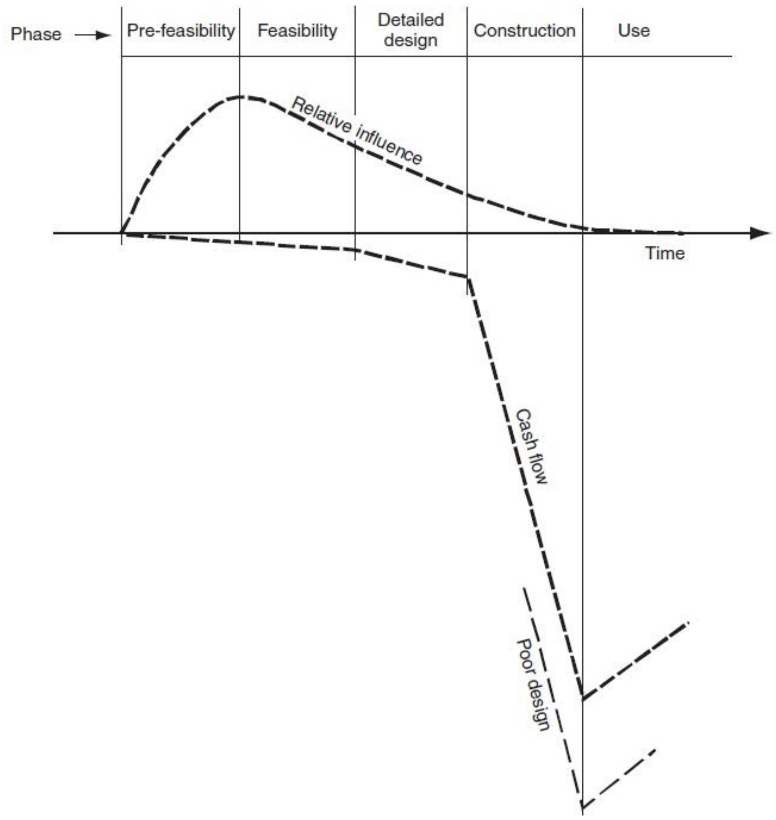

Fig. 7 - Relationship between costs and project stages (Palmström, 2015).

The analysis and implications of the factors of safety requirements by any Rock and Civil Engineering projects is not the subject of this paper.

4.1 Infrastructure risk management

Once the construction phase of the infrastructure has been completed, it should be mandatory to verify the available Factor of Safety (FoS) compared with respect to that proposed or deduced during design phase. This one should be the starting point for verifying the evolution of the finished works during its operation life. In most cases, this post-construction condition is not correctly assessed, which generates increased maintenance and risk remediation costs. These costs are often higher than those during the construction phase and also involve the users.

The relationship of the probability of failure to the safety factor (Figure 8) is related to the quality in engineering studies, (Silva et al. 2008). In this study, based on the analysis of real cases in dams, it is stated that for the cases of high FoS (Factor of Safety), high failure probabilities can be associated with the quality of the engineering projects.

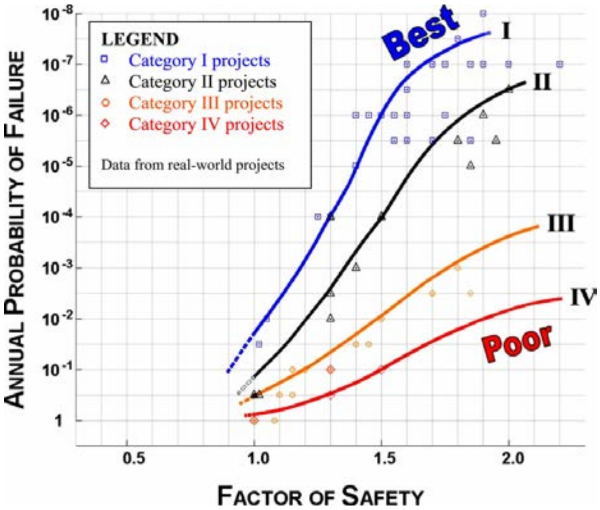

Fig. 8 - Factor of safety versus annual probability of failure (Silva et al. 2008).

Figure 9 adapts the flow chart defined by Fell (Fell et al. 2008), defining risk assessment and risk management analysis process, which can be generally applied to infrastructures with risks due to ground instabilities (slopes, foundations or tunnels), taking as final target risk mitigation and management strategies. The hazard of a phenomenon has a fundamental weight on the degree of risk, which is ultimately defined by exposure and vulnerability (UNISDIR 2009).

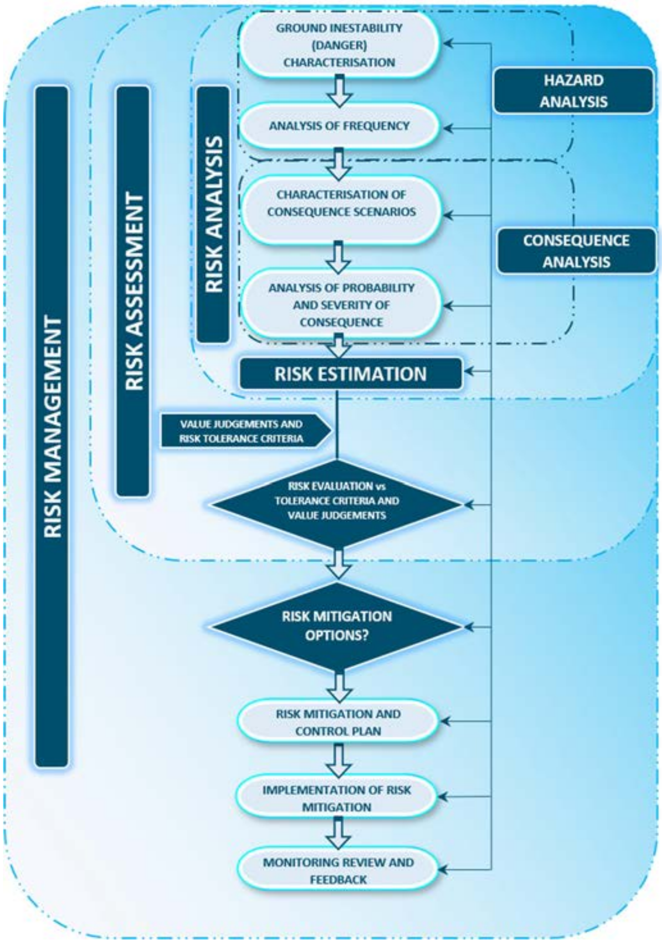

Fig. 9 - Framework of geotechnical risk network (based on Fell et al. 2008)

4.2 Risk management in tunnels

In this section, only the geotechnical risks which can occur in a tunnel are considered. The involvement of the rock mass in the construction of tunnels results in a series of geological and geotechnical risks which have to be assessed in the design and construction of tunnels. (E Matos et al. 2006).

Figure 10 shows the relationships between the technical expert involved in tunnel design, associated with geology and rock engineering, including technical and economic feasibility.

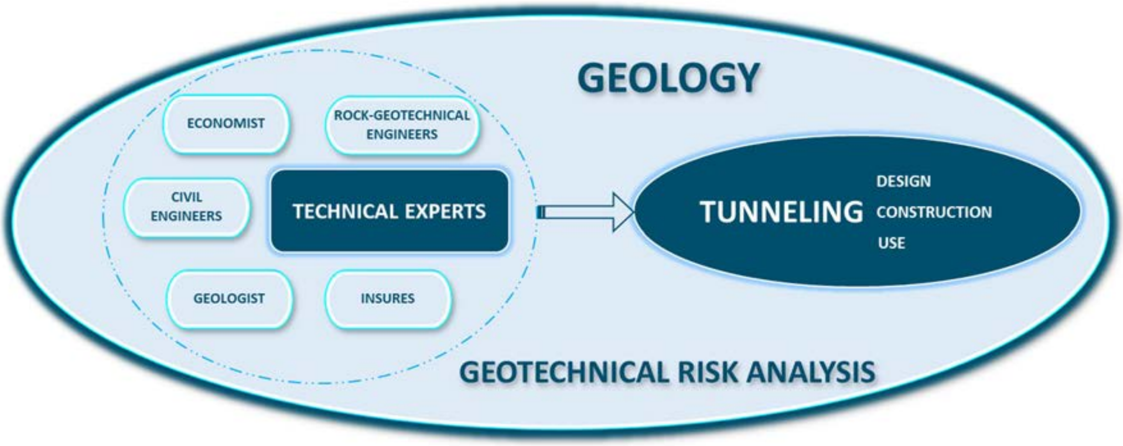

Fig. 10 - Elements involved on risk analysis in tunnels (based on Matos et al. 2006).

Some typical geotechnical risks might be:

- Unstable slopes or rock falls at road o rail infrastructures or tunnel portals.
- Problems with construction through fault zones, low strength of the rock mass, lack of stability and squeezing conditions
- Potential effects of the project to the environment, such as settlements or vibrations.
- Changes of the natural water regime, water inrush in tunnels
- Karst conducts and cavities
- Earthquake loads

As an example of the treatment of geotechnical risks in tunnels, the study of the underground museum in Salzburg (Schubert, 2006) is presented. In the analysis, which started in 1990, the geotechnical hazards were classified into risk factors and solutions were found to mitigate them, thus reducing the costs which were initially assessed.

Table 2, relates the geological risk factors and their probability of occurrence in Monte Carlo analysis, obtaining the volume of ground affected. In addition, the risk factors with the associated potential costs (horizontal axe) are schematically shown in Figure 11.

Geotechnical risk factors	Probability of occurrence		Quantity	Unit
	From	To		
R1 loose, un—cemented conglomerate	1%	3%	96.000	m^3
R2 need of grounting to strengthen of rock mass	5%	10%	12.000	m^3
R3 need of surface treatment of conglomerate	30%	70%	3.000	m^3
R4 extensive water seepage	0%	2%	96.000	m^3
R5 major unfavorable joint, need of pre-stressed anchors	50%	150%	10	Stk
R6 treatment of caves	110%	130%	1.000	m^3

Table 2 - Geotechnical risk factors quantity and probability of occurrence.

4.3 Risk management of slopes

Road and railway infrastructures, with linear designs, usually in some of their sections are located in areas that require excavation for geometric fitting, generating slopes.

In the case of rock slopes, in addition to characterization, analytical, observational and numerical studies, geological and geotechnical risk assessments should be carried out during design and construction. Geological risk assessments, in this case of slope instabilities in transport infrastructures, should be confronted by infrastructure managers using specific tools such as hazard and risk indices.

In this section, mention is made of the implications of geomechanical classifications and rock mass characterisation applied to hazard and risk indices in various studies.

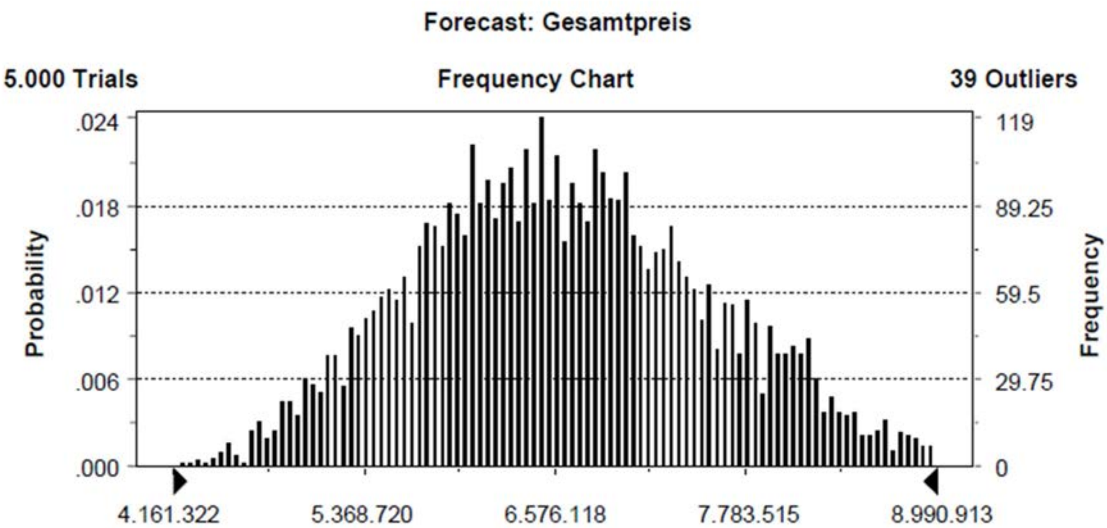

Fig 11 - Geological geotechnical risk factors and their expected cost variation (Schubert, 2006)

The *Rockfall Hazard Rating System (RHRS)* developed by Pierson, 1990 in Oregon for FHWA, considers qualitative rock mass criteria, modified by Budetta (2004) using the SMR (Romana, 1995) geomechanical slope index. This index has 9 exponential scoring categories. The methodology bases its classification on 9 factors grouped into geometry, infrastructure characteristics, geology and geomechanics, climatology and frequency of rockfall instabilities (Geoconsult, 2019). The purpose of the methodology is the evaluation of the characteristics of the infrastructure to allow rockfall conditions according to the original methodology (Pierson, 1990), but adapted to any kinematic instability of the rock mass, planar, wedge, toppling failure (Budetta, 2004). Depending on the danger posed by the hazard, the magnitude and frequency are evaluated, as well as the road platform, in relation to the visibility and distance of reaction of the drivers in case of falling of any object on the road. The volume of this object as well as the slope of the route are also considered.

Geoconsult in 2018 adapted methodology proposed by Budetta (2004) according to Spanish road standards, analysing 27 km of road to categorise the existing risks on the A-136 road in Huesca (Figure 12).

In this case, the infrastructure owner is provided with a tool for monitoring the risks present on the road, as well as with a strategic plan with mitigation measures and criteria for maintenance investment prioritization.

Figure 13 shows the dispersion in the estimation of geomechanical quality in rock slopes defined with RMRb and SMR.

Logically, the rock mechanics and geology component in the risk assessment of this methodology is a key issue, as it is a geological hazard process.

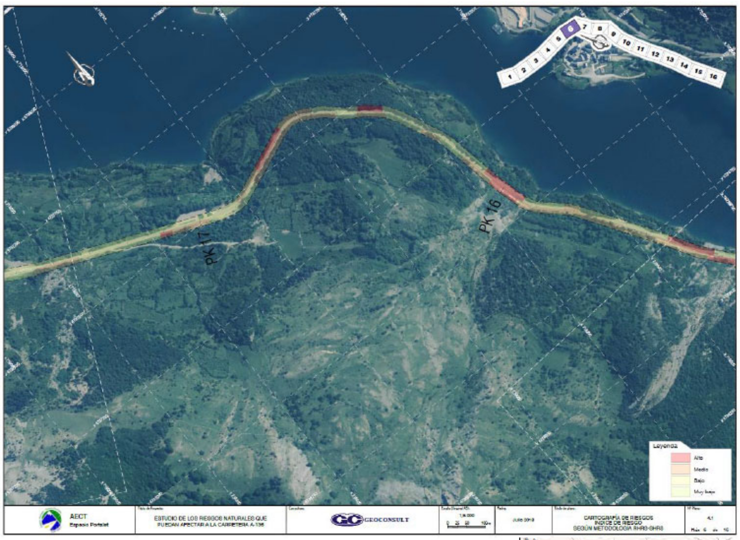

Fig. 12 - Map of a sector of the A-136 road classified with RHRS (Geoconsult, 2018).

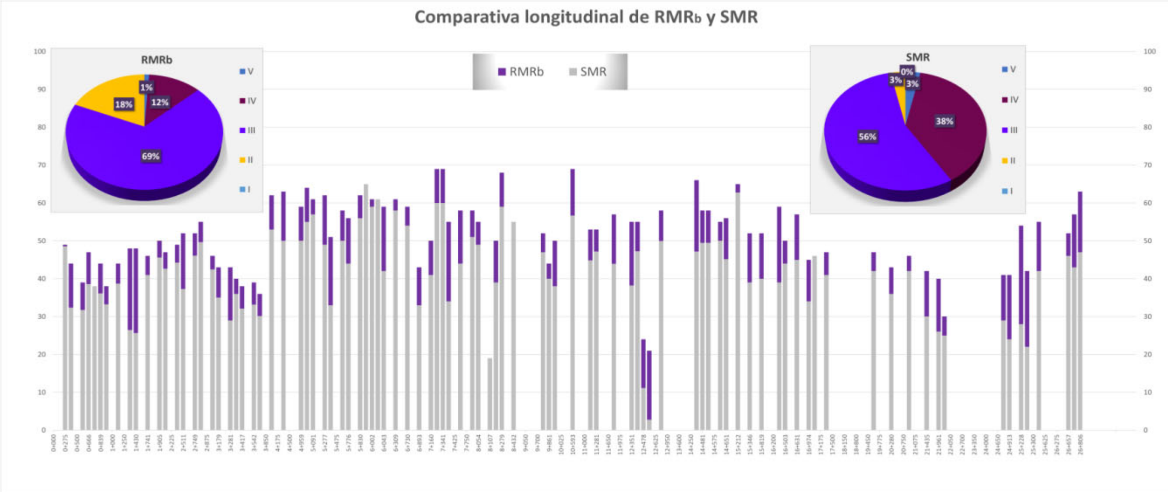

Fig. 13 - Comparison of the geomechanical quality according to RMR_b and SMR in the rock slopes of the A-136 road.

On the other hand, Corominas et al. (2017) used a single quantitative risk assessment criterion (QRA, ECR Spanish acronym) for road infrastructures in Gipuzkoa. This methodology was introduced by Fell et al. (2008).

Quantitative Risk Assessment, QRA, (Fell et al. 2008; Corominas et al. 2017) consists on the quantitative determination of risk based on the probability of failure/breakage and its consequences (Fell et al. 2005), in Risk Points (PoR Spanish acronym) located along the infrastructure analysed in the study.

Parameters are defined as Cost Units (CU) for all situations, considering direct and indirect costs, based on affection and closure conditions of infrastructure due to incidents (mainly of geological hazard such as slopes failures in rock mass). Phenomena related to the rock masses which usually can cause fail in the operation and whose common descriptor is the amount of damage to the infrastructure have been included in Table 3.

Notation	***Mechanism***	***Discipline***	***Cost Unit evaluation***
DR	Rockfall	Rock Mechanics	CU / m^3
CD	Debris Flow	Geotechnical Engineering	
EC	Support Failure	Rock and Civil Engineering	
RL	Brittle failure (lanslide)	Geotechnical and Rock Engineering	CU / m^3 and length

Table 3 – Failure Mechanism, Discipline and Cost Units (based on Corominas et al. 2017).

5. CONCLUSIONS

Geological models and their relationship with the characterization of the rock mass have a fundamental role in rock mass classifications (RMC) for the adequate development of Rock and Civil Engineering projects.

The construction of tunnels, slopes and foundations in transport infrastructures must be undertaken through a well-structured process of analysis and design of the stability of the rock mass in which they are located. The quality of the engineering studies and their control during construction have a direct relationship with the costs of the infrastructure, implying that a low-quality project may involve more failures per year, even with an adequate safety factor, as the uncertainty of the process and investigation intensity followed during the design and construction phases are possibly higher than high quality projects.

Risk assessments of transport infrastructure against geological hazards associated with rock mass stability have a direct relationship with infrastructure operation and costs for the owner and users.

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ITS, OPERACIÓN Y GESTIÓN
ITS, OPERATION AND MANAGEMENT

AN EMPIRICAL ANALYSIS OF UBER FARES: EVIDENCE FROM MADRID

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ABSTRACT

Ride-hailing is an emerging service that is transforming door to door mobility in urban areas. Users can easily request a ride through a smartphone app that informs them of the pickup time, the location of the vehicle, and the fare that they will pay in advance. Even though it is well know that Uber implements a dynamic pricing approach depending mostly on supply, demand and competition with other services, there is still little empirical evidence on the main drivers explaining the fare strategy of the company. Using 10-month data from the Uber's Application Programming Interface (API) in the city of Madrid, this research studies the evolution and trends experienced by Uber fares in terms of several explanatory variables. It also explores the main differences between Uber and taxi fares.

The results indicate that trip distance, day of the week, origin and destination of the trip, and rain precipitation have a statistically significant impact on Uber fares. The findings also show that on average, Uber fares are lower than taxi fares, with the exception of particular hours of the day. The analysis also demonstrates that Uber fares slightly decreased during taxi strikes.

1. INTRODUCTION

Information and Communication Technologies (ICT) are radically changing mobility habits as they help connect customers to services through smartphone applications. These apps have important advantages to riders in terms of information, availability, and payment systems. Taking advantage of ICT, ride-hailing is one of the emerging mobility options that is revolutionizing door to door mobility services.

Users can easily request a ride through a smartphone app that informs them of the pickup time, the location of the vehicle, and the fare that they will pay in advance. The app also facilitates the payment to the user.

Uber, Lyft, Cabify, and Didi Chuxing are examples of ride-hailing companies offering their services through smartphone apps. The popularity of these companies is rising due to their availability, convenience, and quality of service compared to traditional taxi systems (Rayle et al., 2016; Shokoohyar et al., 2020). As a consequence of that, traditional cabs, threatened by ride-hailing apps, have set strikes and demonstrations all around the globe to protest for what they consider unfair competition.

One of the main differences between ride-hailing and taxi services is that ride-hailing platforms freely adjust their fares using real-time dynamic algorithms (K. Chen & Sheldon, 2015), while taxi fares are fixed and generally regulated. That means that ride-hailing fares automatically increase when demand is higher than the supply of drivers within a specific area. Dynamic pricing is also called “surge pricing”, and it is an automated system based on the simple principles of demand and supply conditions. Thus, passengers pay a higher fare for rides during times of high demand. When fares applied sharply increase due to high demand conditions, users are generally informed prior to requesting a ride.

The aim of this study is to explain and understand fare patterns by ride-hailing operators. To that end, we collected data from one of the most popular ride-hailing companies worldwide, Uber, so as to conduct an econometric model to explain Uber fares as a function of several exogenous variables. The research exploits supply data from Uber rides collected in the city of Madrid from September 2018 to June 2019, which were obtained by the Uber’s Application Programming Interface (API).

This paper contributes to the state of the art on transportation networking companies (TNCs) in three main aspects. First, we analyse the fares applied by a ride-hailing operator over a long period of time (ten months), to explore the evolution of Uber fares according to several variables. Some previous studies are based on simple simulation approaches (Pepić, 2018), or online surveys to riders (Smart et al., 2015), but did not examined prices actually offered to ride-hailing customers. Other contributions have focused on fare supply during short periods (days or weeks), or special events (L. Chen, n.d.; Hall et al., n.d.; Jiao, 2018; Shokoohyar et al., 2020), but they lack insight from longer timespans, which is important to obtain robust conclusions on the patterns followed by ride-hailing fares. Second, we compare Uber and taxi fares using real data about prices. And third, due to some particular characteristics of the case study, we study to what extent taxi strikes impact on Uber fares.

The paper is structured as follows. After this introductory part, the state of the art and practice concerning ride-hailing services is provided.

A description of the main characteristics of Uber and taxi services in the city of Madrid (Spain) is then presented. This is followed by the description of the data set, their descriptive statistics and the model specification used for this research. The main findings on the evolution of Uber fares and the comparison between Uber and taxi prices are presented. The last section draws the main conclusions and new research avenues.

2. RIDE-HAILING DEMAND AND SUPPLY: SCIENTIFIC BACKGROUND

The scientific literature devoted to ride-hailing has increased in the past few years in parallel with the increasing adoption of these services worldwide. Despite the limited amount of empirical data available up to date, many contributions have been conducted in different research areas regarding ride-hailing, namely: individuals' adoption and frequency of use of these services, estimates of ride-hailing effects, and knowledge of ride-hailing supply. It is worth noticing that nowadays, the majority of research pieces are focused on specific countries, such as the US and China (see comments by e.g. (Mohamed et al., 2019)), with only a few analyses conducted in other geographical areas.

The first group of contributions has modelled individuals' adoption and frequency of use of ride-hailing, both at the individual and trip level as noted by (Lavieri & Bhat, 2019). These papers conduct econometric models to identify the explanatory factors determining the use of these services . For instance, many research works have concluded that ride-hailing users tend to be young people, are familiar with new technologies, and have a higher level of education (see e.g. (Alemi et al., 2018; Rayle et al., 2016; Wang & Mu, 2018)). Furthermore, it has been found that wealthy individuals and residents of urban areas are more likely to adopt ride-hailing services (Alemi et al., 2018; Goodspeed et al., 2019; Lavieri & Bhat, 2019; Tirachini & del Río, 2019; Yu & Peng, 2019). These papers are typically based on the information collected through questionnaires or geo-located trips provided by ride-hailing operators.

The second group of contributions is aimed at approaching the effects of ride-hailing services on the performance of urban sustainability indicators. For instance, there is evidence that the irruption of ride-hailing services has resulted in an increase of road congestion (see, e.g., (Clewlow & Mishra, 2017; Erhardt et al., 2019; Gehrke et al., 2018; Wenzel et al., 2019)). Regarding the impact on other transport modes, many authors such as (Nie, 2017), (Shaheen et al., 2016), or (Henao, 2017) have found out that transport demand of ride-hailing has been mainly captured from taxi services and, to a lesser extent, public transport. Among the positive effects of ride-hailing, we can mention the improvement of road safety (Peck, 2017) and the encouragement of car-free styles (Jin et al., 2018).

Other aspects such as the real impact of ride-hailing on car ownership decisions remain unanswered, with contributions concluding positive (see e.g. (Gong & Song, 2017)), negative (e.g., (Gehrke et al., 2018)) or even neutral effects (e.g. (Rayle et al., 2016)).

Again, these research works generally use information from surveys or geo-located trips.

Finally, the third group of contributions focuses on the supply side of ride-hailing. Given the scarcity of empirical data and the unfeasibility to get large amounts of information from e.g. questionnaires, these papers have often obtained data through Application Programming Interfaces (APIs) provided by operators. For instance, (Cramer & Krueger, 2016) analysed the utilization rate for Uber drivers versus taxi drivers in five major US cities. They concluded that ride-hailing drivers present a significantly higher fraction of their time and share of miles driven with a passenger in their car. (Berger et al., 2018) examined how the irruption of ride-hailing impacted the taxi supply and found a noticeable decline in taxi drivers' earnings, but not in their level of labour supply. Similarly, for the case of Spain, (Akimova et al., 2020) found that the irruption of ride-hailing companies in this country had a significant negative impact on the profitability of the traditional taxi companies in Madrid and Barcelona. Additionally, (Brodeur & Nield, 2018) studied the influence of weather conditions on ride-hailing demand in NYC, concluding that ride-hailing trips increase by 19% when it rains.

Price is a key factor generally considered when analysing ride-hailing supply. For instance, (Shokoohyar et al., 2020) studied a 13-day database collected from the Uber and Lyft APIs to determine to what extent weather conditions influence ride fares, trip duration, and pick-up waiting time in the city of Philadelphia. They found a statistically significant positive effect of extreme weather conditions on ride-hailing fares during weekdays, and a negative impact during weekends due to the lower demand experienced those days compared to normal weather conditions. By exploiting a randomly-drawn Uber dataset from several US cities, (K. Chen & Sheldon, 2016) studied how driver-partners on the ride-hailing platform respond to the dynamic pricing of trips and concluded that drivers tend to drive longer and provide more trips at times with high surge prices.

Despite the increasing attention devoted to the study of ride-hailing services, the current literature has some gaps that have motivated this research. As can be observed, there is a need in the current literature to analyse the evolution of ride-hailing fares during longer periods of time to capture for instance monthly variations. While previous contributions have focused on short timespans, longer periods may allow e.g. exploring potential seasonal effects on ride-hailing fares and obtaining more robust conclusions on their change over time. Additionally, competition between ride-hailing companies and taxis should be explore more in depth.

While previous contributions such as (Akimova et al., 2020) have focused on the impact on earnings, from the supply side, it should be interesting to compare the evolution of fares in ride-hailing services versus the prices applied by taxis, their direct competitors. In this respect, (Smart et al., 2015) found that, for the case of Los Angeles, Uber rides were cheaper by a considerable measure compared to taxis. While this result is based on an online survey to riders, comparing ride-hailing and taxi fares through more massive datasets would provide additional and useful insight.

Finally, given the direct competition between taxi cabs and ride-hailing services, there is a lack of evidence on how an event concerning the taxi supply (e.g. strikes in the taxi sector) impacts on ride-hailing services.

3. THE CASE STUDY OF MADRID CITY

This section provides a brief description of the case study selected to analyse the trends and evolution followed by ride-hailing fares, and their comparison with prices in the taxi sector. Madrid is the capital of Spain and its most populated city, with a total of 3.3 million inhabitants and a metropolitan area comprising 6.5 million inhabitants. The city has two main ring highways (M-30 and M-40), which absorb a significant share of intra-city trips made by private vehicles. In recent decades, Madrid has experienced rapid growth, and a suburbanization process, so many residents and jobs are moving from the city center (districts inside the M-30 ring) to outer neighbourhoods or municipalities within the Madrid metropolitan area.

Mobility in Madrid is characterized by a strong presence of public transport modes. According to the last Metropolitan Mobility Survey (Consorcio Regional de Transportes de Madrid, 2019), there are 7.9 million trips on average in a working day in the city: 36.1% of trips are made on foot, while private transport and private vehicle trips account for, respectively, 33.8% and 26.3% of the trips. Minority options (taxi, ride-hailing companies, bicycle, motorcycle, etc.) represent 3.4% of urban trips.

Ride-hailing services started to operate in Spain in the city of Madrid in September 2014, with the irruption of Uber. At that time, Uber drivers did not have any license, which was against Spain’s transport legislation, so the service was forced to stop offering rides in the country, therebay ceasing all its activities in December 2014. In order to fulfil with all legal requirements, Uber drivers got VTC licenses and the company’s activities resumed in Madrid in March 2016. It was followed shortly after by the Spanish company Cabify, also offering ride-hailing services. Demand for Uber and Cabify rides sharply increased and extended to other Spanish cities, which caused severe opposition from the taxi sector throughout the country.

The taxi sector reacted with hostility to this new competitor due to a negative impact on their economic profitability. Taxi drivers complained that ride-hailing companies did not pay taxes in Spain, did not comply with labour legislation in the country, and benefited from being allowed to change their fares freely. As a consequence of that, demonstrations and strikes from the taxi sector have been common in recent years in Spain, particularly in Madrid. In February 2016, there was the first march of taxi drivers against ride-hailing services. In January 2019, taxi drivers blocked access to the main road in the city for days and even caused violent incidents (Akimova et al., 2020).

Some particular characteristics can be pointed out in the ride-hailing and taxi sectors in Spain. For instance, unlike other countries such as the United Kingdom or the US, where ride haling services are almost fully liberalised, the number of VTC licenses in Spain is currently limited by the government. Furthermore, since 2018 VTC licences are regulated at the regional level, but ride-hailing drivers can occasionally offer their services in any city of the country, depending on the specific demand needs. By contrast, taxi licences in Spain are limited and regulated at the municipal level, and taxi drivers can only offer their services in the specific city where the licence is awarded. It is also worth noticing that most local governments in Spain have suspended the launch of new taxi licenses for decades. As a result, the number of taxi licences in many cities (and particularly in Madrid) have remained almost constant for more than 20 years (Vassallo et al., 2018), mainly due to the pressure of taxi drivers to keep or increase the prices of their licences in the secondary market. According to the Ministry of Transportation (Ministerio de Fomento, 2020), as of March 2020, there were 63,917 taxi licenses and 16.450 VTC licenses in Spain. In the case of Madrid, there were 15,665 taxi licenses and 8,375 VTC licenses, what makes Madrid one of the Spanish cities with the highest ratio of VTC licenses per taxi licenses.

As noted above, Uber and Cabify are the two most widespread ride-hailing services in Spain. Nevertheless, this paper only focuses on Uber services, data due to the lack of data available for the case of its competitor Cabify.. In Spain, Uber provides three different services, namely UberX, UberBlack, and UberVan. UberX is by far the most popular and demanded Uber product, UberBlack is the premium service (Hughes & MacKenzie, 2016; Jiao, 2018) and UberVan is a service for groups of up to 6 people. Uber fares are determined by multiple factors, namely the base fare, the price per kilometre, the price per minute, and the "surge pricing" factor, which is the output of the dynamic algorithm (Ngo, 2015).

Taxi fares in the city of Madrid are set by the City Council, and are determined according to trip distance, trip duration, day of the week, and time of the day (BOAM Boletín Oficial Del Ayuntamiento de Madrid - Núm. 8546, 2018). It should be noted that trips departing or arriving at the airport have a special fare scheme when the origin or destination is located within the inner districts (inside the M30 ring road). In those cases, a fixed fare of €30 is applied regardless of any other trip characteristics.

There are four components which determine Uber and taxi fares in Madrid in 2019 (BOAM Boletín Oficial Del Ayuntamiento de Madrid - Núm. 8546, 2018; Jimenez, 2019): i) a starting fee, which is fixed no matter the duration or length of the ride; ii) fare per minute; iii) fare per kilometre; and iv) minimum fare, which is a minimum fare for each service to reimburse drivers for short rides. This fare, only applied in the case of Uber rides, is charged when the cost of the ride is below €3.50. Taxi services do not include the "minimum fare" component, but the starting fee applied is significantly higher when compared to Uber rides (the starting fee of Uber X is 0.40€ and the starting fee of the taxi is 2.50€ or 3.10€ depending if it is working day or not and depending on the hour of the day in which the ride was requested). In addition to these four components, Uber applies dynamic pricing in its rides when the demand is particularly higher than the supply of drivers.

4. DATA DESCRIPTION

This section presents the data used to explore the trends and evolution followed by ride-hailing fares, and their comparison with prices in the taxi sector. Multiple sources and type of information were employed . Regarding the prices offered by ride-hailing, we collected the information through Uber's Application Programming Interface (API). This tool allows collecting real-time information of requested rides by controlling the latitude and longitude coordinates (origin and destination point) sent by the script developed by the authors of this paper. As noted above, prices applied by Cabify, the other ride-hailing company operating in Spain, were not available and consequently it was not possible to include this company in the analysis.

For the purpose of collecting information on ride-hailing prices, the authors defined 10 locations throughout the city, which were used as origins and destinations of the requested rides. These locations were selected with the aim to homogeneously cover the whole city (see Figure 1), including both inner and outer neighbourhoods (inside and outside the M-30 ring, respectively). We also included special locations such as Madrid-Barajas airport and Atocha train station, with a high demand for ride-hailing and taxi trips in the city. These locations defined a network with 90 potential origins-destinations in Madrid, but we had to subsequently reduce the combinations in a noticeable way (see comments below). The data were requested to the API and stored at 1-hour intervals from September 1st 2018 to June 9th 2019. Figure 1 shows all routes considered in the analysis.

From the service models offered by Uber in Madrid, we focus on UberX rides because it is the most popular Uber service (Hughes & MacKenzie, 2016; Jiao, 2018). The following information was collected from each ride requested in the Uber API: fare, trip distance, trip duration, and the time the ride was requested (year, month, day, and hour). Uber fare indicates the cost of the ride shown by the app. Trip distance and trip duration indicate the trip distance and duration for a given origin and destination, respectively.

It is worth noticing that trip duration reported by the Uber API is based on real traffic conditions, therefore It can be considered a proxy of road congestion in the city.

In order to capture changes in ride fares over time, we included categorical variables controlling for time-related variables for requested rides, namely month, day of the week and hour (time of day). The analysis also controls for potential differences in ride fares depending on the origin and destination of the requested trip. Consequently, we may expect that rides within the city center would be cheaper, given that ride-hailing supply is generally higher in this area of the city.

Therefore, a categorical variable was created to control for the location of the origin and destination of each, particularly whether they are inside or outside of M30, Madrid's inner ring highway.

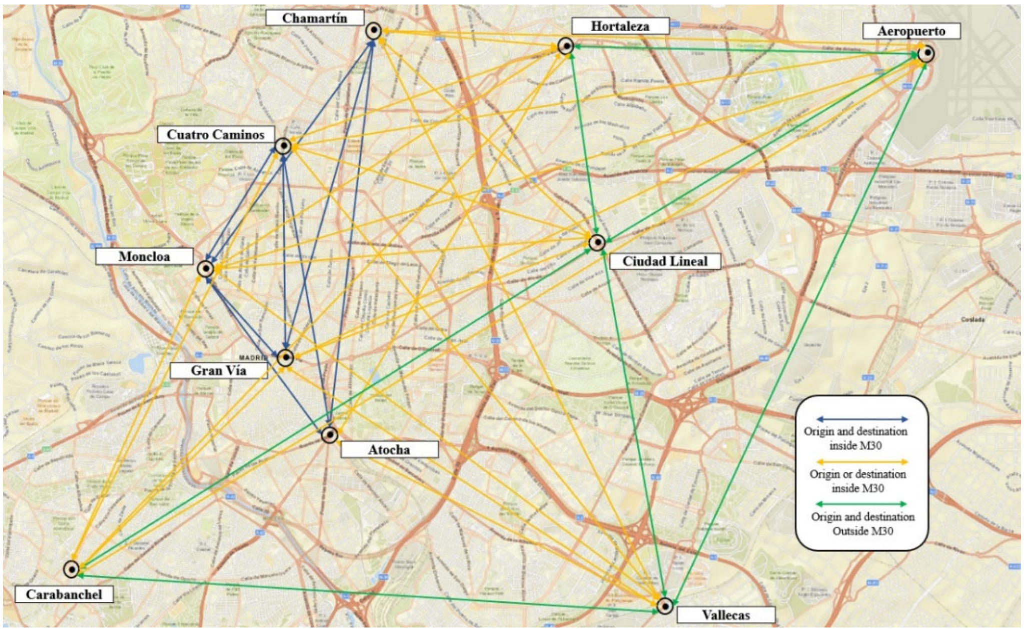

Fig. 1 – Routes selected

In addition to these variables, we also included further information regarding the taxi sector. Firstly, taxi fares were calculated for each ride, following the regulation of the Madrid City Council (BOAM Boletín Oficial Del Ayuntamiento de Madrid - Núm. 8546, 2018) and based on the information collected through the Uber API regarding trip distance, trip duration, type of day, and time of day hour of each trip. This step allowed us to estimate taxi fares and calculate the difference between the prices applied by UberX and taxi services for each specific ride.

The analysis also considers taxi strikes that happened during the period of analysis, in order to control for special events affecting the transport supply of its main competitor. We included a categorical variable capturing the days of strike in Madrid between September 1st 2018 and June 9th 2019.

During the period analysed in this research, there have been taxi strikes for 20 days. Nevertheless, it should be pointed out that a few additional strikes happened in the taxi sector in Madrid in 2018, before the time period covered by the research.

The analysis incorporates weather conditions since they could influence the Uber dynamic pricing and affect ride fares, as found by (Shokoohyar et al., 2020). We collected data on rain precipitation (measured in millimetre) on a 1-hour interval. This variable was obtained from the State Meteorological Agency (AEMET), Ministry of Agriculture, Food, and Environment.

Once the information needed for the research has been collected, a first exploratory analysis of the sample was conducted. It revealed that ride prices for many OD pairs keep constant over time and equals the minimum fare, as explained before. Therefore, these OD combinations were not valid for the purpose of the research so the sample was reduced to 40 OD pairs. A total of 277,840 valid requested rides were finally included in the analysis. Descriptive statistics of the final data sample can be observed in Table 1.

Variables	**Typology**	**Summary statistics**		**Units**
Uber fare (FARE)	*Continuous*	*Mean*	*20.6*	*€*
		Median	*20.0*	*€*
		Max	*149.0*	*€*
		Min	*5.0*	*€*
		SD	*7.6*	*€*
Trip distance (DIST)	*Continuous*	*Mean*	*12.7*	*km*
		Median	*12.3*	*km*
		Max	*36.4*	*km*
		Min	*2.2*	*km*
		SD	*4.8*	*km*
Travel time (TTIME)	*Continuous*	*Mean*	*1161*	*seconds*
		Median	*1140*	*seconds*
		Max	*3180*	*seconds*
		Min	*360*	*seconds*
		SD	*311*	*seconds*
Day of week (DAY)	*Categorical*	*Working days**	*127,760*	
		Saturday, Sunday and holidays	*150,080*	
Taxi fare	*Continuous*	*Mean*	*25.1*	*€*
		Median	*25.0*	*€*
		Max	*66.0*	*€*
		Min	*7.0*	*€*
		SD	*7.22*	*€*
Taxi strike (STRIKE)	*Categorical*	*Strike**	*934*	
		No Strike	*276,906*	
Origin/destination of the ride	*Categorical*	*(1) Origin and destination inside M30**	*27,786*	

Variables	Typology	Summary statistics		Units
(SPAT)		*(2) Origin inside and destination outside M30*	*83,348*	
		(3) Origin outside and destination inside M30	*83,347*	
		(4) Origin and destination outside M30	*83,359*	
Rain precipitation (PREC)	*Continuous*	*Mean*	*0.33*	*mm*
		Median	*0.00*	*mm*
		Max	*91.00*	*mm*
		Min	*0.00*	*mm*
		SD	*2.50*	*mm*
Difference	*Continuous*	*Mean*	*-4.5*	*€*
		Median	*-5.0*	*€*
		Max	*107.0*	*€*
		Min	*-17.0*	*€*
		SD	*3.9*	*€*

Table 1 – Summary statistics of explanatory variables

As exploratory analysis, Figure 2 shows Uber fare behaviour per day, hour, and strike event. Uber fares vary around the day and hour.

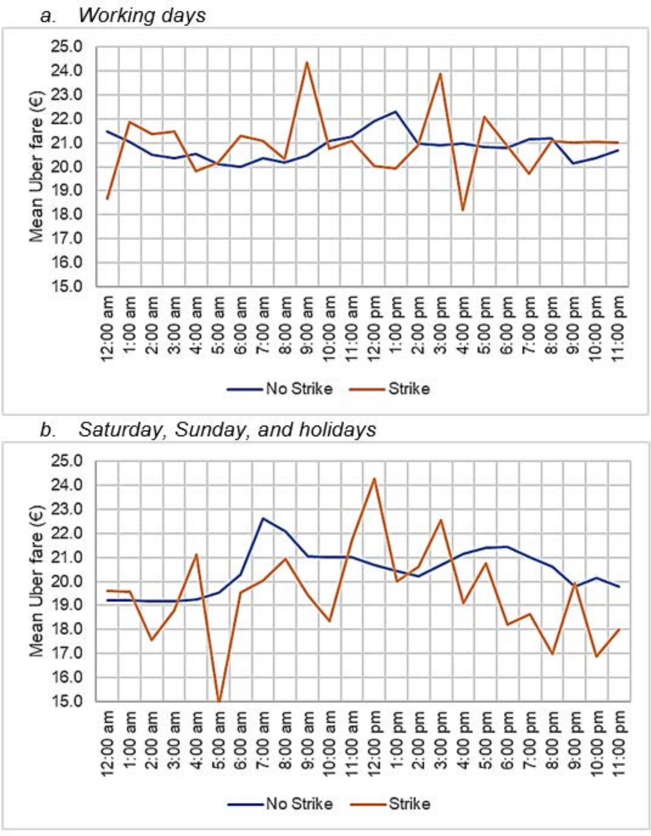

Fig. 2 – Mean Uber fare behavior

5. METHODOLOGY

In order to explore the evolution and trends followed by fares applied in the ride-hailing sector, we adopted a generalized linear model (GLM) framework. The dependent variable to be modelled is the fare applied by Uber services. Nevertheless, the paper also provides some insight regarding differences in terms of prices offered by Uber and taxi services.

GLM is a widely statistical technique used when the response distribution of the dependent variable is non-normal (Oliveira et al., 2018). It is made up of three components: random component, a linear predictor, and a link function. The random component consists of a response variable with independent observations that can be defined by a probability density function of the exponential family (Agresti, 2015). In this case, the Uber fare showed to follow a gamma distribution (k=7.145, θ=0.345) and therefore we used the natural log function, g(μ_i)=ln(μ_i) as a link function. Additionally, a linear predictor relates parameters with the explanatory variables using a linear combination defined as:

$$\ln(Y) = \beta_0 + \Sigma_j \beta_j X_j + \varepsilon \quad (1)$$

In our case, the set of explanatory variables Xj includes: trip distance, trip duration, month of the year in which the ride was requested, day of the week, hour of the day, taxi strike, origin/destination of the ride and rain precipitation, as can be seen in Equation 2:

$$\ln(FARE) = \beta_0 + \beta_1 DIST + \beta_2 TTIME + \beta_3 STRIKE + \beta_4 PREC + \beta_5 DAY + \beta_6 SPAT + \Sigma_i \beta_i MONTH_i + \Sigma_j \beta_j HOUR_j + \Sigma_{k,j} \beta_k DAYxHOUR_j \quad (2)$$

where:

- FARE is the dependent variable to be modelled, Uber fare.
- DIST is the trip distance of the requested ride.
- TTIME is the trip duration of the requested ride.
- STRIKE is a dummy variable that equals 1 when there is taxi strike and 0 otherwise.
- PREC is the rain precipitation, measured in mm.
- DAY is a dummy variable that indicates the day of the week. It equals 1 for non-weekdays (Saturday, Sunday, or holidays), and 0 otherwise (weekdays).
- SPAT is a categorical variable that controls for the location of the origin and destination of each particular ride, as detailed in Table 1.
- $MONTH_i$ is a set of dummy variables reporting the month (i) in which the ride is requested.
- $HOUR_j$ is a set of dummy variables reporting the hour of the day (j) in which the ride was requested.
- $DAYxHOUR_j$ indicates the interaction between DAY and $HOUR_j$ variables.

- B_k is a vector of coefficients to be estimated. The coefficient of variables indicates that when a specific explanatory variable X_i increases by one unit, holding all other predictors constant, the rate ratio (RR) increases by $e^{\beta i}$.

As can be observed, five explanatory variables used in the model are categorical (STRIKE, DAY, SPAT, MONTH, HOUR), so choosing a base reference is needed to explain the modelling results properly. This enables us to determine whether Uber fares are statistically significant when compared to the base reference. For instance, the base reference of STRIKE is when there is taxi strike. The base reference of DAY is working days. Regarding the SPAT variable, the base reference is the ride whose origin and destination is inside the M-30 highway. June 2019 is taken as the base reference of MONTH. Finally, 11:00 p.m. to 12:00 a.m. is considered as the base reference of HOUR. Base references chosen in each case can be observed in Table 1.

6. RESULTS

This section summarizes the main findings of the analyses conducted in this study. Prior to conducting the analyses, we studied potential multicollinearity problems in the sample.

Trip distance and trip duration variables were highly correlated with each other according to multicollinearity tests (Gujarati & Porter, 2009). Therefore, we decided to include only trip distance.

6.1 Uber fares

The results of the model explaining Uber fares are presented in Table 2. The signs of the modelling coefficients and their statistical significance are in line with the expected results.

All explanatory variables are statistically significant and, therefore, the p-value is accepted.

The model confirms the significant impact (with a level of 99% confidence from a statistical point of view) of the variables: trip distance, day of the week, location of the origin/ destination of the ride, and rain precipitation level. The taxi strike variable was significant with a level of 90% confidence.

The trip distance variable is positive and statistically significant, thus indicating that longer distances are associated to higher Uber fares as seems reasonable. According to the modelling results, Uber prices increase by €1.07 for each additional kilometre. Additionally, the variable controlling for the location of the origin and destination of the rides has positive and statistically significant coefficients. This means that coeteris paribus Uber fares decrease when both the trip origin and destination are inside the M-30 ring road.

This result seems reasonable due to the greatest supply density of Uber drivers in the city centre. Some detailed results are provided by the model. When the trip origin takes place inside the M-30 ring and the destination is located outside the M-30, Uber fares increase by 31.6% compared to the base reference. Price rises are lower when the trip origin is outside the M30 and the destination is inside it (+24.2%), and when both the origin and destination of the trip are outside M-30 (+23.2%), compared to the base case.

Variable	Estimate	Std. error	t value	p-value
(Intercept)	*1.929*	*0.0027*	*721.975*	*0.000*
DIST	*0.068*	*0.0001*	*752.292*	*0.000*
STRIKE	*-0.009*	*0.0056*	*-1.696*	*0.090*
DAY	*0.046*	*0.0032*	*14.637*	*0.000*
SPAT_2	*0.274*	*0.0013*	*205.554*	*0.000*
SPAT_3	*0.217*	*0.0013*	*165.084*	*0.000*
SPAT_4	*0.209*	*0.0016*	*134.629*	*0.000*
PREC	*0.003*	*0.0001*	*21.267*	*0.000*

AIC: 1,365,072
Null deviance: 39,791.3 on 277,839 degrees of freedom
Residual deviance: 5,982.7 on 277,777 degrees of freedom
Wald test: 0.0288

Table 2 – Modelling results

Day of the week also evidences to have a significant influence on prices offered by Uber services. The coefficient sign for this variable is also positive and statistically significant (see Table 2). According to the modelling results, coeteris paribus, Uber fares increase by 4.8% on Saturdays, Sundays, and holidays, compared to weekdays.

The influence of the time of day on Uber fares is also analysed (see Figure 3a). The model estimates conclude that, on average, Uber fares decrease by 2.3% from 12:00 p.m. to 5:00 a.m., compared to the base reference (from 11:00 p.m. to 12:00 a.m.). As expected, Uber fares increase on average by 9.5% from 6:00 to 9:00 a.m., coinciding with the morning peak hour. This result may be related to the higher demand and traffic congestion typically observed in this period (Gramaglia et al., 2016; Vassallo et al., 2012). The model also shows that, on average, Uber fares increase by 3.2% from 3:00 p.m. to 9:00 p.m. The afternoon peak hour, which in Madrid happens from 5 p.m. to 7 p.m., is included within that time frame. Fare rises in the afternoon peak hour are significantly lower than in the morning peak hour. Periods not mentioned above were not found statistically significant in the model.

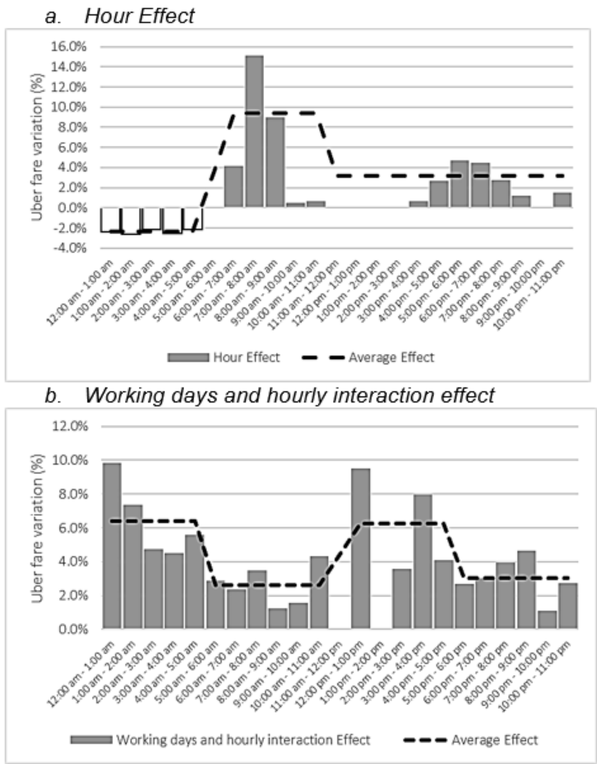

Fig. 3 – Effect generated by the hour to Uber fare

Furthermore, we analysed the day of the week and the hour interaction. This is motivated by the fact that the change in Uber prices at e.g. late hours may be significantly different during weekdays and non-weekdays. As previously mentioned, Uber fares are higher on Saturday, Sunday, and holidays compared to working days. However, the modelling results make it clear that this effect changes quite a lot throughout the day (see Figure 3b). We can identify two time periods when the fare rise is significantly noticeable: from midnight to 4.00 a.m., due to the high demand of people getting back home from night leisure activities (dinner, party, etc.); and from noon to 4.00 p.m., coinciding with the weekend dinner time in Spain. In these two periods, Uber fares increase around 6% according to the modelling results.

Concerning the Taxi strike variable, we obtain a negative statistically significant coefficient with 90% confidence. This result indicates that Uber fare decreases during taxi strikes. According to the modelling results, Uber fares drops by 0.94% compared to the base scenario (no taxi strike). This result appears to be surprising since we may expect that Uber had taken advantage of the taxi strike situation to rise the fares. The explanation we found to this empirical result is that Uber decided to use taxi strikes to capture new clients by maintaining, or even reducing, their usual fares rather than by rising prices. This fact was possible from the supply perspective since, as mentioned above, VTC licences can easily move across different cities of Spain during special occasions or events.

Finally, we found that weather conditions may influence the Uber dynamic pricing and affect the ride fare, which is in line with (Shokoohyar et al., 2020). The coefficient obtained for the rain precipitation variable is positive and statistically significant, and sates that Uber fare increases by 0.3% when rain per hour increases by 1 mm. This is likely due to the higher traffic congestion generally observed during rainy times and, therefore, longer trip duration.

6.2 Comparison of prices offered by Uber and Taxi Services

Furthermore, Uber and taxi fares are also compared. In this analysis we excluded airport trips departing/arriving within the M30 ring because taxi fares for these routes are fixed irrespective of the destination. The difference between the two fares is around €4.5 on average. In general, our findings suggest that taxi fares are higher than Uber ones in all types of day: working days, Saturday, Sunday, and holidays. This result confirms the hypothesis proposed by (Pepić, 2018), who obtained similar results regarding taxi and ride-hailing prices on the basis of a simulation approach.

We found that fare differences are higher in working days, from 10:00 p.m. to 6:00 a.m., compared to the rest of the day (see Figure 4a). This is mainly due to the fact that Uber reduces its fares in this period of time. In leisure days (Saturday, Sunday, and holidays), the trend is similar throughout the whole day (see Figure 4b) with the exception of the midnight period. A t-test was conducted to check whether there is a statistically significant difference between the means of Uber and taxi fares. We found evidence to believe that the difference is lower than 0. This result implies that, for the case of Madrid, Uber prices are lower, in a statistically significant way, than taxi prices.

Finally, we also analyse whether there is a significant fare difference depending on the hour of the day and day of the week. We found that in working days, there is statistical evidence that their means are significantly different except from mid overnight (1:00 a.m. to 4:00 a.m.), late morning (10:00 a.m. to noon), and early evening (from 6:00 p.m. to 7:00 p.m.). Therefore, the analysis suggests that Uber and taxi fares are similar only during these periods. Regarding leisure days (Saturday, Sunday and holidays), there is statistical evidence that Uber prices are significantly lower than taxi fares except from mid-late (9:00 a.m. to 11:00 a.m.) and mid-afternoon (2:00 p.m. to 4:00 p.m.). These findings mean that Uber and taxi fares are only similar during leisure days in these specific periods.

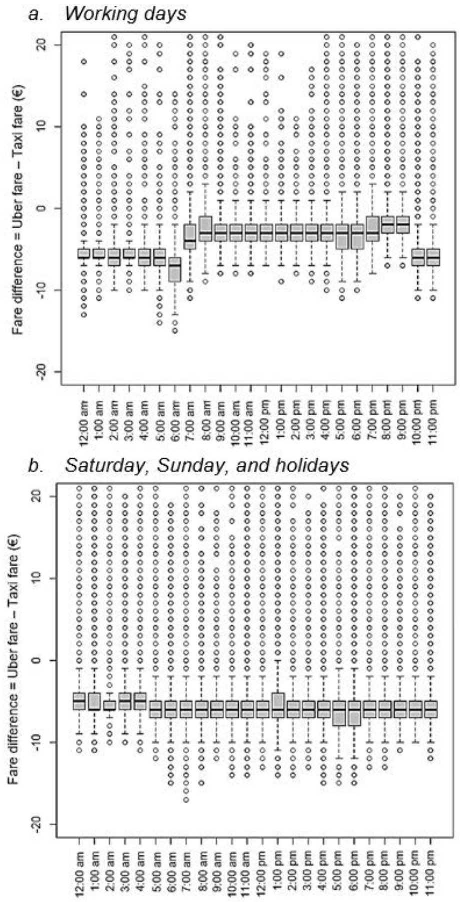

Fig. 4 – Uber and taxi fare difference behaviour

7. CONCLUSIONS

This study explores the evolution and trends experienced by ride-hailing prices, according to different explanatory variables: trip distance, the time the ride was requested (year, month, day and hour), origin/destination of the ride, weather conditions and taxi strikes. To that end, we applied an econometric specification using 10-month data (from September 2018 to June 2019) for Madrid obtained from the Uber's API. In addition, the paper explores the differences between Uber and taxi fares.

The results indicate that trip distance, the time the ride is requested, the origin/destination of the ride and rain precipitation significantly increase the fares offered by Uber. Particularly, Uber prices tend to increase during rainy conditions, but decrease in areas with higher service supply, such as the city centre. The modelling results show significant differences in Uber prices throughout the day. Uber fares increase significantly during the weekday morning peak hour (+9.5%) and, to a lower extent, during mid-afternoon and mid-evening (+3.2%) coinciding with the afternoon peak hour. By contrast, Uber prices significantly drop overnight (-2.3%). In addition to this, it is worth noticing that Uber fares are significantly higher during leisure days, likely due to the higher demand of leisure trips observed in this type of days.

Additionally, the results from this research show that Uber may have taken advantage of taxi strikes to capture new clients through fare reductions since, according to the model results, violent strikes conducted by the taxi sector coincided with a small decrease in Uber prices. This was possible from the supply side because the Spanish legislation makes possible to transfer ride-hailing supply licences across cities for high demand periods.

This research also found that, at least for the case of Madrid, Uber prices are on average significantly lower than taxi fares, with the exception of particular times of day within off-peak hours. The results suggest that taxi fares are around €4.5 higher than Uber in any type of day: working days, Saturday, Sunday, and holidays.

Some aspects can be pointed out for further research. Extending the analysis conducted in Madrid to other geographical areas (e.g. American cities) would provide broader insight. While the ride-hailing sector is regulated and the number of ride-hailing licenses are limited in Spain, this is not the case in many other cities. Additionally, studying the reasons motivating individuals' choices towards ride hailing and taxi adoption would be of the greatest interest to understand users' behaviour.

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EXPERIENCIAS DE SISTEMAS COOPERATIVOS COMO CATALIZADORES PARA ALTOS NIVELES DE AUTOMATIZACIÓN EN LA CONDUCCIÓN

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RESUMEN

Más allá de las aplicaciones para mejorar la fluidez y seguridad del tráfico, los sistemas cooperativos se están planteando como herramientas catalizadoras para lograr mayores niveles de automatización de los vehículos. El objetivo consiste en que los vehículos puedan disponer de información con un horizonte de percepción superior al que les proporcionan sus sensores embarcados y que, en la actualidad, están limitando sus prestaciones de funcionamiento autónomo y los escenarios en los que se pueden desenvolver como tales.

En este sentido, se han desplegado 2 corredores cooperativos interconectados en vías periurbanas de Madrid, concretamente, en la entrada por la autovía A6 y un tramo de la vía de circunvalación M30 totalizando más de 20 km. Estos corredores cooperativos están formados por un conjunto de RSUs (RoadSide Units) que se comunican con los centros de control C-ITS y que proporcionan una cobertura continua y con muy bajos tiempos de latencia a lo largo de todo el recorrido.

De esta forma, los vehículos dotados de OBUs (Onboard Units) podrán recibir esta información en tiempo real y, en caso de ser conducidos de forma autónoma, podrán realizar ciertas maniobras como la adaptación de la velocidad o maniobras de cambio de carril sin intervención del usuario.

En este artículo se trata la arquitectura desplegada y se presentan los resultados de los ensayos que se han realizado, tanto de la eficiencia en la transmisión de la información desde el centro C-ITS a las RSUs y su difusión a las OBUs de los vehículos, como la respuesta de los vehículos con conducción autónoma ante las indicaciones recibidas.

1. INTRODUCCIÓN

Los sistemas cooperativos se definen como aquellos sistemas de seguridad, eficiencia y confort en el entorno vial basados en el intercambio de información entre vehículos y/o infraestructuras, mediante comunicaciones inalámbricas (Cruz, 2019). Incluso se puede extender el intercambio de información a usuarios que no se encuentren en el interior de un vehículo en el instante de recibir el servicio mediante el uso de dispositivos móviles o tabletas. Al encontrarse el vehículo conectado en un entorno cooperativo posibilitará que además de poseer los datos propios y los percibidos por medio de los sensores embarcados, podrá disponer de la información transmitida por el resto de los vehículos, las infraestructuras a su alrededor y centrales de tráfico (Jiménez, 2012).

Car 2 Car – Communication Consortium (https://www.car-2-car.org/) busca el desarrollo, prueba y despliegue de sistemas cooperativos en Europa basados en la comunicación de corto alcance entre vehículos, entre vehículos e infraestructuras y entre vehículos y otros usuarios de la carretera para mejorar la seguridad y la eficiencia vial. Otras comunicaciones complementarias, como la telefonía, serán consideradas cuando sean requeridas. El principal objetivo del consorcio es garantizar la interoperabilidad de los sistemas cooperativos, abarcando todas las clases de vehículos a través de marcas y fronteras representando a empresas de vehículos o infraestructuras, autoridades y organizaciones relacionadas con los C-ITS e institutos de investigación.

En los últimos años, se han acometido diferentes proyectos en España para el despliegue de estos servicios en corredores de carreteras reales. En concreto, el proyecto Auto C-ITS (https://www.autocits.eu/) tiene por objetivo el contribuir al despliegue de los servicios cooperativos en Europa mejorando así la interoperabilidad de los mismos entre países, y promoviendo el papel de los servicios cooperativos (C-ITS) como catalizadores para la implementación de la conducción autónoma. Para ello se han desarrollado tres proyectos piloto en tres grandes ciudades europeas situadas en el corredor atlántico: Madrid, París y Lisboa (Figura 1).

Fig. 1 - Proyectos piloto del proyecto Auto C-ITS

El piloto español formado por INSIA-UPM, INDRA y la DGT ha desplegado en el carril de vehículos de alta ocupación (VAO) situado en la A-6 desde el km 7 al km 17 entre las carreteras M-30 y M-40 (Figura 2). El piloto ha desplegado tres servicios C-ITS Day 1, en los que los vehículos autónomos y conectados realizan las maniobras de seguridad basándose en la información recibida de la autoridad de carreteras a través de una infraestructura C-ITS. Se marca con indicadores en color rojo muestran las RSU que cuentan con conectividad 5G mediante la que se comunican con otras RSU y los vehículos de la carretera, además de conexión a internet para comunicarse con el centro de control.

En verde se muestran las RSU que solo cuentan con conectividad 5G sin salida a internet que hacen las funciones de repetidores de los mensajes obtenidos del centro de control a través de las RSU en rojo.

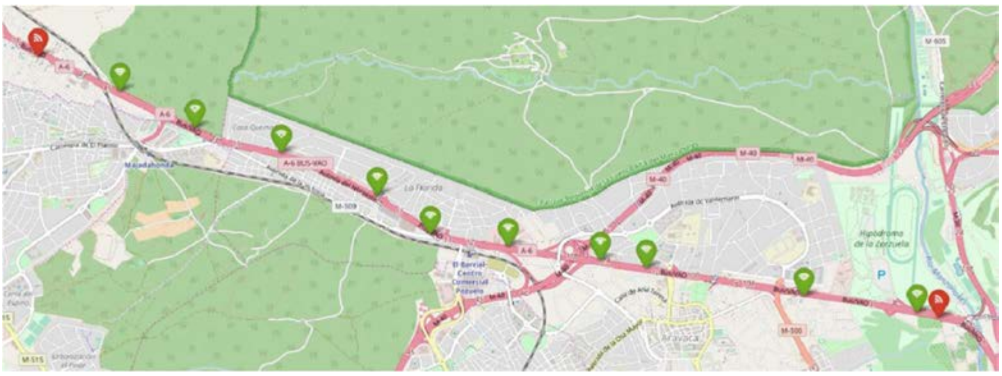

Fig. 2 - Ubicación de las RSUs C-ITS en la A-6 (km 7, km 17)

La plataforma europea C-ROADS (https://www.c-roads.eu/pilots/implemented-services.html) es una iniciativa de diferentes Estados miembros y operadores de carreteras que desean colaborar para lograr el despliegue de servicios C-ITS de forma armonizada e interoperable en toda Europa. La armonización es el activo principal de la cooperación C-ROADS, ya que garantiza un despliegue sostenible y eficiente de los C-ITS. En consecuencia, todos los participantes comparten la visión de los objetivos principales que son, además de la armonización, la implementación a través de pilotos de los servicios Day 1 y Day 1.5, las demostraciones de la implementación de C-ITS y el avance hacia una implementación a gran escala.

A nivel español, (C-ROADS Spain), pretende impulsar la participación de todas las entidades del sector, además de influir en las decisiones a tomar en Europa. Está compuesto por 5 pilotos (Madrid, SISCOGA en Galicia, Cantábrico, Mediterráneo y DGT 3.0), cada uno de ellos con su particular conjunto de tecnologías y servicios C-ITS. Esta heterogeneidad tiene como objetivo cubrir un amplio espectro de casos, con el fin de evaluar el impacto de la movilidad conectada en muchos escenarios representativos.

2. FUNCIONAMIENTO DE LAS COMUNICACIONES V2X

La comunicación V2X se refiere a la capacidad de un vehículo de poder comunicarse con cualquier otro receptor, ya sean infraestructuras (V2I), peatones (V2P), otros vehículos (V2V) o con redes (V2N) (Figura 3). Mediante la transmisión de mensajes, el vehículo puede conocer en tiempo real la situación de los demás vehículos próximos en la vía, enviando y recibiendo información sobre una retención del tráfico, una bajada de la velocidad, la necesidad de cambiar de carril por un obstáculo en la carretera o el peligro que puede haber más adelante debido a un accidente, entre muchos otros eventos posibles.

Gracias a los centros de control de tráfico, se puede controlar en tiempo real la situación en las vías y, si es necesario, mediante este sistema de comunicaciones, enviar información hacia los vehículos, utilizando mensajes que serán recibidos por las infraestructuras, que posteriormente los diseminarán a los vehículos en su rango de comunicaciones. Para ello, se emplean módulos de comunicación V2X. Estos módulos tienen la capacidad de enviar y recibir mensajes (ETSI-ITS, 2014), tengan el origen que tengan, siempre que esté verificada su autenticidad. En caso de estar instalados en la vía, se denominan Road Side Units (RSUs), situados en infraestructuras altas como pueden ser pórticos de información o farolas para, de esta forma, tener visión directa con los vehículos y así transmitir con mayor facilidad y rango los mensajes. Esta versión de módulos de comunicaciones está hermetizada para tener la capacidad de soportar las inclemencias del tiempo. Las unidades localizadas en los vehículos son On Board Units (OBUs), las cuales son en esencia iguales que las RSUs, con un tamaño más contenido para estar colocadas en el vehículo sin perder apenas capacidad de carga.

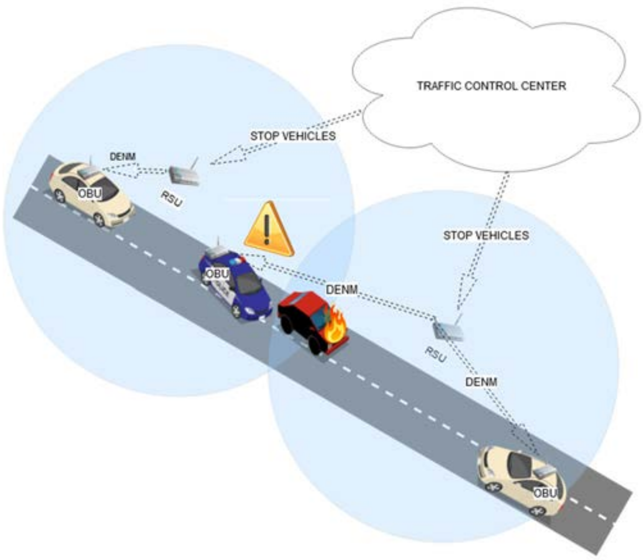

Fig. 3 - Diagrama de funcionamiento de las comunicaciones V2X

Un ejemplo típico de la comunicación V2X sería el control de un atasco. El centro de control de la autoridad encargada del tráfico, la Dirección General de Tráfico (DGT) en España, enviaría un mensaje a las RSUs de la carretera situadas en el rango cercano al atasco, indicando una ruta alternativa que permita la descongestión del tráfico. Al recibir este mensaje, se enviaría a continuación a las OBUs de los vehículos en el rango que indique el centro de control, avisando con antelación a los conductores del atasco.

La comunicación V2X tienen un gran potencial en el futuro de los vehículos conectados y autónomos, pudiendo en la actualidad avisar al conductor de posibles pasos a seguir mediante los ADAS (Advanced Driver Assistance Systems) en la conducción y, en el futuro, controlar totalmente las capacidades del vehículo y el recorrido a seguir mediante el envío de mensajes.

3. FUNCIONAMIENTO DEL VEHICULO

Con el fin de probar la capacidad de los corredores cooperativos para ser catalizadores de la conducción autónomo, se emplea un vehículo Mitsubishi i-MIEV (Figura 4), automatizado por el Instituto Universitario de Investigación del Automóvil (INSIA), perteneciente a la UPM.

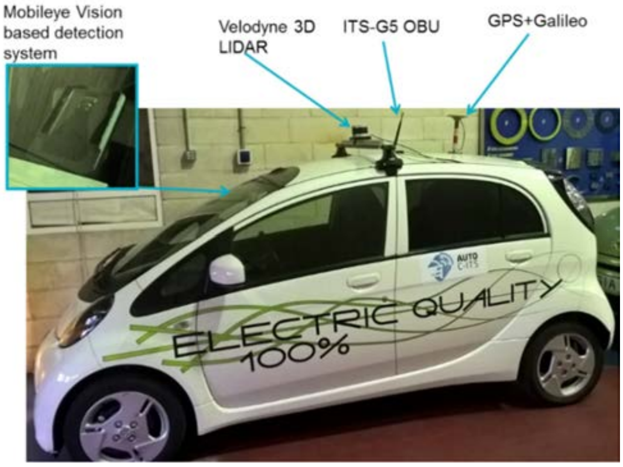

Fig. 4 – Detalle del vehículo autónomo del INSIA

Este vehículo ha sido automatizado siguiendo el esquema de automatización de la Figura 5. Este esquema sigue la misma distribución utilizada por el vehículo Stanley (Thrun et al, 2006) de "The Stanford Racing Team" en la competición "2005 DARPA Grand Challenge" (Buehler et al, 2007).

Se pueden encontrar en primer lugar los sensores con los que cuenta el vehículo en la actualidad que son un GPS con corrección inercial, una base de datos en la que se encuentra el mapa pregrabado mediante sus posiciones GPS, la lectura de la velocidad y el ángulo de volante que se recogen del CAN BUS del vehículo, el módulo de comunicaciones V2X, además de una cámara Mobileye y un LiDAR. Dentro del módulo de percepción debe destacarse para el objeto de los ensayos que se ha implementado un generador de waypoints a partir de los puntos GPS en bruto guardados en la base de datos.

En el bloque de planificación se encuentran los dos módulos de alto nivel principales en el vehículo; por un lado, el path tracking que realiza el cálculo de la velocidad y el ángulo de volante necesario para seguir la planificación del mapa y, por otro lado, el sistema decisiones que recoge la consigna calculada por el módulo de path tracking además de las consignas recibidas de los sensores Mobileye y LiDAR y la consigna dada por el módulo de comunicaciones. El módulo de toma de decisiones se encarga de centralizar la información recibida de cada uno de los módulos y enviar al control la consigna más adecuada en cada momento.

El último paso del ciclo de control corresponde a los módulos de control de velocidad y control de giro de volante los cuales reciben las consignas del módulo de toma de decisiones y las convierten en señales adecuadas para los actuadores del vehículo. Todas las funciones del vehículo controlan a través de una pantalla táctil que permite activar/desactivar el control autónomo además de seleccionar los sensores que se utilizan en cada momento y el mapa pregrabado a utilizar.

También cuenta con la posibilidad de realizar el control del vehículo de manera manual dentro de automatización a través de un teclado.

En el esquema se han señalado en rojo aquellos módulos que no se utilizan en las pruebas del presente estudio.

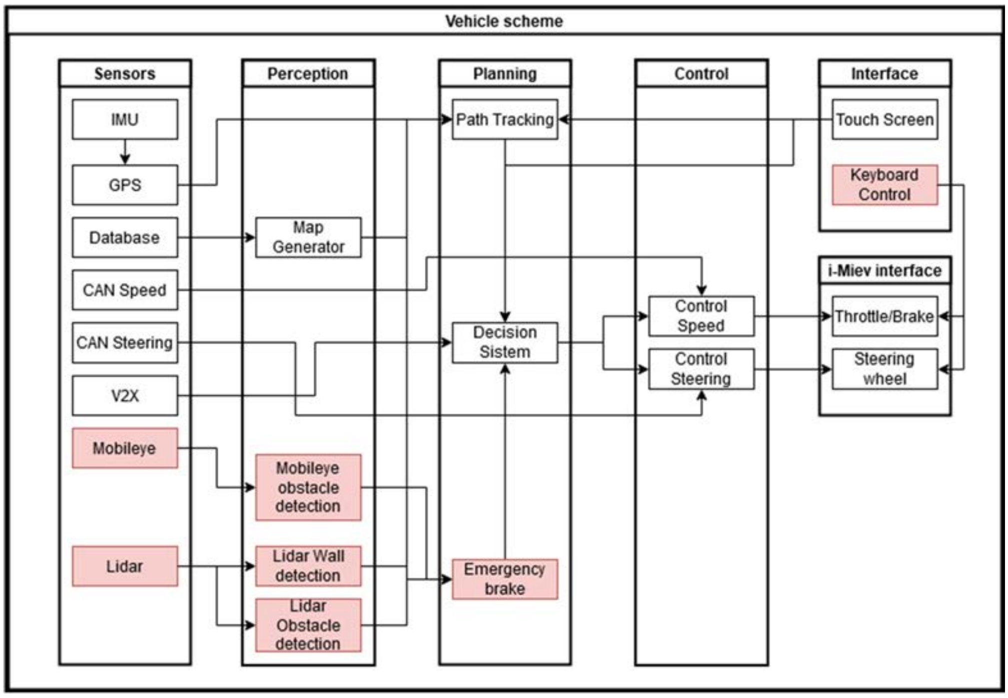

Fig. 5 – Esquema del Sistema de control del vehículo autónomo de INSIA-UPM

4. ENSAYOS EN CARRETERA

Se han realizado ensayos en carretera con tráfico a lo largo de los corredores cooperativos desplegados y que proporcionan cobertura continua. En concreto, en este artículo se muestra el caso de un ensayo en el carril bus-VAO de la autovía A6 en la salida de Madrid.

El ensayo con un recorrido de 7,8 kilómetros se ha realizado de manera completamente autónoma. El objetivo de este ensayo es mostrar el comportamiento del vehículo en una posible situación real, en la cual durante la conducción recibe la información de los eventos, emitidos por la DGT, debido a retenciones en la vía. Durante el recorrido se han simulado 3 eventos en la carretera cuyo radio de acción se puede ver en la Figura 6.

Fig. 6 - Representación de la ruta realizada en el ensayo

Para los eventos emitidos en el ensayo, se ha seguido el método de definición de eventos del “common data dictionary” del estándar de comunicaciones V2X el cual clasifica la naturaleza los eventos por causa (ETSI-ITS, 2019) y subcausa (ISO, 2019), asociándoles a cada uno de los mismos un protocolo de actuación definido por los centros de control de tráfico de cada Estado.

Para este ensayo se han utilizado tres eventos diferentes con dos tipos de consigna de actuación del vehículo. Por un lado, los eventos pueden indicar una consigna de velocidad máxima en el radio de relevancia del evento. El vehículo mantendrá la velocidad mínima entre la velocidad marcada por el mapa definido previamente y la consigna de velocidad de evento. Por otro lado, los eventos pueden indicar la necesidad de un cambio de carril, hacia el izquierdo (por defecto, el vehículo circula por el carril derecho) para lo cual el vehículo recalculará el trazado del mapa para situarse en el carril inmediatamente siguiente a la izquierda del actual.

Los eventos que se han emitido para este ensayo son los siguientes.

- El evento A consiste en una reducción de velocidad a 35 km/h debido a una retención. Este evento se encuentra situado en las coordenadas (40.474913, -3.833989) y tiene un radio de acción de 200 metros. Este evento ha sido definido con causa 6, subcausa 0 que indican que se encuentra una superficie deslizante.
- El evento B con causa 6, subcausa 0 que indican que se está realizando un trabajo en la carretera, consiste en un cambio de carril y posterior regreso. Este evento se encuentra situado en las coordenadas (40.465152, -3.797245) y tiene un radio de acción de 250 metros.
- El evento C definido con causa 26, subcausa 0 que indican que hay un vehículo lento en la carretera, consiste en una reducción de velocidad a 20 km/h debido a una retención. Este evento se encuentra situado en las coordenadas (40.464283, -3.789678) y tiene un radio de acción de 100 metros.

5. RESULTADOS

En este apartado se muestra el comportamiento del vehículo tanto durante los eventos descritos anteriormente cómo durante su conducción en modo autónomo. Para ello se van a revisar dos características principalmente que son el control de la velocidad y el control del ángulo de volante.

En la Figura 7 se muestra la gráfica de velocidad durante el ensayo. El vehículo comienza parado y acelera progresivamente hasta alcanzar su velocidad objetivo de 60 km/h. Se muestran algunas oscilaciones el control de velocidad de ±5 km/h debido a la orografía del terreno. En la sección indicada con el número 1 se encuentra el primer evento el cual consiste en una reducción de velocidad a 20 km/h, El vehículo realiza una reducción brusca de velocidad hasta situarse en la velocidad objetivo y la mantiene durante el radio de relevancia del evento. Al salir del radio de relevancia recupera progresivamente la velocidad hasta los 60 km/h fijados por el mapa. En la sección marcada con el número 2 se produce el siguiente evento que consiste en un cambio de carril, el cual no conlleva cambio en la velocidad. Al llegar a la sección marcada con el número 3 se observa una reducción de velocidad a 35 km/h como indica el evento C. Para concluir el ensayo el vehículo realiza automáticamente una frenada progresiva hasta detenerse.

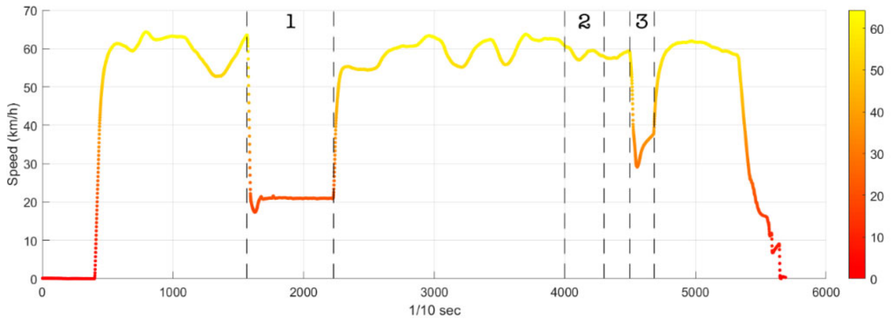

Fig. 7 - Perfil de velocidad

En la Figura 8 se observa en detalle el evento de cambio de carril. Como se puede observar, la actuación del evento se realiza con un pequeño desfase correspondiente al tiempo que tarda el vehículo en procesar los eventos y actuar en consecuencia. Este retardo, menor a un segundo, se observa tanto a la entrada como a la salida del evento.

Fig. 8 - Detalle de la maniobra de cambio de carril

La Figura 9 muestra la evolución del control del ángulo de volante durante el ensayo, este mantiene el vehículo centrado en el carril en todo momento excepto durante el evento B que, como se ha descrito anteriormente, conlleva un cambio de carril. En la ampliación de la gráfica se muestra el momento en el que el control realiza el cambio de carril ejecutando un giro a la izquierda que rectifica para alinearse con el carril izquierdo y posteriormente, al salir del radio de relevancia del evento, un giro a la derecha que lo devuelve al carril inicial. Durante el resto de la gráfica se perciben las correcciones para el mantenimiento en el carril.

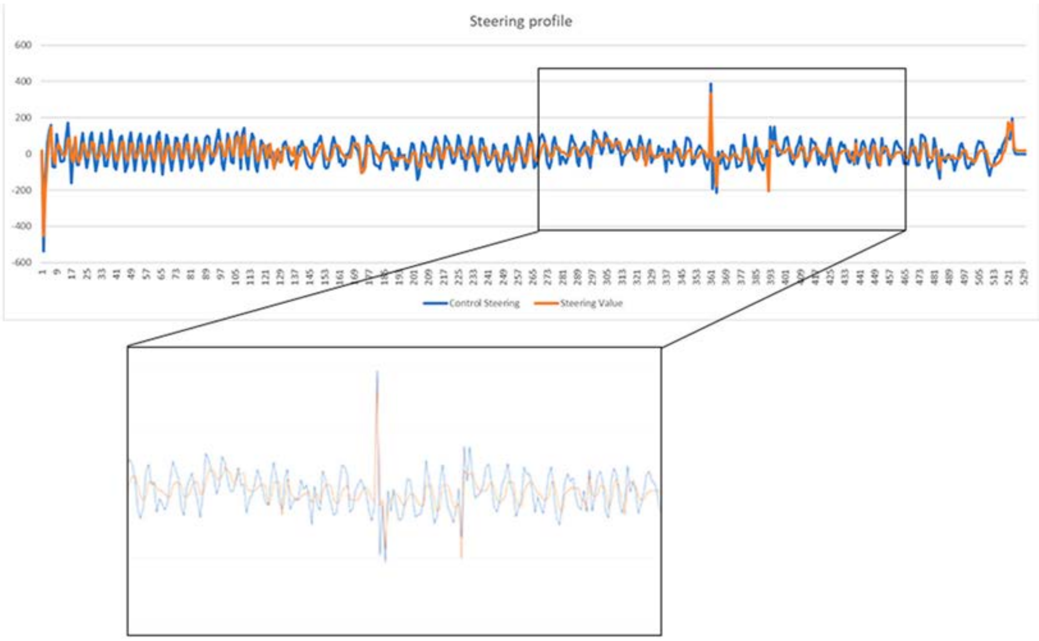

Fig. 9 - Detalle de control de ángulo de volante

6. CONCLUSIONES

En este artículo se ha mostrado cómo las indicaciones en el corredor cooperativo permiten la operación de un vehículo autónomo en función de consignas externas. El vehículo es capaz de conducir de manera completamente autónoma sobre un mapa pregrabado, manteniéndose en su carril y pudiendo ejecutar las acciones de reajuste de la velocidad junto con un cambio de trayectoria cuando ha resultado necesario, como respuesta a la información de los eventos emitidos por el centro de control de tráfico. De esta forma, parece afianzarse la afirmación de que los sistemas cooperativos tendrán un papel crucial en el ecosistema de la conducción autónoma, además de servir como catalizadores para los altos niveles de automatización en la conducción.

AGRADECIMIENTOS

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TINNGO: TRANSPORT INNOVATIVE GENDER OBSERVATORY.
SPANISH HUB. TAXI CASE STUDY.

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ABSTRACT

It is well - known that women are generally under-represented in some technical fields, as it is the specific case of the transport sector. This lack of balance gender-wise is even more visible in the taxi industry, leading to a gender gap that should be filled in the next years.

Flexibility, loyal customer network and friendly environment are some of the opportunities highlighted in the study. Besides, entry barriers are also outlined, like the initial investment, misunderstandings between colleagues at the beginning and shortage of communication skills.

All the findings derive from real women who have been working in the industry for more than ten years, so that the evolution of the taxi sector from a gender point of view has been also considered and explained through real lived experiences.

In the present study, an exhaustive analysis of the situation of the Spanish taxi sector is presented and analyzed. Based on real interviews to female taxi drivers, the main opportunities, and entry barriers and obstacles of working in the taxi sector are collected and used to assess how the transport sector fits the key needs of the interviewees and favor the work-life balance.

All data regarding the city and participants to the case study are kept anonymous.

This analysis is done in the framework of the European project TInnGO which main objective is to create a framework and mechanisms for a sustainable game change in European transport through a transformative strategy of gender and diversity sensitive smart mobility.

1. INTRODUCTION

According to the Women in Transport ETP Platform for change, only the 22% of the employees in the European transport sector are women. Moreover, the principal users of the public transport for their daily movements are women too. In fact, usually the women's daily mobility is characterized by fragmented short travels, with several stops during the day, whereas men usually make direct travels form work to home mainly by private vehicle.

Considering these facts, the European project TInnGO proposes to investigate the reasons behind this situation. The TInnGO project: Transport Innovative Gender Observatory is funded by the European Union's Horizon 2020 research and innovation programme (Grant Agreement no. 824349)

The objective of TInnGO is to promote gender equality in all areas of transport at European level, applying strategic mechanisms to facilitate access and participation of the population both as users and workers and through the adaptation of infrastructures and services to the population and gender needs.

The main result of this initiative will be the development of a Gender Innovation Observatory in European Transport. To feed this platform, ten hubs across Europe are collecting data and address locally important issues in intelligent mobility with a gender perspective and mainstreaming analysis.

The main activity of these hubs is the analysis of the current situation at local level, the global understanding of problems and analysis of solutions, the generation of new knowledge and its exchange between the different hubs. As a result, gender equality guides will be developed to evaluate the activities developed in their environment.

All the information collected, and the smart mobility concepts developed are uploaded to a transport gender observatory and open innovation platform developed by TInnGO. (https://transportgenderobservatory.eu/)

Among the ten hubs, the Spanish hub focused onto two areas: one related to the transport safety and security from the perspective of users and vehicles; and the other one centered in the gender equality in employment, considering both passenger and freight transport.

The Spanish hub is involving companies in the sector to analyze the current situation in Spain and providing their point of view.

The aim of this hub and TInnGO project is to take a step forward in gender equality in transport by introducing new strategies in gender equality in an integrated way for the whole society. In this sense, focusing on the employment perspective, the Spanish hub developed an analysis on the taxi sector employment, highlighting the main challenges and needs of the women taxi drivers.

2. OVERVIEW: THE TAXI INDUSTRY

The transport sector is not gender – balance, according to Women in Transport EU platform for change only the 22% of transport workers are women. If we focused on the land transport the percentage is even smaller up to 14% according to the transport.

Focusing on the taxi sector the percentage in the greater cities is lower. For example, in London the percentage of female taxi drivers registered are around the 2% as defined in (http://femaletaxidrivers.co.uk/, s.f.)

2.1. Description of the national context in the transport sector

The transport sector in Spain is made up of many small companies. Following the data provided by the Spanish National Statistics Institute (INE) based on the national classification of economic activities (CNAE), 5.2% of working people are employed in the transport sector. 19.35% are female and 80.65% are men. The following graph elaborated by data from the National Statistics Institute, Employed by gender and branch of activity from 2009 to 2019, shows the evolution of the number of people working in the industry over the last 10 years and the differences between male and female employees (INE, Insituto Nacional de Estadística - , n.d.).

Fig. 1: Evolution of transport workers over the last 10 years by gender

The evolution of the transport sector has only undergone minor fluctuations over the last decade. 2019 was the year with the highest volume of workers, with 829,200 male employees and 198,900 female ones, whilst 2013 was the year with the smallest number of workers, with 690,300 male workers and 147,400 female ones.

The following table, elaborated by data from the National Statistics Institute and called Employed by gender and branch of activity, shows a breakdown by different transport areas, with women accounting for between 11% - 44% of the jobs, depending on the sector (INE, Insituto Nacional de Estadística - , n.d.):

2019	**Both**	**Men**	**Women**
Road and pipeline transport	599,700	531,300	68,400
Maritime and inland waterway transport	25,600	18,400	7,200
Air transport	56,500	31,600	24,900
Storage and related transport activities	227,800	168,500	59,300
Postal and courier activities	118,500	79,300	39,100
Total	1,028,100	829,200	198,900

Table 1: Employed by gender and branch of activity in transport and storage.

2.2. Description of the taxi sector in Spain

The case study performed in Spain has been focused on the road transport sector and has concentrated specifically on the taxi sector. There are a total of 69,792 taxis in Spain. The graph below (see Fig. 2) shows how many taxis there are in the different regions of Spain, with Madrid having the largest taxi fleet and La Rioja the smallest, the number of total number of taxi vehicles in each region is shown. The data is obtained from the National Statistics institute called public service cars by region, autonomous cities and provinces, territorial scope and availability of taximeter in 2018 (INE, Instituto Nacional de Estadística, 2018).

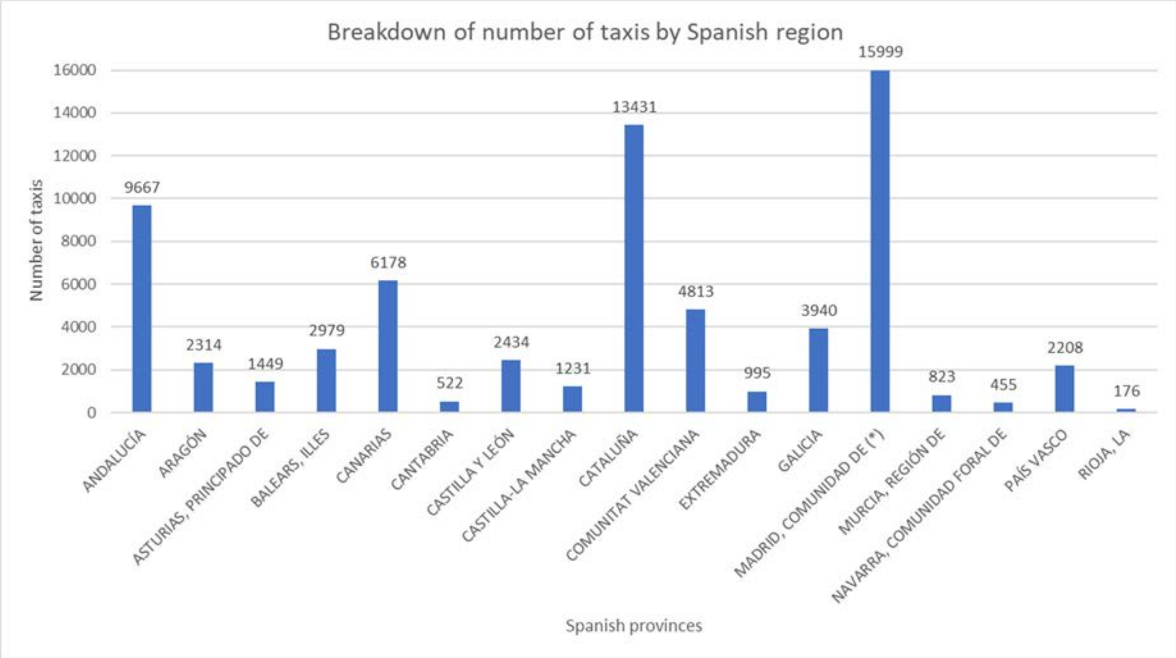
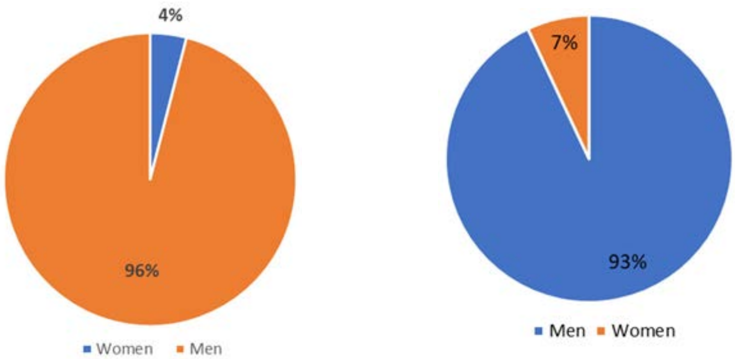


Fig. 2: Breakdown of number of taxis by Spanish region

Following infotaxi.net, only 4% of taxi drivers in Spain are women (Haro, 2019). The taxi industry traditionally a male-dominated profession. Nevertheless, the number of women working in this sector has increased in a small but significant way over the years.

Nationality-wise, around 50% of taxi drivers are Spanish and the other 50% are foreigners, implying that multiculturality in the sector is very high (see Fig. 3).



a) b)

Fig. 3: a) Breakdown of taxi drivers by gender, most of the taxi drivers are men; b) Taxi licenses. Almost all of the taxi licenses belong to men in the Spanish city under analysis.

In the city where the interviews took place there are approximately 3,000 taxi licences, where less than 10% belongs to female taxi drivers. There are around 5,000 taxi drivers in total, because around 2,000 licences have two drivers (see Fig. 3b**)**.

Most of taxi drivers in Spain are self-employed people who work using their own vehicles.

However, there are also taxi drivers that are salaried employees and work for other self-employed taxi drivers sharing their employer's taxis. In these cases, both chauffeurs have a legal agreement in which the salaried employee gives their boss a fixed percentage of the money earned during their working day based on the number of rides they pick up.

Taxis are considered as a public service that is regulated by local councils. Therefore, each region has a different way of working, with a different regulatory framework, that regulates days of rest and working hours. No gender bias is explicitly applied and conditions for both male and female taxi drivers are the same.

Generally, Taxi drivers are members of taxi associations which support them in administrative tasks and by providing and managing platforms to optimize booking performances. In order to book a taxi, the clients (taxi users) can contact a taxi booking company which will look for the closest taxi driver available to assign the requested ride.

Taxi drivers must register with these booking companies first before they can be assigned rides and customers.

3. METHODOLOGY

The present case study has been carried out by ITENE consultants in the framework of Task 9.1 Identification of current and future issues in the employment of women in Smart Mobility (SM.). This task was led by University of Copenhagen (UCPH) (UCPH, 2019).

The interviews were based on a common questionnaire provided by the leader of the task with the aim of investigating career path of the interviewees, opportunities, and barriers for employment in the sector and work life balance activities. As the sector is masculinize, it is difficult to get the contact of the female taxi drivers. In this case, the contact with potential female taxi drivers was achieved by contacting a dedicated association known beforehand.

The first interviewee and the association encouraged the other taxi drivers to participate.
Seven interviews were performed by ITENE both face to face and by phone. In each case the questionnaire was filled with the required information and any additional detail was also considered. It is fairly to highlight that the on-site interviews provided more information that the interviewee made by phone. The face-to-face meeting and the direct contact made the interviewees feel more comfortable and share they own experiences and feelings with more details.

Before the interview, the interviewees read the participation sheet which informed about the purpose of the study, the main benefits and risks of participating, the participation was voluntary, what would happen with the results.

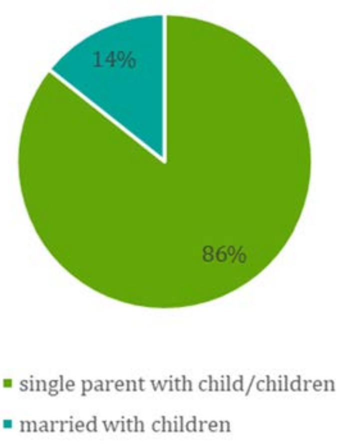
The participation sheet also informed about the data protection and confidentiality following the General Data Protection Regulation 2016 (GDPR) and the Data Protection Act 2018. Finally, they signed a consent form before starting their participation in the study.

4. CASE STUDY

4.1 Overview of the family and working background of the participants

A total of seven female taxi drivers were interviewed. In the following, they are identified with the numbers Interviewee 1 to Interviewee 7.

All of them are self-employed workers in Spain, owning their taxi licences and vehicles. Six of the interviewees were Spanish and one was from another European country. Most of them have been working in the taxi sector for more than 10 years. They are experienced taxi drivers mainly working in the city centre and they have seen how the sector has changed over the years (see figures Fig.4 to Fig.6).



a)

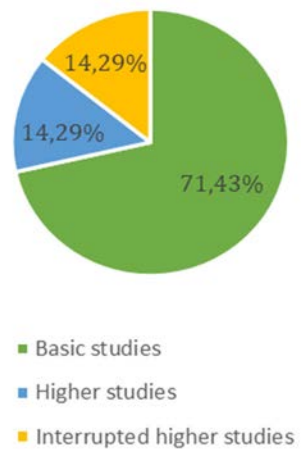


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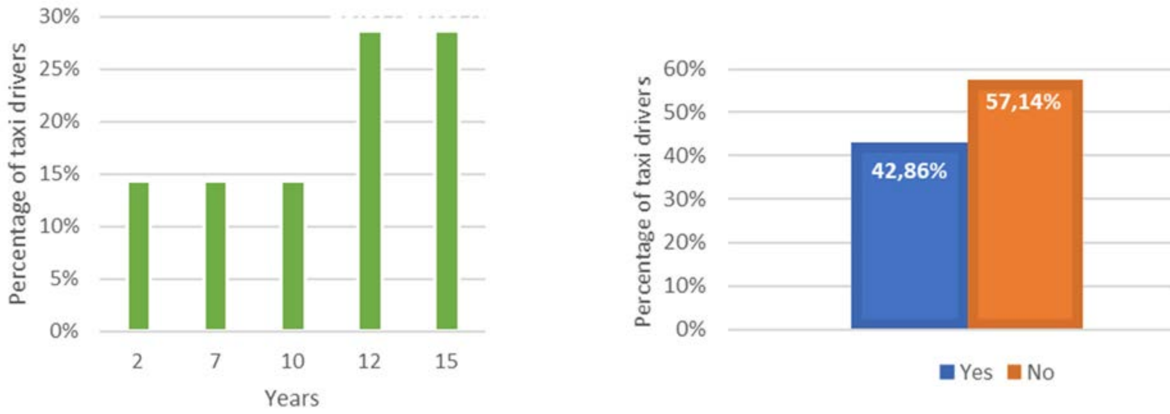
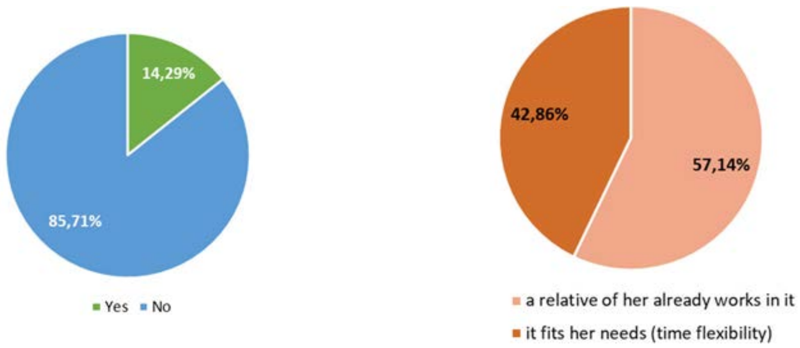
Fig. 4: a) Family situation: most of the interviewed are currently single parents with child/children; b) Study qualifications of the female taxi drivers: most of the interviewed had accomplished basic studies, mostly related to administration fields.



a) b)

Fig. 5: a) Years working as a taxi driver. Most of the interviewees have been working as taxi drivers for more than 10 years. b) Do they employ an additional driver? Around the 40% of the interviewees employed a chauffeur.



a) b)

Fig. 6: a) Do they work at night? Most of the female taxi driver do not work at night shifts; b) They decided to become a taxi driver because… Main reasons for choosing to work in the taxi industry is a relative of the interviewee already works in the sector and the time flexibility.

4.2 Findings about opportunities in the sector

- Flexibility

Most of the interviewees chose to work in the taxi industry to accomplish with family commitments so they could organise their own working timetable (see **Fig. 6b**). Being self employed gives them flexibility and working as a taxi driver let them the chance to define its working schedule. Actually, Intesparviewee 7 remarked that she is able to take care of her children since during the week, from Monday to Friday, she is less busy than on weekends... All of them have been working mothers and keeping the work-life balance is crucial for all of them. As an example, one interviewee claimed that is key for her to be able to "*get out of the office because my kid has the flu*". In addition, another advantage of being a taxi driver for Interviewee 3 is the ability to quickly recover from a work accident because it is usually related to car damages that have a straight and easy solution.

- Family support

Four out of seven interviewees declared that have relatives working as taxi drivers, that is generally how they came in contact with the taxi sector (see **Fig. 6b***)*. For example, Interviewee 3 shares her licence with her husband, so two people operate under one licence, doubling income. In addition, Interviewee 7 thinks that sharing licenses in family is a good way to earn extra income in university terms. Interviewee 4's son already works as a taxi driver.

All the interviewees had previous experience in working in other sectors. Three out of seven interviewees like being a taxi driver and one of them admitted that *"being a taxi driver was her dream job"*. The other four interviewees still dreamed about their ideal job but due to their age and money needs, they decided to keep working as a taxi driver until retirement. Most of them plan to hire another chauffeur because it would allow them to have more time for themselves (four out of seven taxi drivers have one already).

- Friendly environment and support

The working environment in the taxi sector is pleasant, for women, men and multicultural drivers. They support themselves and endorse the taxi drivers that follow the rules, including in situations that the customers do not respect another colleague. Interviewee 7 described one specific case that happened to her: she was the first taxi in the queue and two women went straight forward to the taxi directly behind that of our respondent, because it was driven by a male taxi driver. The male colleague explained that they needed to take the first taxi in the queue (our respondent's taxi), but astonishingly the users refused to go with a female taxi driver. The male taxi driver calmly answered: *"If you don't want her as a taxi driver, I am not going to provide you with the service either"*. Our respondent only discovered this fact some time later, when her colleague told her what happened. She really appreciated his support.

In addition, all the interviewees belong to common groups in chat platforms in order to share between colleagues new potential races. Within this groups our interviewees feel more comfortable and supported in the sector. They can share their own experiences and make networking with the colleagues.

- Multiculturality

All of them agreed that they work in an international environment, in terms of customers and colleagues. The taxi sector comprises a range of different cultures and people, sharing the same difficulties and opportunities. Arabic cultural has a different approach to women, and sometimes it generates ambiguous situations due to different perception of the female role in society. Nevertheless, good work relationships have been built thanks to dialogue and understanding.

- Customer loyalty

All of them positively valued the daily contact clients and colleagues. Customer-wise, most users are glad to see a woman as a taxi driver. In fact, they remarked that "*foreigners are more surprised than Spaniards when they see a female taxi driver*". For example, Interviewee 3 stated that in *her country she would have not worked as a taxi driver because of the lack of safety on the road. On the other hand, many women there usually drive buses*".

Taxis belonging to women are considered cleaner and tidier than the men ones. Moreover, the interviewees stated that customers highly appreciate them as drivers, since they are considered to be safer and more cautious drivers than male drivers. As a consequence, they feel more comfortable, confident and secure when depending on women on the road. One of the respondents shared a customer sentence: "*My husband gets hysterical in the car and we get there later than when we go with you, as you always keep calm.*

All these features make female taxi drivers more appealing for the customers of all genders. In fact, one distinctive characteristic is that they usually have loyal customers. Interviewee 7 explained that she had faithful clients that called her monthly, and others once or twice a year for trips of different lengths. In addition, one of these loyal customers hired her to take their children alone to school in her taxi."

- Support gender initiatives

Being a taxi driver gives the opportunity to contribute to the welfare of the society. The interviewees joined a national initiative that aims at supporting women that are victims of gender crimes. Our interviewees explained that some taxis (all of the respondents included here) have a purple ribbon on their taxi aerial which means that if a woman feels unsafe or she has been victim of gender violence will make use of a free ride to get to a safer place.

Fortunately, only one of the interviewed taxi drivers has had to provide this type of service.

4.3 Findings about entry barriers in the industry

- Investment

The initial investment to entry in the taxi sector is very high. The first step is to obtain the taxi driver title. Once the title is obtained, there are two big investment. On the one side the acquisition of a taxi license and the purchase of a taxi vehicle. These two acquisitions are expensive and not everyone can afford them. Therefore, one of the main reasons to entre in the sector is because a relative already work on it (see **Fig.6**). The active taxi drivers know who will leave the sector, who will retire, and they get advantage of getting new licenses.

In addition, some of the taxi drivers share the licenses with their familiars.

- Initial Colleagues' mistrust

As the taxi sector is strongly male-dominated, at the beginning of working in the sector, more than ten years ago (see **Fig. 5**) many of the respondents had to put up with a range of comments about being a woman, defending her right and ability to work as men do.

Interviewee 3 admitted that when she started this job, she had several run-ins with colleagues. For example, during her first year, a colleague told her that she should not have been a taxi driver because she was a woman. She defended herself by replying "*I am just doing the job that your son doesn't want to.*" She has never had a problem with this colleague ever since. Interviewee 6 argued with another colleague, who claimed that *driving a taxi was not a job for women*. Despite of initial rushes, relationships among colleagues improved and currently, the respondents are well-considered and accepted in the taxi community.

The basic condition for acceptance is to abide by the rules of work: do not overtake a colleague on the inside, do not work on your rest days, respect the queue. Respect is gained by working according to the rules.

- Communication

The taxi sector daily deals with many different customers from different countries. Foreign languages usually represent an issue for the respondents, that would appreciate to receive English-speaking courses to improve their communication skills, better than the general basic courses they have received so far.

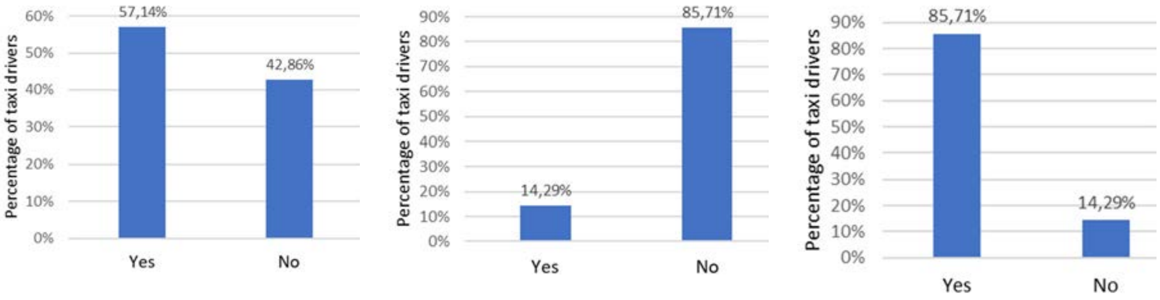
- Customer rejection

Although it is not common, surprisingly, some of the interviewees have experienced rejection by female customers. Interviewee 6 had a small misunderstanding with a customer that she had to pick up at a railway station. The customer had requested a taxi service, and when he saw that a female taxi driver was waiting for him, he claimed that the booking service should have notified him that the taxi driver was going to be a woman instead of a man.

- Hustle and bustle of the road

Enjoying driving is a mandatory requirement to join this profession together with the ability of keep calm in the traffic and the ability to manage tense situations. Interviewee 7 confessed that when she was younger, she hated driving because she got nervous, but that she had been able to overcome her fears and now she enjoys driving on a daily basis.

All the respondents have generally anecdotes along they careers but these female drivers do not have issues on a daily basis and most are very happy and glad to be taxi drivers (see Fig.7)



a) b) c)

Fig. 7: a) Do they dreamed about other jobs? Reviewing the dreamed jobs around the 57% dreamed with another job although the majority will keep as taxi driver. b) Do they plan to change job in the next 10 years? Only one respondent will change the job, all the other respondents will keep as taxi driver. c)Are they happy with their job? All of the interviewees, except one, are satisfied with their current job (taxi driver).

5. CONCLUSION

The Spanish taxi industry has been traditionally a masculinised transport sector and still only the 4% of the taxi drivers are women. Despite the high entry investment to purchase both taxi license and vehicle, the growing opportunities offered by this field make this job more and more appealing for women, mostly because it favours the work life balance and allows the employees to coordinate properly their daily duties. The family support, one of the key reasons to start working in this industry, also allows to take an advantage of one taxi license, increasing the family income. The friendly work environment makes female drivers feel supported, gender independent. The multicultural environment helps them to know and respect other cultures, adopting many different points of views of the situations they live on the road. Thanks to their patience and calm driving the interviewees have been able to build a loyal customers network that trust them and their way of driving. Moreover, the sector offers the opportunity to support gender initiatives in order to help citizens in difficult situations.

In conclusion, the interviewees are pleased to work as a taxi driver since this job gives them the chance to have regular incomes and run a family at the same time. Although the sector is still highly male - dominated, more women are expected to join the taxi industry in the next years, reducing the gender gap that is currently affecting the transport sector.

FUNDINGS

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Identification of current and future issues in employment of women in SM lead by University of Copenhagen

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PLATOONING OF CONNECTED AUTOMATED VEHICLES ON FREEWAYS: A BIRD'S EYE VIEW

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ABSTRACT

A platoon can be defined as a group of consecutive vehicles that exchange information, so that they drive in a coordinated way, allowing very small spacings and still travelling at relatively high speeds. The concept of vehicle platooning is not new. In fact, scientific articles on platooning were published as early as the 1970s, and the first large-scale pilot test on platooning was carried out at the end of the 1990s. The main purpose of these early research works was to improve traffic efficiency and reduce consumptions, as well as to develop the existing technology.

These contributions were very valuable, although somehow limited by the relevant technology still being in its infancy. Precisely, the development of technology and communications in the last years has given new impetus to research on vehicle platooning on freeways as one of the possible forms of cooperation among connected automated vehicles (CAVs). The point of view of these recent studies has also been extended: in addition to traffic efficiency, the role of platooning is analyzed in terms of safety, sustainability, business productivity, etc.

In this context, there are today many scientific publications on vehicle platooning with different purposes, set in distinct scenarios and based on diverse vehicles and technologies (regular or segregated lanes, cars or trucks, vehicles with different SAE levels, etc.).

In order to organize and consolidate the existing knowledge, a comprehensive and systematic review must be performed.

This work represents a first approximation to this more ambitious objective. Firstly, platooning has been conceptualized in order to facilitate its analysis and comparisons among studies. Secondly, key publications on platooning have been analyzed to determine the most significant impacts expected from its implementation.

Finally, some important research gaps and disparate findings on the topic have been identified.

1. INTRODUCTION

Since the development of the first intelligent transport systems in the 1980s (Weiland and Purser, 2000), researchers, companies and administrations have been working to apply developments in technology and communications to combat the undesired externalities caused by transport, particularly by road transport. Especially during the present century, decisive advances in vehicle automation, monitoring and communication networks, both Wi-Fi and mobile, have allowed this struggle to be taken to a higher level and definitively visualizing future autonomous and connected mobility as feasible. Several cooperation strategies based on different communication schemes among mobility agents, namely vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-all (V2X) communications, are being developed with the aim of improving traffic flow and safety and reducing transportation environmental impacts (Fagnant and Kockelman, 2005; Maiti et al., 2017; Razmi et al., 2020).

One particular form of cooperation, the concept of vehicle platooning, started to attract interest as early as the 1970s. At that time, vehicles involved in platooning projects and research were passenger cars and, mostly, heavy vehicles, fitted with *ad hoc* designed sensors (Tsugawa, 2016). Additionally, the role of infrastructure was often decisive in those years, during which numerous studies on Automated Highway Systems (AHS) emerged. In this early research, the most attractive benefits expected from platooning were those economic ones linked to potentially lower fuel consumption (Browand, 2004; Lammert et al., 2014; Alam et al., 2015; Tsugawa, 2016). On the contrary, current studies mainly focus on light vehicles with a high degree of automation *per se* (Maiti et al., 2017; Bian et al., 2019; Sala and Soriguera, 2020). In addition, the importance of infrastructure is decreasing in relative terms, while that of communications is increasing (Bian et al., 2019; Jia et al, 2019; Li et al., 2020). Also, the expected benefits of platooning in terms of improved traffic flow and safety are tipping the balance towards research in these areas (Xu et al, 2013; Ye and Yamamoto, 2018; Jo et al., 2019; Calvert et al, 2019).

Nevertheless, the most addressed platooning-related topic is the so-called *string stability*. Researchers of different fields propose varied longitudinal and lateral control strategies to avoid that, due to the close vehicle formation within a platoon, state disturbances propagate and amplify along the string of vehicles.

These studies start by mathematically defining string stability, continue using particular analysis methods to derive conditions that ensure this stability and, finally, design controllers that satisfy them (Feng et al., 2019). Each of these steps can have many variants, depending not only on the approaches used, but also on the target platoon system characteristics (e.g. vehicle features, following policies, etc.). The great variety and complexity of string stability studies would require a particular comprehensive review. Therefore, this topic is out of the scope of this paper.

Instead, the present work is aimed at providing an overview on research and developments on platooning, particularly focusing on its expected impacts on areas such as traffic flow, road safety, human drivers' behavior, consumptions and emissions (Figure 1). An extensive literature review has allowed identifying and summarizing the most significant results on each topic, taking into account both the distinct contexts considered and the different analysis methodologies employed. Previously, a brief classification of platooning typologies is provided, in order to facilitate the understanding of their possible influence on the results. Finally, the paper highlights those issues with more uncertainty, either because they have hardly been addressed or because the results obtained have been disparate.

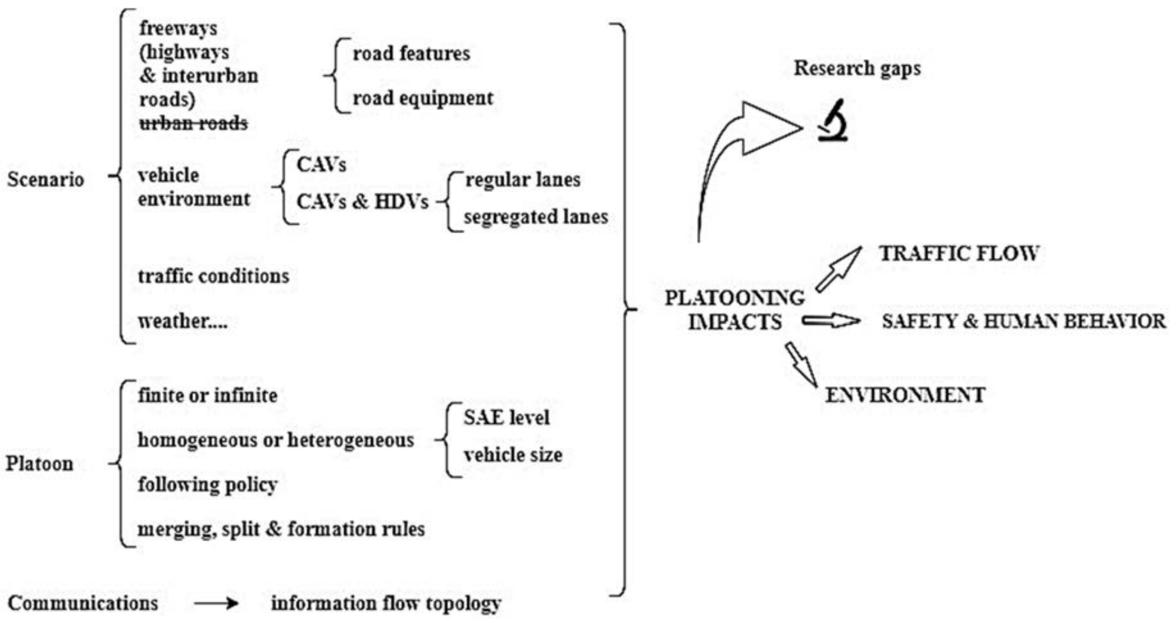

Figure 1. Graphical abstract of the article (own elaboration).

Authors have used a semi-structured approach to choose the papers that underpin this review. In the first stage, only those studies published in scientific journals indexed in the Journal Citation Reports platform were considered. From these studies, the ones containing the words *platoon*, *platooning* or *road train* in the title, abstract or keywords were searched in the Scopus database. A quick scan of the abstract allowed identifying those referring exclusively to traditional vehicles, urban environments or intersections (the word *platoon* is often used to identify a set of vehicles arriving at/leaving a signalized intersection during a particular cycle), which were disregarded.

Also those published in journals from fields other than transportation, vehicle or communications engineering, or associated areas (e.g. environment, psychology). Among the remaining papers, those with the highest number of citations were selected. Increasing minimum thresholds were established according to their year of publication. The final set of chosen references was supplemented with studies obtained from backward snowballing, being the acceptance criteria (e.g. indexing or number of citations) in this case looser than for the main papers.

The remainder of the paper is structured as follows: Section 2 classifies platooning according to three different criteria, which is important for the subsequent comparison of studies. Sections 3, 4 and 5 respectively summarize, as per the performed review, platooning impacts on traffic flow, safety and human behavior, and the environment. The most important conclusions of the analysis are extracted in Section 6, in which remaining research gaps are also highlighted.

2. PLATOONING TYPOLOGIES

It would be possible to differentiate numerous typologies of platooning based on diverse criteria. The following subsections attempt to perform this classification in a simple and concise way, according to the type and number of platooned vehicles, the information flow topology and the following policy within the platoon.

2.1 Classification according to the type and number of platooned vehicles

Usually, research on platoons focuses on vehicles of similar size, i.e., light (e.g. Gouy et al, 2014; Ye and Yamamoto, 2018) or heavy vehicles separately (e.g. Ramezani et al., 2018, Calvert et al., 2019). So far, only a small number of authors have tried to define strategies for the formation of platoons of vehicles with different sizes (e.g. Sun and Yin, 2019). The diverse mechanical features of these vehicles (acceleration and deceleration capacity, maximum speeds, speeds and gears on slopes, etc.) are obstacles to overcome. However, there are others such as the difficulty that large differences in size between consecutive vehicles may represent for sensors and communications, or the lack of comfort/the feeling of insecurity they may cause to drivers or passengers (think, for example, of a car placed between two large trucks) (Feng et al., 2019). These challenges are compounded by the fact that, unless a particular strategy is defined, the relative position within the platoon of these differently sized vehicles would vary in real time.

Another differentiating factor among vehicles is their degree of automation. In this regard, it should be noted that very few studies specify the SAE level (SAE, 2016) of the vehicles they are considering, and authors refer to them loosely as (cooperative) "autonomous vehicles", “automated vehicles”, “self-driving cars” or “human-driven vehicles”, among others. Therefore, the reader must suppose this automation level based on the capabilities vehicles are provided with throughout the text.

Some researchers argue that, as platooning involves driving at short intervehicle distances for an extended period, and eventually at high speeds, reactions to safety-critical events such as the sudden braking of vehicles ahead should not depend on the human factor.

Accordingly, SAE levels 4 and 5 are preferred, as human intervention is restricted to very limited occasions (Konstantinopoulou et al., 2019). Nevertheless, especially for the case of truck platooning, most current field operational tests and implementations feature heavy vehicles of SAE levels 1 and 2. Eminently video cameras, radars and vehicle-to-vehicle communications are used to keep close formations travelling at medium-low speeds, being drivers still quite actively involved (Kockelman et al., 2016; Kuhn et al., 2017; Knoop et al., 2019; Calvert et al., 2019). Although some improvements are achieved, the overall potential advantages of platooning cannot be maximized with these lower levels of automation. In this context, institutions like the European Road Transport Research

Advisory have assumed a simpler classification (when compared to the SAE one) for heavy vehicles that specifically limits the platooning possibilities they have (ERTRA, 2015). For the remainder of this paper, the term CAVs will refer to cooperative medium-high automated vehicles.

In this context, it is called *homogeneous platoon* that consisting of vehicles of the same (or similar) characteristics in terms of size and degree of automation. On the contrary, a platoon is *heterogeneous* if there are notable differences of any kind among its vehicles, either in size, degree of automation (including traditional human-driven vehicles – HDVs-) or both.

Regarding the number of vehicles in the platoon, it is possible to differentiate between *finite platoons*, for which a maximum number of vehicles is set, and *infinite platoons* (Feng et al., 2019; Zhou et al., 2021). Obviously, real platoons will always be finite, but the use of infinite platoons in research allows simplifying and generalizing the analysis of platoons with a high number of vehicles, seeking to maximize all potential benefits of this mode of cooperative driving. However, some authors question the interest of research on infinite or very long platoons. On the one hand, common challenges of cooperative driving, such as information flow and management, are accentuated. On the other hand, it seems unlikely that a large number of vehicles would decide to take at the same time a same route long enough so as to make a profit, unless it is a predetermined management decision. For example, a decision linked to logistics, i.e., an agreement among different companies whose goods must be transported from similar origins to similar destinations. In case this kind of platoons would be materialized, another aspect to take into account would be their interactions with other non-platooned vehicles. Although this aspect is important for any kind of platoon, some particular measures only advisable for medium-short platoons would have to be imposed for large platoons.

One example would be their driving restricted to the leftmost lane, so as not to prevent other vehicles, for instance, from entering or exiting a freeway or from making a lane change (Eckhardt et al., 2016). Note that, for the case of long truck platoons, this situation would be just the opposite of the current one, in which heavy vehicles usually drive in the rightmost lane. Additionally, very large truck platoons could lead to an accelerated deterioration of existing pavements and structures (Song et al., 2021).

2.2 Classification according to the information flow topology

Although platooning can benefit from V2X communications, the information exchanged among vehicles is key to achieve a good performance and, particularly, to ensure string stability. Not only information on other vehicles' speeds or positions, but even slight accelerations, decelerations or direction changes, among others, must reach each particular vehicle in time so that it can react accordingly. In this way, disturbances diminish and their propagation and amplification along the string of vehicles are avoided.

Logically, for a particular vehicle within the platoon, information coming from its nearest vehicles will be not only relevant, but also more feasibly obtainable from the point of view of sensors and communications. Therefore, information flow topologies (IFTs) such as *predecessor following* (PF), *two-predecessor following* (TPF) and *bidirectional* (BDL) are widely used in research. In parallel to the development of powerful communications, more generalized schemes such as *r-predecessor following* (rPLF) are being increasingly applied. For their part, other studies consider that some information about the leader, especially (but not only) its position, should reach the whole platoon. Taking into account that the leader will be relatively far away from some members of the platoon, the exchange of information among nearby vehicles is considered necessary anyway. In this context, *predecessor leader following* (PLF), *two-predecessor leader following* (TPLF) or the generalized *r-predecessor leader following* (rPLF), as well as *bidirectional leader* (BDL) IFTs are more and more commonly used in the studies (Zheng et al., 2016; Feng et al., 2019; Gong et al., 2019). Figure 2 represents the information flows of these configurations.

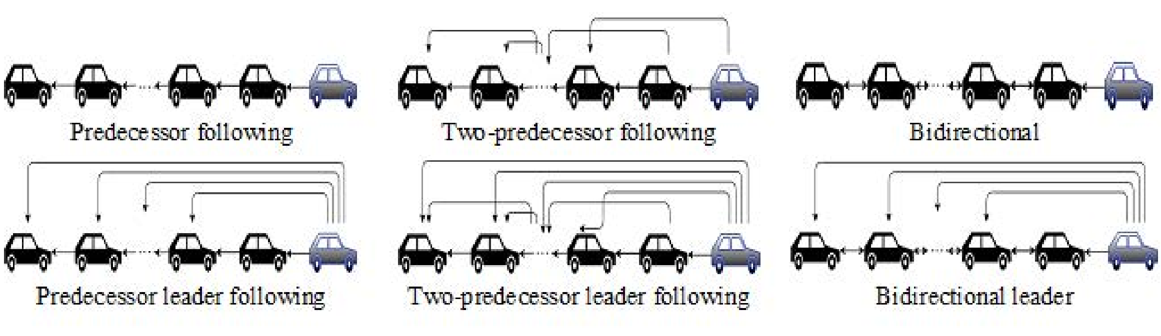

Figure 2. Most typical information flow topologies for platoons (the leader vehicle is highlighted. Own elaboration).

The possibility that an increasing number of vehicles can exchange information with each other despite being at considerable distances is the result of improvements in communications. However, the greater the amount of information transmitted, the greater the likelihood of communication delays, packet losses and other related issues, usually associated with the congestion of the communication channels (Xu et al., 2013; Zheng et al, 2018; Li et al., 2020). Therefore, the fact that more vehicles exchange information does not necessary imply either a higher degree of stability within the platoon or more benefits linked to a particular platooning behavior. Researchers try to find a tradeoff in this regard.

Another aspect that must be highlighted is that neither of the former information flow configurations is static, as both the vehicles and their positions within a platoon change over time. Accounting for these dynamic changes in real time is one of the main challenges for researchers on platooning (Feng et al., 2019).

2.3 Classification according to the formation, split or following policies

The first condition for the potential benefits of platooning to be exploited is that there is a sufficient penetration of vehicles with a level of automation that allows platooning (Bergenhem et al., 2012; Janssen et al., 2015). However, the strategies on the basis of which platoons are formed also play an important role. The *a priori* least favorable strategy in this respect would be the so-called *opportunistic platooning* (Liang et al., 2014; Sala and Soriguera, 2020*)*, also known as *on-the-fly platooning*, according to which only those CAVs that happen to drive consecutively in the same lane would form a platoon. More efficient would be the *cooperative platooning*, whereby all CAVs within a certain range would try to join in a platoon, respecting the maximum lengths established, if any (Sala and Soriguera, 2020). Even more optimal strategies have been designed in the field of logistics. One example is the *online, dynamic planning or real time platooning*, according to which, just before or during the journey, vehicles announce their destination and/or tentative routes so that other interested vehicles can platoon with them during part or the total of the journey. Another example is the *offline, static* or *scheduled platoon planning,* in which trips are announced in advance to facilitate the coordination among companies (Bhoopalam et al., 2018). Many side aspects complicate this coordination, as, for instance, the mandatory rest stops for drivers in the transportation sector (Goel, 2010; Goel, 2014).

Although the relevant legislation has yet to be updated, it is expected that a minimum number of rest stops will continue to be mandatory, except for SAE level 5 vehicles. With lower automation levels, the driver will have to be prepared to react to any emergency. The type of load carried could also be relevant for the suitability or not of forming/joining a platoon in some specific cases (e.g. living beings against dangerous products, etc.) (Meisen et al., 2008).

Other details concerning the formation and split of platoons at the individual vehicle level are also under study. The fact that a vehicle joins a platoon, as well as when it leaves it, is not trivial. Getting these operations right is essential not only to maximize the benefits of platooning, but also to avoid traffic flow disturbances. In terms of merging, some authors advocate that a platoon should maintain its speed and the joining vehicle should accelerate to catch it. This is the so-called *catch-up strategy* (e.g. Liang et al., 2013; Ko, 2019). Other authors are in favor of a *slow-down strategy*, that is, a slight deceleration of the platoon to facilitate the merging of the vehicle that has announced its willingness to join it (e.g. Meisen et al., 2008; Ko, 2019). There are also intermediate solutions (e.g. Saeednia and Menéndez, 2016; Saeednia and Menéndez, 2017; Farag et al., 2019). Additionally, some authors assume that vehicles should join existing platoons at the back, and others consider the merging in the middle or at the front (e.g. Farag et al., 2019; Paranjothi et al., 2020).

Fewer studies address vehicles' leaving of the platoon. These often stress the importance of this maneuver to be announced in advance, especially to the immediate follower, which, among other things, will have to close the gap left by the departing vehicle (e.g. Maiti et al., 2017; Duret at al., 2019; Paranjothi et al., 2020). Again, a single tail split will have different consequences for the platoon's stability and efficiency than a single front split or a split from the middle, and each of them must be separately and deeply analyzed yet (Maiti et al., 2017). In any case, both the merging and the diverging possibilities will also depend on the vehicles' characteristics, especially the size (Maiti et al., 2017, Farag at al., 2019).

Apart from these different building/splitting strategies, any vehicle in a platoon follows a pre-established following policy during its journey. The three main policies considered so far are the *constant distance policy*, the *constant time distance policy* and the *nonlinear distance policy*. In the two first, followers drive respectively maintaining a fixed distance in space, either in terms of gaps or spacings (e.g. Gong and Du, 2018; Jia et al., 2019; Li et al., 2020) or in time, usually in terms of time headways, but also of time gaps (e.g. Dolk et al., 2017; Bian et al., 2019; Wang et al., 2020). These distances vary across the different studies, depending, among others, on vehicles' size and level of automation. Constant time headways between 0.6 and 1 s are quite common in the literature, whereas the variability in space distances is much broader. For example, Zhou et al. (2017) considered a spacing of 7 m for truck platooning, while Zheng et al. (2018) worked with 25 m for generic platoons.

The *nonlinear distance strategy* (e.g. Orosz, 2016) is usually implemented with the aim of improving platooning string stability and overall benefits, as it better accounts for the influence of the road characteristics (mainly of slopes) on the mechanical capabilities of vehicles, especially if they are heavy. Other less used following policies can be found in the literature, some of them more complicated and difficult to implement in practice, and others that, on the contrary, only impose minimum (but not maximum) space or time distances for the sake of safety (e.g. Zhou et al., 2017).

A few authors (e.g. Vukadinovic et al., 2018) have also addressed the definition of following policies for the leader with respect to other platoons or individual vehicles travelling ahead in the same lane.

3. PLATOONING EFFECTS ON TRAFFIC FLOW

Platooning is expected to have a first positive impact on traffic flow directly linked to the fact that vehicles drive maintaining short distances between them, i.e., occupying less space. This allows for a better use of road capacity (van Arem et al., 2006; Shladover et al, 2015; Nowakowski et al.,2015; Lioris et al., 2017). Further research is needed to quantify this improvement, which will in any case depend on the scenarios (penetration rate of CAVs, platoons' frequency and length, following policies, road characteristics, etc.). If these would be really positive, capacity could be doubled or tripled at intersections (Kockelman et al., 2016; Lioris et al., 2017) and even quintupled on freeway stretches (Kockelman et al., 2016; Sala and Soriguera, 2020). Mainly for heavy vehicles, which are normally a minor share of the flow with particular features, coordinated driving within a platoon could lead to an additional improvement for traffic flow as a result of an increase in traffic homogeneity (Nieuwenhuijze et al., 2012; Ramezani et al., 2018). In this context, travel time savings are also expected (Jo et al., 2019).

However, it is also claimed that too long platoons would increase traffic congestion if the capacity of a certain segment would be surpassed (Bhoopalam et al., 2018). Especially for the case of platoon formation under scheduled planning, this could be a consequence of too many vehicles driving the same route if no restrictions are set. An appropriate traffic assignment model could avoid these issues (Angelelli et al., 2016; Bhoopalam et al., 2018).

Platoons' length, especially depending on the driving lane, could cause other undesirable disturbances such as hindering or impeding the maneuverability of other vehicles wishing, for example, to change lanes or enter or leave a freeway (Nowakowski et al., 2015; Calvert et al., 2019). This could cause sudden accelerations or decelerations on their part, resulting in shockwaves and even in dangerous situations. Precisely because of their greater disruption to other vehicles, Calvert et al. (2019) claim that truck platooning should not be allowed in saturated traffic flow to avoid higher delay times in the overall network.

The mixed scenarios with CAVs sharing roads with HDVs will be particularly complex. Indeed, the interactions among these different vehicles and their consequences for both traffic performance and traffic safety are unclear no matter the cooperative driving mode of CAVs, but also widely researched (Razmi et al, 2020). For the specific case of platooning, even with a high penetration rate of CAVs (i.e. a favorable scenario for platoon formation), HDVs could, intentionally or not, interrupt them if no proper strategies are defined.

This would prevent making the most of platooning potential benefits for traffic flow and, again, generate risky situations. In this context, dedicated lanes for CAVs could minimize these interactions and, additionally, favor platoon formation (Kockelman et al., 2016; Talebpour et al., 2017; Lee et al., 2018; Razmi et al, 2020).

Moreover, higher speed limits could be allowed in these lanes without compromising safety and increasing traffic flow benefits (Ye and Yamamoto, 2018). Tsugawa et al. (2016) particularly addressed the use of dedicated lanes for truck platooning, observing a doubling of capacity, albeit under ideal conditions. However, dedicated lanes would only be reasonable for appreciable penetration rates of CAVs, depending the minimum required rate, among others, on the total number of lanes on the target roads. Traffic conditions would also play a role in this regard. Minimum penetration rates of CAVs between 15% (Yang et al., 2019) and 50% (Xiao et al., 2019) so that dedicated lanes are profitable can be found in the literature, which indicates that more research is needed. In fact, some negative consequences linked to dedicated lanes have already been detected and must be further analyzed. For example, a possible congestion increase in the non-dedicated lanes because of the non-cooperating vehicles having less capacity available (i.e., less lanes) and/or the formation of shockwaves because of abrupt lane changes linked to this vehicle distribution (Talebpour et al., 2017; Zhong, 2018; Xiao et al., 2019). Even when no so determining, permanent dedicated lanes would prevent HDVs from taking advantage of the capabilities of CAVs to reduce traffic instabilities for the whole flow (Ntousakis et al., 2015; Gueriau, 2016; Xiao et al., 2019; Amirgholy et al., 2020). Therefore, some researchers opt for dynamically dedicate lanes to platoons (or to CAVs in general) when appropriate (e.g. Chen et al., 2016, Zhong, 2018; Razmi et al., 2020). Most of them agree that their use should be optional, i.a. to prevent abrupt maneuvers of lane changing vehicles that could lead to shockwaves (Talebpour et al., 2017). The possibility of CAVs sharing these lanes with high occupancy vehicles (HOV) of any SAE level or that of allowing general HDVs to use these lanes after paying a toll have also been considered (Xiao et al., 2019; Liu and Song, 2019). Especially this last policy should be carefully implemented so that dedicated lanes are still worth reserving.

A summary of the mentioned findings is included in Table 2. As already indicated, string stability of platoons is beyond the scope of this work. However, it must be noted that it is a prerequisite not only for platooning to contribute to improved traffic flow, but also to ensure that its effect is not exactly the opposite (Ploeg et al., 2011; Nieuwenhuijze et al., 2012; Calvert et al., 2019).

SCENARIO	IMPACT (EX. REFERENCES)
Mixed environments	✓ Capacity increase (Kockelman et al., 2016; Lioris et al., 2017) ✓ Traffic stabilization & homogenization (Ramezani et al., 2018; Amirgholy et al., 2020)
	× Capacity overrun (Angelelli et al., 2016; Bhoopalam et al., 2018) × Disruptions (Nowakowski et al.,2015; Calvert et al., 2019)
Segregated lanes	✓ Capacity increase (Tsugawa et al. 2016; Lee et al., 2018) ✓ Free flow & high speeds (Ye and Yamamoto, 2018; Razmi et al, 2020)
	× Congestion in regular lanes (Zhong, 2018; Xiao et al., 2019) × Shock waves due to abrupt lane changes (Talebpour et al., 2017; Razmi et al, 2020)

Table 2. Main impacts of platooning on traffic flow (✓positive; × negative)

4. PLATOONING EFFECTS ON SAFETY AND HUMAN BEHAVIOR

There are two main points of view when addressing the relationship between platooning and road safety: focusing on the vehicles that form one particular platoon, or in terms of each platoon's interactions with other single or platooned vehicles (Table 3). Some expected issues regarding the latter perspective have already been appointed, such as those linked to HDVs performing risky maneuvers to, for example, surpass a long platoon (Axelsson, 2017). However, there are more. In fact, driving simulator studies have shown that human drivers change their normal driving behavior when interacting with a platoon, even when this "interaction" is only its observation. The most common consequence is these drivers imitating the platoon intervehicle distances relative to other forward moving HDVs and/or accelerating to run parallel to platoons if their speeds are higher (Skottke et al., 2014; Razmi et al, 2020). Taking into account that humans have longer reaction times than CAVs and are more error-prone, dangerous situations and accidents related to this behavior are expected (Schakel, 2010; Yang et al., 2019). Nevertheless, their importance for the overall computation of the accident rate has yet to be quantified (Razmi et al, 2020).

The factors behind this behavioral change are not completely understood, but a few studies have shed some light on the topic. For example, trust in technology seems to play a role (Al Haddad, 2020; Zhao et al., 2020). In fact, the effect of trust has already been observed in studies addressing the acceptance and intention to use of different systems.

These studies also showed that trust is dynamic and evolves over time and with extended exposure to automation (Ghazizadeh et al., 2012). This may be the reason why previous experience with automated vehicle (AV)-like functions, such as adaptive cruise control (ACC) or cooperative adaptive cruise control (CAAC) systems, is often associated with greater relaxation/confidence and bolder behavior on the part of drivers interacting with platoons. Indeed, even in traditional environments, drivers tend to drive faster and in a more aggressive way (shorter gaps, more abrupt maneuvers, etc.) if their vehicles are equipped with these systems (Hoedemaeker and Brookhuis, 1998; Bianchi et al., 2014; Balk, 2016). Notwithstanding, CACC reduces drivers' stress and fatigue, which could mitigate the potential unfavorable consequences of this tendency (Stanton and Marsden, 1996). Going back to mixed environments, drivers of traditional vehicles are influenced differently depending on the period interacting with the platoon and on the platoon significance in terms of length or height. In this regard, the longer the time or the more significant the platoon (e.g. long truck platoons), the shorter their accepted distance to the vehicle ahead (Gouy et al., 2014; Yang et al., 2019). As mentioned, more research is needed to fully understand these interactions, both analyzing the aforementioned factors under different boundary conditions, and addressing other remaining questions such as the impact of drivers' gender, age, driving experience, physical and mental condition, etc.

CONTEXT	IMPACT (EX. REFERENCES)
Mixed environments	✓ More stability (Stanton and Marsden, 1996; Gueriau, 2016) ✓ Reduced human role (Nieuwenhuijze et al., 2012; Turri et al., 2017)
	× Risky interactions (Axelsson, 2017; Calvert et al., 2019) × Drivers' bolder behavior (Skottke et al., 2014; Razmi et al, 2020)
Safety within the platoon	✓ Coordination (Xu et al., 2013; Bhoopalam et al., 2018) ✓ Minimal human role (Axelsson, 2017; Rahman and Abdel-At 2018)
	× String instabilities (Axelsson, 2017; Feng et al., 2019) × Disengagement & takeover (Varotto et al., 2015; Favaro et al., 2019)

Table 3. Main impacts of platooning on safety (✓positive; × negative).

Within a platoon of CAVs, lower reaction times, vehicle coordination and an inferior role, if any, of the human factor are expected to reduce the number of rear-end collisions (Xu et al., 2013; Bhoopalam et al., 2018). This improvement has already been demonstrated by means of microscopic simulations.

For example, for a penetration rate of CAVs of 40%, Rahman and Abdel-At (2018) observed a significant reduction in the longitudinal crash risk along a dedicated lane for platoons (for CAVs in general), in which these followed a constant time headway policy of 0.6 s. However, side aspects such as those pointed out in section 3 (e.g. the effects of the disturbations caused by vehicles trying to change lanes) or the aforementioned possible changes in human drivers' behavior were neglected in the study. These authors also observed that safety conditions, albeit to a lesser extent, also improved with the presence of the same rate of CAVs with no vehicle segregation. Again, there is need for further studies considering, among others, different road geometries, different policies both for the platoon formation, split and driving and different overall traffic conditions. (Axelsson, 2017). Moreover, this must be done considering *homogeneous* and *heterogeneous* platoons separately, as specific formations accounting for vehicles' size, engine capabilities, etc. can also influence the consequences, for example, of an emergency braking (Bhoopalam et al., 2018). String instabilities, often linked to unsafe situations, must be specifically analyzed and addressed.

It must be borne in mind that the human factor cannot be disregarded within the CAV-platooning framework either. Unless platoons consist of SAE level 5 vehicles, drivers will continue to play a role, at least in emergency contexts. Depending on the vehicle level of automation, there will be certain situations that CAVs will not be able to handle. Thus, they will require drivers to resume the control of the driving task. Within a platoon, i.e., with short distances among vehicles and at relatively high driving speeds, both the drivers' reaction time and the quality of these reactions will be key to avoid multiple vehicle collisions. A study performed by Varotto et al., (2015) with ACC-equipped vehicles showed that drivers needed on average 3.85 s to resume control after sensor failure. Note that this could be a cause for disengagement of CAVs, also in platooning scenarios.

Eriksson and Stanton (2017) additionally observed that reaction times rose to 6.06 ± 2.39 s if drivers were performing a secondary task. Still not on platooning but with platooning-capable vehicles of SAE levels 2 or 3, studies analyzing real data collected in California found that their drivers' reaction times to take control of the vehicle after disengagement had a stable distribution at 0.83 s (Dixit et al., 2016). However, there were differences depending on the type of disengagement (the cause, if active or passive, etc.), the type of road and the previous number of miles travelled in these automated vehicles. Reaction times were found to increase with increased vehicle miles travelled, which was assumed to be related to a gradual increase in trust (Lv. at al., 2018). Simulation has also been used to assess disengagement and takeover in highly automated vehicles. Favaro et al. (2019) analyzed the reactions of 40 human drivers (50% male and 50% female) placed in 36 simulated autonomous technology disengagement scenarios. The study showed that vehicle speed significantly affected the takeover, much more than other factors as, for instance, the driver's age. A similar observation can be found in Zhang et al (2019).

In addition, they noticed that reactions were faster and more appropriate in very risky situations, if drivers had had previous similar takeover experiences and if they were not performing another visual task during the automated driving. Zeeb et al. (2016) also confirmed the role of distraction. For their part, Roche et al. (2020) found a link between drivers' stress level and takeover overreactions. If these same tendencies apply to the specific case of platooning and which their consequences would be taking into account platooning specific driving characteristics is still a research niche. As leaders play a special role in platoons, driver's reactions should be specifically analyzed for this position in the string.

5. ENVIRONMENTAL IMPACTS OF PLATOONING

Most authors agree that platooning will have positive effects from the environmental point of view. Indirectly, platooning is expected to contribute to the improvement of traffic flow and, therefore, to avoid the overconsumptions and harmful emission peaks linked to congestion. Directly, platooning lowers air drag (Wadud et al., 2016; Turri et al, 2017). As aerodynamic drag accounts, for example in highway driving, for 50%–75% of tractive energy requirements (Kasseris, 2016), platooning would allow reducing the average energy consumption and emissions when compared to those linked to single non-cooperative vehicles (Scora and Barth, 2006).

Focusing on platooning direct benefits, their relevance will depend on several factors.

Zabat et al. (1995) analyzed some of them using wind tunnel tests and numerical simulations to assess fuel savings for van platooning in different scenarios. These comprised, among other variables, different intervehicle distances and platoon lengths. The total savings range for all boundary conditions was between 10%-30%, but values between 20%–25% were the most frequent. Clearly, longer platoons achieve higher total savings (Zabat at al., 1995; Bhoopalam et al., 2018). Fuel economy also improves for smaller intervehicle spaces (Zabat at al., 1995; Zhang et al., 2020). Platooning speed, on the contrary, does not seem to play an important role in this regard (McAuliffe et al., 2018; Zhang et al., 2020).

For its part, the size of the platooned vehicles is determinant. Several studies have demonstrated that consumption-related benefits can be especially significant for truck platooning, particularly on highways (Patten et al., 2012; Silberg 2013; Nowakowski et al., 2015; Bhoopalam et al., 2018). As for lighter vehicles, intervehicle distances again have a strong influence. For example, Browand et al. (2004) observed in track tests with tandem trucks that fuel consumption savings reached 11% when these distances were of 3-4 m, but descended to 8% for distances between 8-10 m. Humphreys et al. (2016) perceived this tendency using simulation. Masses and loads limit savings, but their influence is weaker (Lammert et al., 2014, Zhang et al, 2020).

However, for any specific vehicle size, namely for heavy vehicles, individual reductions in energy consumption significantly differ depending on their position within the platoon, consistently with the physical concept of air drag. Indeed, after intervehicle spaces, position is the variable with the greater impact (Zhang et al, 2020). In track tests, leaders were found to save 2.7% to 5.3% of the average fuel needs, while followers increased these figures to 2.8-9.7% (Lammert et al, 2014). Although the exact percentages for savings/consumptions depend on many other boundary conditions, the role of position can be unambiguously observed. For instance, Lu and Shladover (2011) reported, for a test performed with a 3-truck platoon on a real road, reductions in fuel consumption of 18% and 23-24%, respectively for the leader and the followers. Computational fluid dynamics are also often used to assess air drag reduction and, subsequently, consumption savings.

Using this method, Davila et al. (2013) observed that benefits for the followers were double those for the leader. Taking into account the influence of position, some authors have proposed different strategies to proportionally divide the total savings achieved by the whole platoon during a common trip among all members of the string. This distribution is especially suitable for the case of truck platooning under scheduled planning (Bhoopalam et al., 2018). In fact, without a solution to balance out these unequal gains, effective platoon formation would probably be undermined, as no company would want their trucks to be leaders. On the contrary, a good coordination among companies could result in benefits for all and, thus, promote platooning (Zhang et al, 2020).

SCENARIO	IMPACT (EX. REFERENCES)
All (stronger impacts for automated heavy vehicles & uninterrupted traffic)	✓ Reduced energy/fuel consumptions linked to reduced air drag (Lu and Shladover, 2011; Turri et al., 2017) ✓ Reduced energy/fuel consumptions linked to traffic flow improvements (Alam et al., 2015; Bhoopalam et al., 2018) ✓ Lower emissions linked to lower consumptions (Scora and Barth, 2006; Wadud et al., 2016)
	× Improvements dependent on many variables (Zabat at al., 1995; Zhang et al., 2020) × Unequal distribution of savings in the platoon (Davila et al., 2013; Lammert et al, 2014)

Table 4. Main environmental impacts of platooning (✓positive; × negative).

Table 4 summarizes the preceding findings. It must be noted that most of the aforementioned studies have been performed using vehicles with a low-medium level of automation and petrol or diesel engines. Higher energy savings are expected when vehicles are fully automated and electric.

On the one hand, SAE level 5 vehicles will allow for smaller intervehicle spacings and squeeze eco-driving modes. Indeed, Stephens et al., (2016) predict consumption savings to reach, at least 25%, for highway car platooning during non-peak hours. Higher percentages would apply for truck platooning. On the other hand, Alam et al. (2015) have demonstrated that energy savings while platooning are higher than fuel consumption savings, and internal losses are expected to be negligible for electric engines. Other factors such as not needing to implement significant rest periods for drivers will also allow optimizing consumptions (Zhang et al, 2020). Nevertheless, additionally *ad hoc* strategies such as cooperative look-ahead control could help to achieve extra savings in fuel and energy consumption until highly automated vehicles hit the road (Alam et al., 2015).

6. CONCLUSIONS AND REMAINING CHALLENGES

The development of automated and connected transport will offer users new forms of mobility that are more pleasant and comfortable, in which travel times can be used to perform other activities. It will also allow for an increase in the competitiveness of companies associated with the expected reduction in transportation costs and route optimization, among others (Martínez-Díaz et al, 2018). However, the main objective of future mobility is to put an end to current transport problems, i.e. congestion, accidents and environmental damage. The performed analysis confirms that platooning is one of the forms of cooperative driving with the greatest potential in this respect.

First, the frequent formation of medium length platoons could lead to an increase in road capacity due to the small intervehicular distances maintained. In addition, string-stable platoons could accentuate the proven ability of cooperating vehicles to reduce traffic instabilities and, thus, to improve traffic flow. This latter improvement over traditional driving would be even more noticeable when heavy vehicles are involved. Second, coordination within vehicles and, thus, the avoidance of abrupt maneuvers carried out on an individual basis, would also lead to an enhanced safety. This improvement would become more noticeable as the penetration rate of vehicles with a high degree of automation increases, in parallel with the decrease in the weight of the human factor.

Third, platooning would involve a reduction in energy and fuel consumption while driving, which would also result in a drop of harmful emissions. These improvements are mainly linked to lower air drag for the followers and would be particularly advantageous in the case of truck platooning. In addition, there are also environmental benefits linked to the aforementioned improvement of traffic conditions.

Notwithstanding, in order to fully reap these benefits and to avoid potential unwanted effects of platooning, studies must consider increasingly realistic (and thus complex) contexts. Although more gaps exist, research on the following issues is especially required (Figure 3):

- *General IFT*. Most research on platooning (including research on string stability) assumes one or several specific IFTs. Therefore, their results are associated with these particular configurations. Such fixed schemes could be imposed in certain circumstances, e.g. scheduled platooning in logistics. However, it is expected (and desirable) that future platoon formation will be dynamic and highly volatile. I.e. vehicles may join or leave the platoon quite fluently. There is need for more general platooning strategies reliable for all possible IFTs.
- *Heterogeneous platoons*. As indicated, only a few studies consider the possibility of vehicles of different sizes and/or automation capabilities conforming a platoon. Indeed, their feasibility has yet to be determined. If suitable strategies could be derived, platoons would form more frequently and, consequently, their potential benefits could be better exploited.
- *Mixed environments*. Although already addressed, the large number of possible scenarios makes it necessary to dive deeper into this topic. The simultaneous presence of platoons and single vehicles on the same road should be analyzed comprising all vehicles' degree of automation, size and mechanical characteristics, road features (e.g. number of lanes, longitudinal profile), general traffic management strategies set (e.g. variable speed limits, lane change restrictions, dedicated lanes), weather conditions, etc. Platoons' actual impacts will ultimately depend on their interactions among them and with other vehicles.

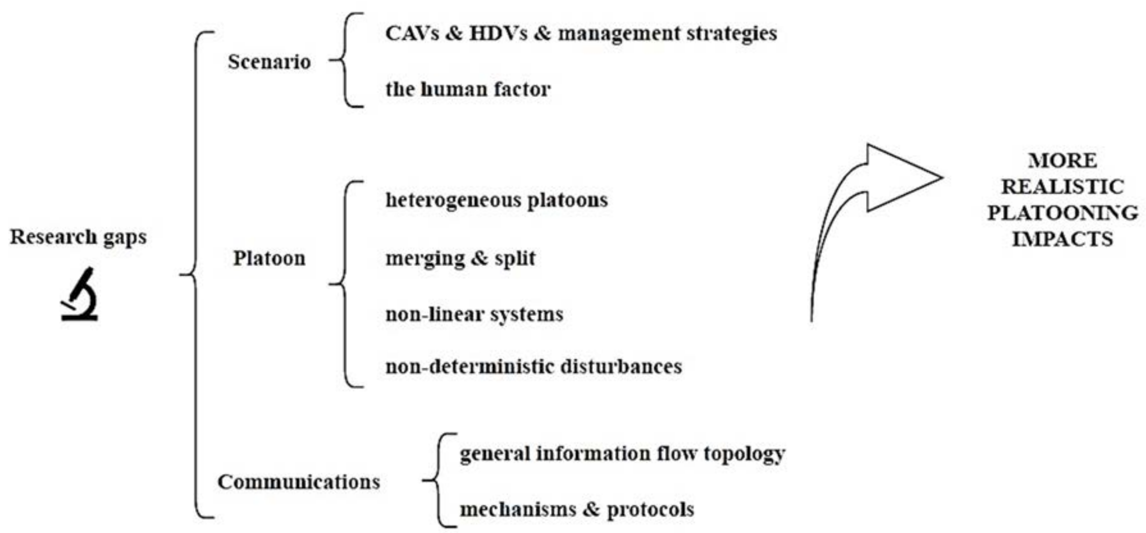

Figure 3. Key research gaps on platooning (own elaboration).

- *The human factor*. Especially for safety reasons, drivers /passengers' behavior in the aforementioned mixed environments, both within and out of platoons, must be further examined. This analysis should cover people's expected role, highly linked to vehicles' automation level, but also users' particular features, both identifying (e.g. age) and circumstantial (e.g. fatigue level).

- *Communication mechanisms and quality*. It is key to determine the information type (i.e. variables), quantity (i.e. how many agents it comes from, including infrastructure) and frequency (i.e. how often it is updated) that needs to be exchanged among vehicles in order for a platoon to circulate efficiently and safely. Given platoons' dynamic nature, this exchange is a challenge in itself. However, there are additional problems, such as the limited capacities of communication networks. Research must account for the possibility that these become congested, resulting in delays in the reception of information and/or in some data not reaching the intended recipients. In addition, a balance must be struck among interoperability, privacy protection and the prevention of cyber-attacks.
- *Non-linear platooning systems and non-deterministic system disturbances*. Most studies, also those focusing on string stability, consider vehicle dynamics within the platoon to be linear either *per se* or by the introduction of linearization techniques. In addition, stochastic external disturbances that can affect the platoon are usually disregarded. Both assumptions allow simplifying the analyses, but also affect any derived results, as none of them matches reality.

As mentioned, more questions remain in topics as diverse as platoons' string stability, above all the lateral, platooning planning and routing in logistics, or network design accounting for platooning, among others. The authors would like that this overview encourages new research contributions on this promising form of cooperative driving.

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CROSS-CASE ANALYSIS OF BUS OPERATION IN DIFFERENT CONTEXT: OVIEDO (SPAIN) AND TANGIER (MOROCCO)

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ABSTRACT

One of the main problems in urban areas is the steady growth in car ownership and traffic levels. Therefore, the main challenge to reach sustainable and liveable cities is focused on a shift of the demand for mobility from cars to collective means of transport. For this purpose, buses are a key element of the public transport system. This paper presents a cross-case analysis, from a diagnostic through big data management of the urban bus operation in Oviedo (Spain) and Tangier (Morocco). For this aim, several performance indicators (KPIs) were estimated for both networks and services. In the evaluation of the service the KPIs were grouped in five categories considering the consumption of resources (inputs) and the results or production obtained (outputs). Once the KPIs were estimated, they were compared to minimum requirements needed to satisfy demand depending on the cities characteristics (population, cover area, alternative transport systems). Finally, a qualitative comparison of the overall performance of the two networks was done. Results showed that even though at first sight, the service characteristics might seem different:

Tangier´s network is made up of 44 lines, with a length of 795 km and a fleet of 192 buses. While Oviedo´s network has 16 lines with an extension of 205.9 km and a fleet of 67 buses there are several common indicators like the monthly average of users in urban lines that rounds 125,000 passengers, a capture ratio of 40 persons per bus, and a similar bus availability every 1000 inhabitants (0.22 and 0.30). However, it was possible to observe some gaps in the system functioning, mainly in Tangier´s network which overall performance is worse than Oviedo´s in most of the analysed aspects.

1. INTRODUCTION

According to the World Economic Forum, by 2020, 56.2% of the world´s population lives in urban areas. Consequently, impacts related to mobility are growing; like traffic congestion, GHG emissions and pollutant, and traffic accidents.

The main problem is the excessive dependence on private vehicle, which without appropriate measures will derive in significant challenges to sustainability.

Among several factors, transport systems determine the form and socio-economic development of a city. Mobility and accessibility provided by the transport system play a major role in shaping cities, influencing the location of social and economic activities and the style and pace of life by facilitating trade, permitting access to people and resources (Zuidgeest, 2005).

Population growth produces urban expansion, which, together with dispersal of amenity and activity have increased the demand for and dependence on motorized transportation. To address these problems and their impact on the transport infrastructure, improvement in bus systems (and hence operations) in developed and developing countries can be considered a potential cost-effective approach to reach transport sustainability.

Regarding medium-size cities, bus is often the most common and, in most cases, the only public transport service available, as most of the cities have no metro o tram network. For example, in the European Union in 2014, 57.6 billion passenger journeys were made using public transport of which 55.8% used buses, with metro systems accounting for 16.1 %, tramways or light rail 14.5 %, and suburban railway 13.6% (UITP,2016).

In comparison to private vehicle dominated urban transport systems, those that are largely reliant on buses produce significantly less congestion, lower energy consumption and emissions. This is because buses are inherently efficient both in terms of road space and fuel consumption per passenger kilometre. Depending on the type of bus (standard, articulated, bus-train or double articulated), a fully load bus can replace between 5 and 40 cars with a corresponding fuel saving ranging from 40 to 97% (UITP, 2015). All the potential benefits mentioned, have produced a speedy evolution in bus and related technologies infrastructure, concepts of operation, business models and operations best practice or benchmarking, with increasing evidence that buses can be considered an appropriate alternative to meet sustainability requirements. This is in terms of efficiency, emissions, space occupancy as well as operational effectiveness as buses are more easily adapted to passenger requirements and do not require heavy infrastructure. Moreover, buses represent a safe transport mode registering low accident rates compared to other surface modes.

Public transport performance (in this case bus qualitative performance) can be understood in two dimensions. The first dimension relates to public values and users' expectations of the society (Jorgensen and Bozeman, 2007; Koppenjan et al.,2008). The second dimension of performance refers to ways of measuring broad goals into quantitative metrics.

These metrics are performance indicators (KPIs), such as emissions/passenger or average distance to public transport stops. Measuring the performance of bus systems service by different indicators can be influenced by different elements of the organisation of public transport systems, such as the ownership structure operator (public or private), contractual allocation of risks, or integration fares. (Hirschhorn et al., 2019). Therefore, when possible, the overall performance of the system should be estimated by composite indicators which can be useful due to their ability to integrate large amounts of information into easily understood formats.

The objective of this paper is to evaluate Oviedo´s and Tangier´s bus networks and services through the estimation of several KPIs based on the data provided by the operator (ALSA). The qualitative analysis of their overall performance, together with the cross-case analysis between their urban bus systems will allow designing policy-packages to improve sustainable operation according to each country´s reality.

This paper is structured as follows. Section 2 reviews the indicators to analyse a bus network performance. Section 3 sets territorial context and presents the indicators estimated for both study cases. The results of the cross-case analysis to evaluate the networks performance are presented in Section 4 and finally Section 5 provides some conclusions and propose future research.

2. REVIEW OF BUS PERFORMANCE INDICATORS

Efficiency and performance measures in public transport are necessary to monitor progress toward a planned target. Efficiency measures compare realized and optimal levels of outputs and inputs. They can also be used as means of evaluating recently realized or proposed extensive changes towards increased deregulation or reorganization.

The performance criteria´s should serve as an instrument to evaluate the system condition, level of service, and safety provided to costumers based on economic, environmental and community policy goals. Performance indicators should also evaluate day-to-day performance for strategic management, analysis of options and trade-offs. One of their main objectives is to give information for decision on how to allocate resources and help prioritize improvements to the neediest areas. In general performance measure indicators should be policy driven, which can be used in analysis of options and trade-offs, decision making on resource allocation, and monitoring to provide clear accountability and feedback. In addition, they can show trends, or warn of problems, influencing both immediate actions and long-term plans.

The efficiency of public transport system has been reported in terms of operational indicators, engineering indicators, labor indicators, social indicators, resource indicator and financial indicators on literature.

The NCHRP (2005) report categorizes performance measures for general transport assets under Preservation of assets, Mobility and accessibility. Operations and maintenance, and Safety. Public Transport Authority of Western Australia (2004) in their annual report used five categories of performance measure with indicators. This includes Use of public transport measured by passenger per service km and total passenger-kilometres, Service reliability, Level of overall customer satisfaction, Customer perception of safety and Level of notifiable safety incidents. In the context of developing countries Armstrong-Wrigth and Sebastian (1987) listed passenger volume, fleet utilization, vehicle-km, break-down in service, fuel consumption, staff ratio, accidents, and cost of bus services as operation performance indicators in addition to quality indicators. Additionally, Iles (2005) grouped efficiency indicators under labor, operational, engineering, personnel, and financial indicator. The relevance and appropriateness of each measure depends on the context of analysis and on data availability. For this research, data provided by ALSA which is the operator of bus services in both cases was used to estimate the indicators that will be presented in the following sections.

3.TERRITORIAL CONTEXT AND METHODOLOGY

3.1 Study cases and data sources

Despite their geographic proximity Spain and Morocco have considerable economical and cultural differences. A clear prove is their GDP, while Morocco´s GDP per capita is around 2.650 euros, Spanish GDP per capita is almost ten times higher reaching 24.500 euros.

This difference translated to transport is observed in their motorisation rates. By 2019 Spain had 513 vehicles each 1.000 inhabitants, while Morocco only 105.

For this research, Oviedo´s and Tangier´s bus networks were defined as case studies since both can be considered medium-size cities in their countries and have the same operator (ALSA) which ensures the availability of comparable data. The difference in context and countries reality of the two networks was considered of interest to be able to design policy-packages that include measures that can be transferable to other cities with similar characteristics but different contexts.

The municipality of Oviedo with a population of 220,000 inhabitants (INE 2019) is the capital of the region of Asturias, located in the north of Spain.

The Oviedo Metropolitan Area is composed of the core city and several parishes around, which are between 4 and 12 km away from the city.

The modal share is 66.4% for walking and biking, 24.1% for car and motorcycling and only 8.5% for public transport (Observatorio de la Movilidad Metropolitana, 2019).

Public Transport Authority of Asturias plans the urban bus network and Transportes Urbanos de Asturias (TUA) operates it under an administrative concession. In 2019 the total ridership was approximately 12.0 million.
The urban bus network of Oviedo has 15 daytime lines and 1 night-time line with a fleet of 67 buses to cover the service. Seven of the daytime lines run along the city and transport 90% of the users, while the other 8 lines connect the city with the parishes and carry the remaining 10% of demand.

Tangier, the capital of Tangier-Assilah Prefecture, has a population of 943,817 inhabitants (Haut-Commissariat au Plan, HCP). It is the most important prefecture in the Tangier-Tetouan-Al Hoceima region in Morocco. and is divided into three urban communes and nine rural communes.

Currently Tangier´s public transport network is covered by the urban and metropolitan bus network operated by ALSA. Tangier´s network is made up of 44 routes grouped in 27 urban and 17 rural lines. It had a total ridership of 40.3 million in 2019, from which 40 million of passengers used the urban lines. Although a feasibility study was carried out in 2015 for the construction of a tram network, following the examples of Rabat and Casablanca, no progress has yet been made on this issue.

To perform the performance analysis of this research, aggregated monthly data for all the lines in both networks have been gathered. Lines G, U and V from Oviedo, and 27 and 30 from Tangier were not considered due to unavailability of full data. Since they are recently incorporated lines, their performance does not affect the quality of this study.

Data has been obtained from different sources according to its nature:

- Urban area, route layouts and bus stops were downloaded from TUA and ALSA website.
- Monthly bus supply and demand variables were provided by ALSA, the operator of both networks.

Figure 1 presents the bus networks of Oviedo and Tangier which performance will be analysed in the following sections.

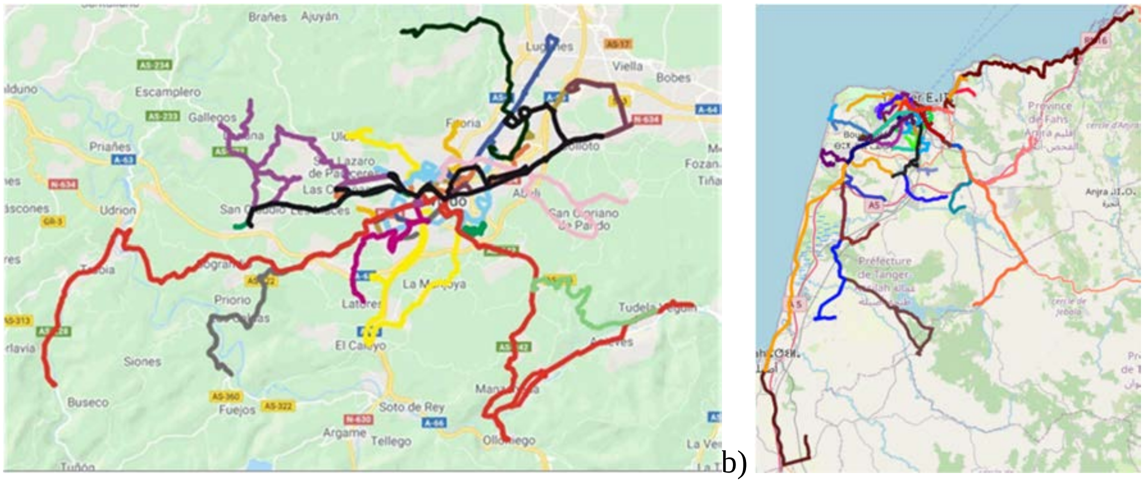
a) b)


Figure 1 a) Oviedo's and b) Tangier´s bus network

3.2 Oviedo´s and Tangier´s network´s performance indicators

In order to evaluate the performance of the bus service of Oviedo and Tangier, and based on the data availability for each network, the service efficiency was estimated through the analysis of KPIs grouped in five categories. Fleet, supply, and accessibility (inputs) and quality and operational performance (outputs) presented in figure 2. These indicators take into account both users´ and operator´s perspective.

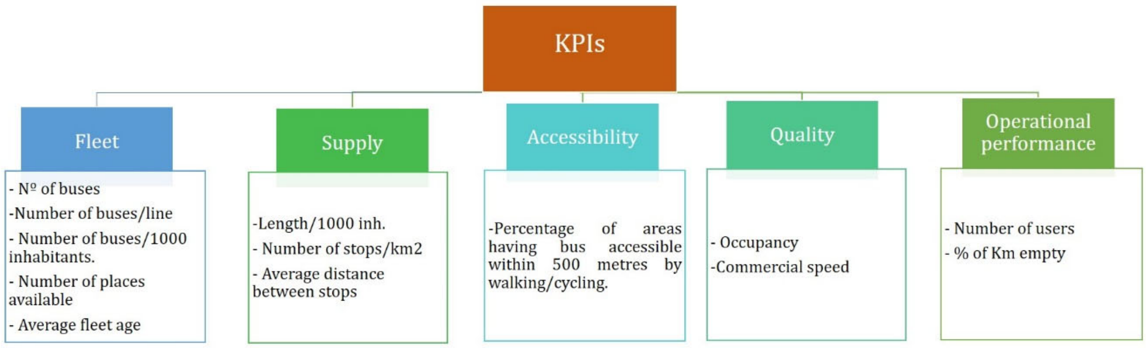


Figure 2 System efficiency indicators considered.

3.2.1 Fleet

One of the most important factors of quality and level of service of public transport is the availability of adequate infrastructure, including road and vehicle infrastructure. In both Oviedo and Tangier, road availability is not a key issue influencing the performance of the bus networks considered in the present research so no further analysis would be conducted.

On the other hand, vehicle infrastructure determines the capacity and speed of the bus. Number of spaces/vehicles offered on the line at a given time would influence on the comfort of the passengers specially on peak hours when the bus occupation is higher. Table 1 presents the details of bus infrastructure for both cases considered.

The most common bus configuration reflects the number of places available for people sitting, the number of places for people standing, and the number of places available for people with reduced mobility (RMP). It can be seen that Tangier´s most common bus configuration does not have places for people with reduced mobility. However, other bus configurations available on its fleet do.

Case	Most common bus configuration	Nº buses	Nº Buses/ line	Nº buses/1000 inhabitants	Nº places available/1000 inhabitants		
					Sitting	Standing	Reduced mobility
Oviedo	25+66vp+2rm+D	67	4.19	0.3	9.55	25.50	0.59
Tangier	33+62vp+D	190	4.32	0.2	6.70	11.08	0.10

Table 1 Vehicle data of both networks

The number of buses required per 1,000 population will depend on the public transport mode share, the presence or otherwise rail or other public transport modes, the capacity of the buses and the extent to which they may be utilized in terms of daily kilometres per bus.

With so many variables involved, the minimum requirement varies considerably from city to city, but typically lies between 0.5 and 1.2 buses per 1,000 population (Public-Private Infrastructure Advisory Facility- World Bank). Considering that in Oviedo and Tangier buses are the main public transport system, table 1 shows that both fleets have less buses than the required ones to fulfil the population needs properly. It can also be seen that, although the fleet sizes of the two cases are considerably different, they present a very similar number of buses available for each line. However, the number of places available each 1,000 inhabitants shows that Oviedo´s network has almost the doble of vehicle infrastructure for its population compared to Tangier.

3.2.1.1 Average fleet age

The average vehicle age is a useful indicator of the status of the fleet. If the fleet has an even age profile, the average age of the fleet will be approximately half the age of the oldest vehicle. An acceptable average age depends on factors such as the types of vehicles operated, levels of utilization and operating conditions, and is sometimes influenced by legislation, for example, in some countries the operation of the buses over a certain age is not permitted.

A high average age may be because high standards of maintenance enable vehicles to be successfully operated over a long life, but more often it is because there are not sufficient funds available for fleet replacement (more frequently in developing countries). For a reasonable well-maintained fleet of premium quality vehicles operating on urban services in developing countries, the average fleet age would typically be between five and eight years, being stricter in developed countries.

The average fleet age of Oviedo is 5.3 years with the newest bus having less than 1.5 years and the oldest one around 8.5 years. In the case of Tangier, the average age of the fleet is around 5.2 years with the newest having less than 2 years and the oldest around 6.5 years.

3.2.2 Supply

Supply refers to the presence of a public transport network or mode in an area/locality. There are several indicators that represent the supply of a transport system. The indicators considered for the present work are:

3.2.2.1 Length/1000 inhabitants

Network coverage measures use data that are generally already registered by the operator and thus are easier to calculate, however, they generally provide more macroscopic results that can be misleading at first glance.

Table 2 presents the length of the two networks, together with the network length every 1,000 inhabitants. The results show that despite the fact that Tangiers network is more than 4 times longer than Oviedo´s network, the length of network available every 1,000 inhabitants is 60% higher in Oviedo.

3.2.2.2Number of stops

Bus stops represent user´s access to the service. Table 2 shows that Oviedo´s network has a total of 273 stops while Tangier´s network has 386 stops over its entire length. Analysing the geographical distribution of the stops there is a similar number of stops every square kilometre in both networks (1.46 and 1.28 respectively). However, Oviedo´s network has triple the number of stops per 1,000 inhabitants than Tangier.

<table>
<tr><th rowspan="2">Case</th><th colspan="3">Network length (km)</th><th rowspan="2">Network length/ 1000 inh.</th><th rowspan="2">Nº of stops</th><th colspan="2">Nº of stops</th><th colspan="2">Average distance between stops (km)</th></tr>
<tr><th>Rural length</th><th>Urban length</th><th>Total length</th><th>/km^2</th><th>/1000 inh.</th><th>Rural lines</th><th>Urban lines</th></tr>
<tr><td>Oviedo</td><td>115.7</td><td>80.01</td><td>195.71</td><td>0,81</td><td>273</td><td>1.46</td><td>1.24</td><td>0.86</td><td>0.59</td></tr>
<tr><td>Tangier</td><td>313.4</td><td>481.6</td><td>767.2</td><td>0,5</td><td>386</td><td>1.28</td><td>0.41</td><td>1.14</td><td>0.58</td></tr>
</table>

Table 2 Supply indicators

3.2.2.3 Average distance between stops

The average spacing between stops must find a balance between cost and journey time.

This last one includes the passenger´s walking time, waiting time, boarding time, in vehicle time, alighting time and walking to destination time. It is important to notice that in the case or urban lines, at first sight, very small spacing could seem more comfortable for the user, however, it produces an increase in the total time, since each passenger journey would be interrupted by numerous intermediate stops. On the other hand, more spaced stops make the journey faster, but forces the users to walk longer distances to reach the bus. An acceptable distance between stops rounds 500 meters.

Table 2 shows that urban lines of both networks are quite close to this recommendation (580 and 590 metres for Oviedo and Tangier). On the other hand, and as expected, rural lines have longer distances between stops, which is completely normal due to density in the areas covered by these lines.

3.2.3 Accessibility

The accessibility of a transport system is the ability to reach the mode (bus in this case) within a reasonable time period, by a reasonable path (unobstructed infrastructure) and presence of information systems to access to the stop.

It can be expressed as a percentage of areas having a stop of public transport accessible within 500 metres by walking/cycling and walkability in areas being served by bus system (Abreha, 2007).

Table 3 presents the percentage of area of Oviedo and Tangier that has access to bus service within 500 metres. As can be seen, Oviedo has lower accessibility to bus service within this distance compared to Tangier.

City	(%) Area covered by the service
Oviedo	44
Tangier	54

Table 3. Oviedo´s and Tangier´s accessibility to bus service

Regarding the availability of user information. None of the networks has real time information on the bus stops, this fact has been identified as one of the most important issues to solve to improve users ´perception of the service quality.

3.2.4 Quality

The quality of the service is related to the comfort of the service offer during travel/ride. To analyse the quality of the service in the two cases studied, the bus occupancy and average commercial speed were considered.

3.2.4.1 Bus Occupancy

The standard bus size in Oviedo has 25 seats and takes 66 further standing passengers, while the standard bus in Tangier has 33 seats and takes 62 standing passengers. The capture ratio of the buses in the different lines of the two networks are presented in figure 3.

This ratio shows the average occupancy of the buses and was estimated by dividing the total number of passengers of each line by the number of buses that provided the service to that line.

The red line in the figures presents the seats available in a standard bus of each fleet. Figure 3 a) and b) shows that almost all urban lines in both networks have all their seats occupied most of the time which can influence the quality and comfort perception of the user. It is also possible to observe that the occupancy of line 20 in Tangier´s network is close to the full capacity of the bus including seating and standing passengers. On the other hand, lines like B in Oviedo´s network and L4, L13 and L23 in Tangier´s network register really low occupancy (below half the seating capacity of the average bus of their fleet) showing that they could be optimized.

Regarding rural lines, figure 3 c) and d) shows an irregular occupancy in Oviedo´s lines, with line L registering a capture ratio 40% higher than the seating capacity of an average bus, while line K registers an average capture ratio of only 4 passengers. Tangier´s lines present less pronounced differences between them; however, it is also possible to see lines with really high and really low occupancy levels (LI9 and LI7 respectively).

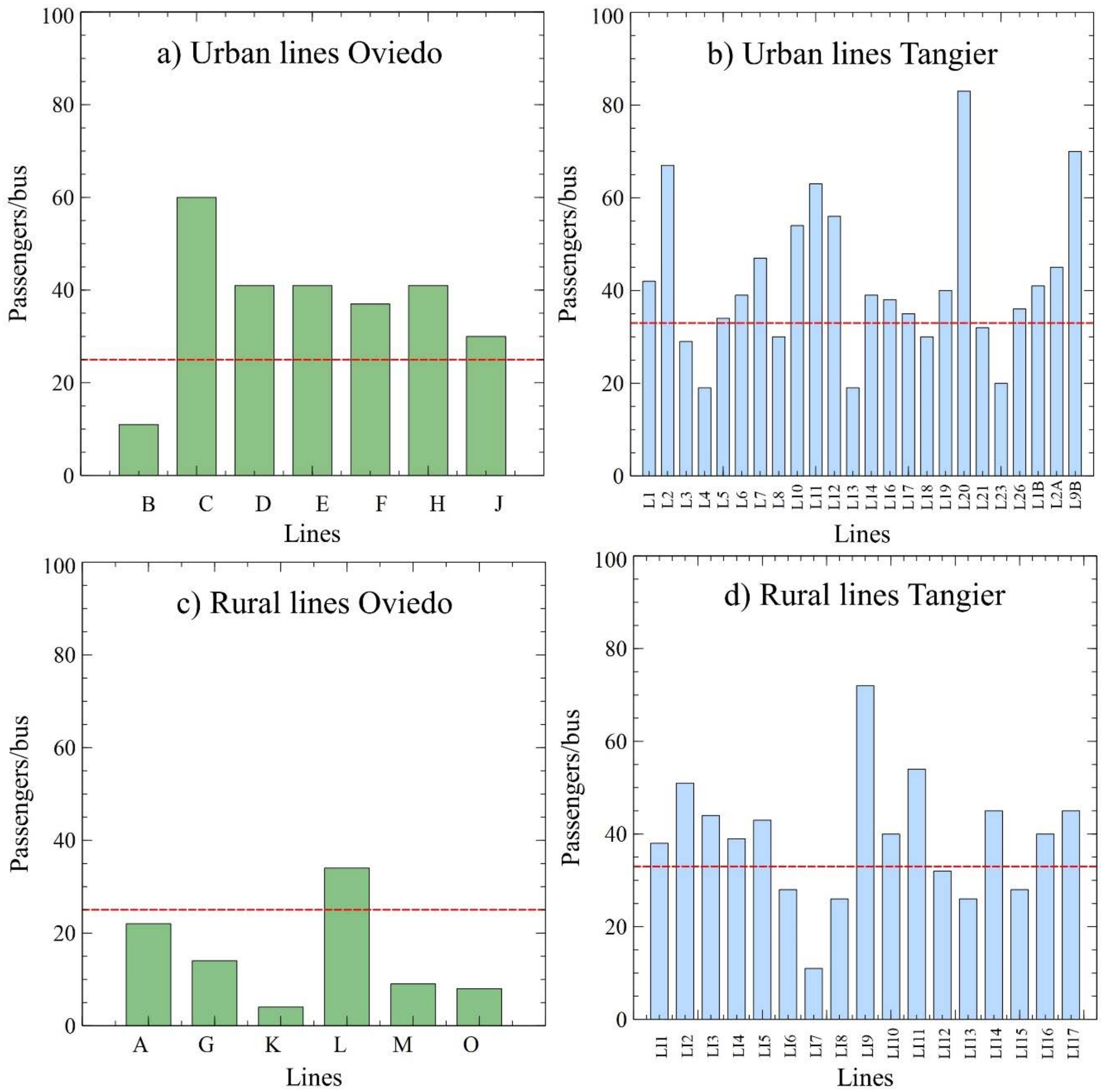


Figure 3 Capture ratio of urban lines a), b) and rural lines c), d)

3.2.4.2 Commercial speed

The bus operating speed is influenced by vehicle and alignment speed, as well as by stopping at passenger stops and traffic conditions. In this case, the average operating speed of bus travel along bus route was estimated dividing the total number of kilometres by the number of hours the bus was on service. Figure 4 presents the speed of all the lines of the two bus networks analysed (Oviedo and Tangier) and the average speed of each typology (urban and rural). It is possible to see that most of the lines with except of line B in Oviedo´s network have a commercial speed higher than 10-12 kph which according to Armstrong-Wrigth and Sebastian (1987) is the recommend minimum speed at which public bus systems should operate in dense areas with mixed traffic.

Figure 4 also shows a clear difference in the average speed of the lines depending on its category (urban or rural) as expected rural lines register higher average speeds due to traffic conditions and higher distances between stops in this typology.

For both categories, average commercial speed in Oviedo is lower than in Tangier.

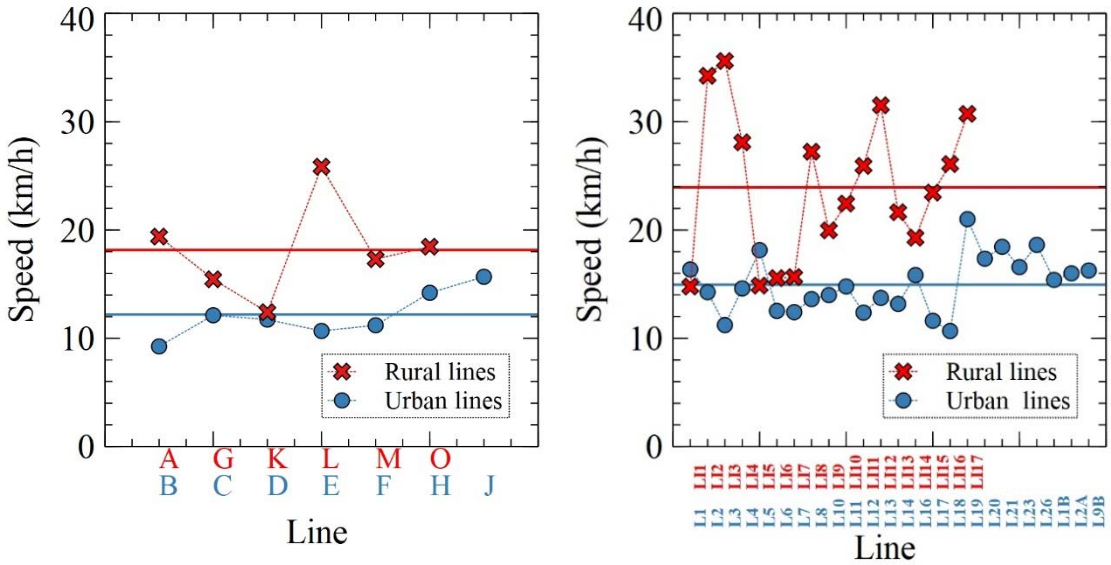


Figure 4 Commercial speed of the different lines of the networks.

3.2.5 Operational performance

To optimize the operational performance of the network is a major interest for the operator in order to get the highest profit offering at the same time a good service to the users. Three different KPIs were considered to determine the operational performance of the two networks:

3.2.5.1 Average users per month

The number of passengers per month of the different lines of the bus network is one of the most important data to take into account when analysing its performance. It allows the comparison among the lines of the network and helps to identify the ones that are beyond the average. Figure 5 a) and b) presents the average number of passengers registered per month in 2019 for the urban lines for Oviedo´s and Tangier´s networks. Although a uniform distribution of the number of passengers would be optimum, figure 6 a) and b) shows a considerable difference between the lines with the highest and the lines with the lowest ridership in the two networks. In fact, both networks have one special line (C in Oviedo and 20 in Tangier) that registers 2 and 5 times the average of passengers of the network, respectively.

Figure 5 shows that the highest ridership in Tangier´s network is almost three times the one of Oviedo. Despite the multiple differences between the urban lines of the two networks observed in figure 5, it is possible to observe that both register an average of 125,000 users per month.

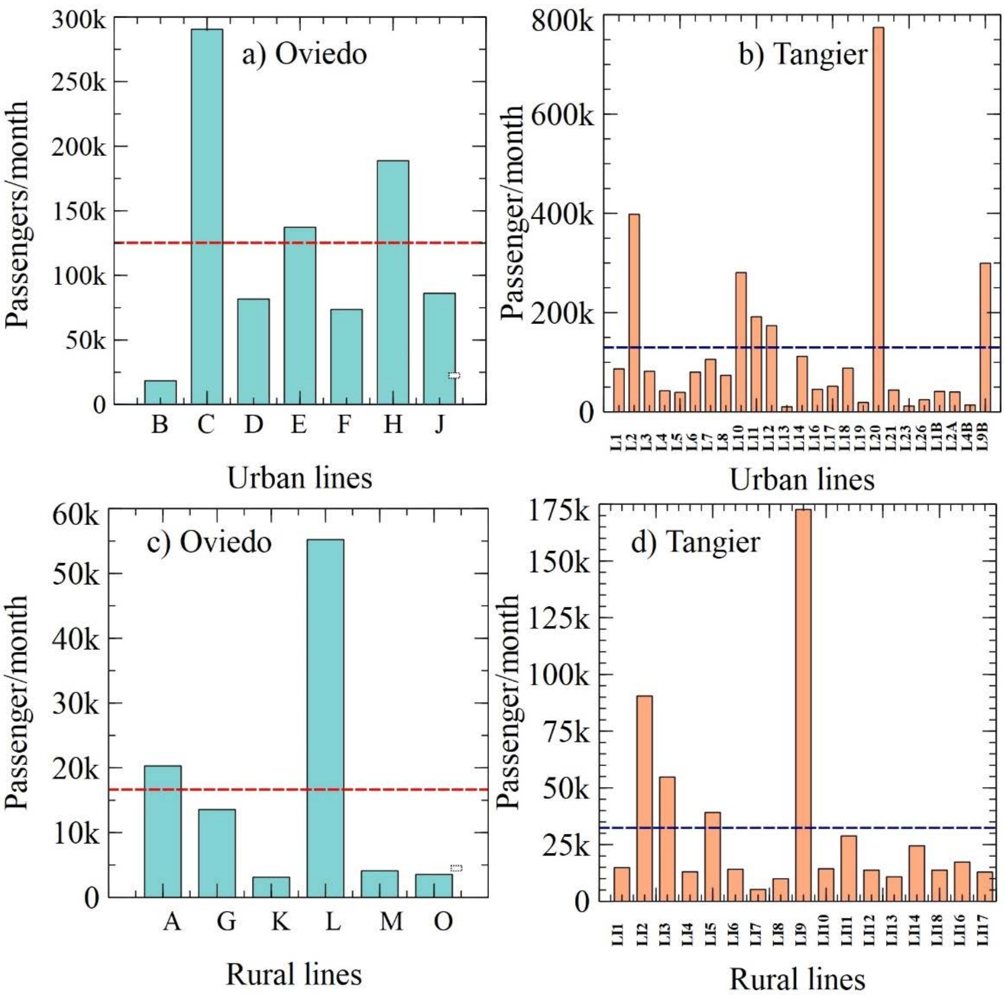


Figure 5. Average number of passengers urban lines a), b) and rural lines c), d)

With respect to rural lines, the same behaviour is observed, one line of each network hoards the passengers of the network. However, the average of users for this typology differs, Tangier´s rural lines have an average of passengers 80% higher than Oviedo´s lines.

3.2.5.2 Percentage of kilometres empty

This parameter presents the number of kilometres during the service in which the bus is empty, when it is not performing passenger transport service. This may be due to the routes to the fleet´s garages, to the service maintenance or because they are poorly planned. This is another very important factor to optimize the service of a bus line. The higher the percentage of empty kilometres, the worse the fleet operation will be, since empty trips are supposed to be journeys that in no case are generating any type of economic retribution for the operating company.

Figure 6 presents the percentage of kilometres empty of the urban and rural lines of the two networks.

Based on the operator's experience, values between 5 and 10% are considered acceptable for urban lines. In this research a limit of 10% was established for the entire network. It is possible to see that Oviedo´s network has no problems with the percentage of kilometres empty since all its lines have values lower than 10%. On the other hand, Tangier has 7 urban and 4 rural lines that exceed this value, so they should be deeper analysed to identify the causes and optimize their performance.

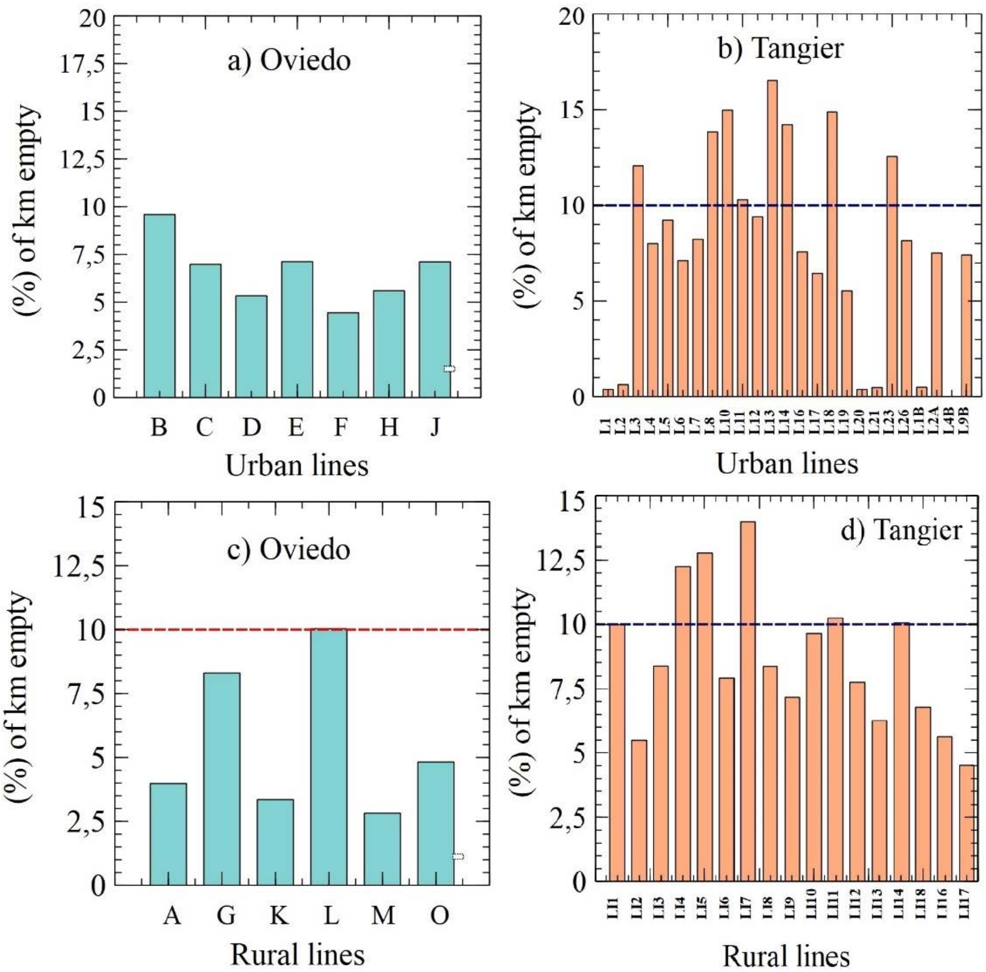


Figure 6. Percentage of kilometres empty for Oviedo´s and Tangier´s network.

3.2.5.3 Frequency

Frequency measures how often transit service is provided, either at a location or between two locations. The most commonly used measures are frequency (transit vehicles per hour) and its reciprocal headway (time interval between transit vehicles). Depending on the volume of transit vehicles and passengers moving through and stopping on a street, bus headways are recommended to be over 15 minutes for low volume, between 10-15 minutes for moderate volume, 2-6 minutes for high volume and combined headways under 2-3 minutes for very high volume (TCRP, 2003).

The average frequency of urban and rural lines is 21 and 65 minutes in Oviedo, and 33 and 120 minutes in Tangier respectively. As can be seen, the two networks analysed present higher headways than the recommended, which increases the passengers waiting time and makes them look for different transport alternatives.

4. OVERALL PERFORMANCE

The performance indicators presented in the previous sections, focused on specific aspects of the networks´ performance. In this approach, the indicators are readily measured and validated and are easy to interpret. However, there are two major drawbacks: they represent a partial indication of efficiency and they may provide conflicting message.

To estimate the overall performance of the two networks analysed, each of the indicators estimated in the previous section was compared with respect to efficient behaviour obtained from literature to identify the performance of each of the categories. As some of the variables are qualitative, the scores were given with personal judgment based on some characteristics.

Table 4 presents the summary of the qualitative evaluation of the two networks based on the values obtained for each of the KPIs estimated. Four different levels of efficiency were defined. Below poor (B.P.) when the system does not accomplish the minimum requirements, Poor to moderate (P-M) when the system satisfies the minimum requirements but there still is a lot to improve, Moderate to good when the performance is acceptable, and Above Good (A.G.) when there is no need to improve in any aspect.

Category		B.P.	P-M	M-G	A.G.
Infrastructure	Oviedo		P		
	Tangier		P		
Availability	Oviedo			P	
	Tangier		P		
Accesibility	Oviedo		P		
	Tangier			P	
Quality	Oviedo			P	
	Tangier		P		
Operational performance	Oviedo			P	
	Tangier		P		
Safety	Oviedo			P	
	Tangier			P	

Table 4 Qualitative summary of Oviedo´s and Tangier´s networks performance

Finally, as the scores given to the different categories of indicators are qualitative and subjective, a graphical technique was used to show the overall performance. Figure 7 presents the qualitative scores of all the categories studied in this analysis for the two networks analysed.

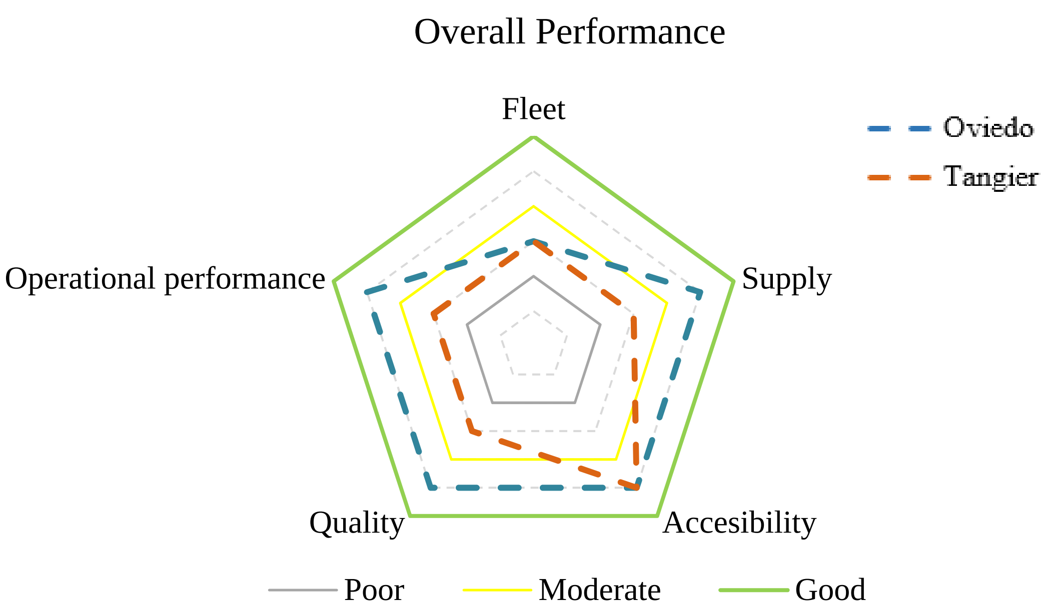


Figure 7 Overall performance of Oviedo´s and Tangier´s bus networks

5. CONCLUSIONS

This paper has aimed to realize a preliminary cross-case analysis of bus operation in different contexts, Oviedo (Spain) and Tangier (Morocco) through aggregated data provided by ALSA, the operator of both networks. Several indicators grouped into six main categories were estimated to evaluate the overall performance of the two networks operation. The results show gaps in the systems functioning that may be fixed through the implementation of some short-term solutions.

The infrastructure availability (mainly the vehicles of each network) can be considered insufficient to fulfil the needs of the population. According to the Public-Private Infrastructure Advisory Facility- World Bank, the ratio of buses per 1,000 inhabitants should be around 0.5 and 1.2 buses, but Oviedo has a ratio of 0.3 and Tangier of only 0.2.

This, together with the fact that in the two cities buses are the main public transport alternative, shows the need to increase the fleet of the networks. With respect to availability, Oviedo presents better indicators as higher frequencies and lower average distances between stops. Tangier´s network has higher distances between stops and really low frequencies existing lines where the buses pass every two hours, which is not comfortable for the users that end up looking for different transport alternatives.

Even though accessibility of both networks can be considered acceptable (more than 50% of the city has access to the bus service within 500 meters) it should be improved since one of the main characteristics and objectives of public transport, is to cover as much of the population as possible. Regarding the quality of the service provided, Oviedo´s network registers better quality indicators mainly due to its lower occupancy of the buses. The commercial speed of all the lines in the two networks meets the requirements of being at least 10-12 kph, and the average age of the fleet would never exceed the recommended limits due to contract conditions that force the operator to change the vehicles every certain number of years. Finally, based on accidents statistics and on the measures implemented by the operator (limited speed in Tangier and Speed control in Oviedo), both networks show a moderate to good safety in the service provided.

Oviedo´s network and services overall performance is better than Tangier´s. However, the problems identified through the analysis performed can be solve by implementing some changes in the network operation. Therefore, this work establishes the basis for two future works. The first one is to carry a quantitative analysis of the performance of the two networks including more data from other sources. The second one is aimed to propose a policy package to improve the performance of both networks according to each country´s reality.

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LOGÍSTICA, OPERACIONES Y TRANSPORTE DE MERCANCÍAS
LOGISTICS, OPERATIONS AND TRANSPORTATION OF GOODS

ANÁLISIS COMPARATIVO DE LOS PUERTOS MÁS IMPORTANTES DE ESPAÑA USANDO BOOTSTRAPPED DEA

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RESUMEN

El objetivo del presente trabajo de investigación es estudiar los valores de eficiencia de una muestra de los doce principales puertos de contenedores del mundo junto con los puertos de Bahía de Algeciras, Valencia, Barcelona y Tanger Med (Lloyd's List, 2018) durante el periodo 2014 – 2018. Es importante realizar el análisis de comparación de estos cuatro puertos frente a los más importantes del mundo para ver el comportamiento de su eficiencia cuando forman parte de una muestra compuesta por el conjunto de las principales terminales de contenedores. En este estudio se aplica en primer lugar el Análisis Envolvente de Datos (DEA) con escalas retorno constante (CCR) y variable (BCC), con orientación input. En una segunda etapa aplicamos la metodología Bootstrap con el propósito de obtener la eficiencia corregida, además de los correspondientes intervalos de confianza para cada una de dichas eficiencias.

Los factores clave de competitividad portuaria, y que permiten a un puerto ser más eficiente, dependen del tipo de tráfico. Las variables elegidas, tanto inputs como output, dependen de la operativa y de ahí que las variables seleccionadas, de los puertos que conforman la muestra de nuestro análisis, influyen directamente en dicha operatividad.

Tras un riguroso y amplio análisis sobre las variables a emplear en estudios de eficiencia portuaria de los numerosos investigadores, gran número de autores han coincidido en el uso de la longitud de los muelles, sobre todo de los de calado superior a catorce metros, del número de grúas de muelle, y de la superficie de la terminal, como inputs.

Del mismo modo, muchos estudios optan por analizar dicha eficiencia tomando como dato de salida (outputs) el número de TEUs (Twenty Equivalent Units) manipulados.

Los puertos están en continuo avance, intentado automatizar las terminales que les sean posibles para así poder incrementar la eficiencia y ser más productivos, con el fin de mantenerse en el ranking de los principales puertos de contenedores del mundo. Este estudio tiene como objetivo analizar la eficiencia de los puertos seleccionados y comprobar en qué medida su eficiencia productiva corregida ha ido evolucionando a lo largo del periodo de los últimos 5 años.

Los resultados muestran que entre los puertos españoles el que presenta mayor eficiencia en los dos modelos estudiados es el puerto de Algeciras, que pese a tener menor volumen de equipamiento y capacidad que el puerto de Valencia. Otro puerto que presenta unos importantes valores de eficiencia es el puerto de Tánger, con resultados muy próximos a los puertos de Algeciras y Valencia. Tanger-Med está aumentando su número de contenedores manipulados progresivamente y en los próximos años se prevé que con las nuevas terminales dicho tráfico sea bastante más elevado, pudiendo ser una fuerte competencia para el puerto algecireño, debido también a la posición estratégica que presenta.

1. INTRODUCCIÓN

El transporte marítimo mundial ha ido experimentando en los últimos años un gran crecimiento. Desde 1985 viene aumentando de forma ininterrumpida y en el caso concreto del comercio marítimo en contenedor el desarrollo ha sido muy importante, debido también al gran incremento del tamaño de los buques, llegando a ser como uno de los pilares de la globalización.

Los puertos están adquiriendo cada vez más importancia en todo el mundo, ya que son centros de desarrollo económico y social y constituyen puntos de conexión esenciales entre el transporte marítimo y el terrestre. Debido a esto, la eficiencia de las actividades que se llevan a cabo en todo el recinto portuario es un factor de gran relevancia, para que la mercancía que es transportada por vía marítima pueda llegar a los distintos puntos finales de consumo, intentando que sea al menor coste y tiempo posible.

En cuanto al rendimiento de los puertos de contenedores, se ha ido incrementando continuamente desde los últimos diez años, aunque desde 2014 de manera más lenta que antes. En ese año, el transporte mundial de contenedores aumentó un 5,3 %, mientras que en 2015 tuvo un aumento menor, de un 2,3 %. Sin embargo, teniendo en cuenta algunos datos, se estima que en unos 30 años el volumen de transporte internacional pueda aumentar hasta cuatro veces más.

Después de que en los años 2015 y 2016 se produjeran aumentos moderados de volumen en los principales puertos de contenedores del mundo, en 2017 se registró un firme regreso a la trayectoria del crecimiento, tal y como lo muestra la edición de 2018 de la “Lloyd’s List’s One Hundred Container Ports”. Las instalaciones portuarias incrementaron el manejo de contenedores en 2017, representando un crecimiento del volumen de casi el 6% con respecto al año anterior, en el que fueron manipulados unos 700 millones de TEUs en los puertos de todo el mundo.

Con respecto al continente con la economía mejor conectada de la red marítima global en 2016 fue Asia. El dominio chino continúa teniendo un papel importante, ya que gran parte de sus puertos se siguen manteniendo entre los principales del mundo. En Europa destacan Rotterdam, Amberes y Hamburgo, encontrándose dentro de los veinte primeros puertos del mundo. Con respecto a España, los puertos de Algeciras y Valencia compiten por el primer puesto, estando en el listado de los 40 puertos más importantes del mundo. Con respecto al continente africano, el puerto que tiene mayor relevancia es el de Tánger.

El crecimiento económico mundial, que en 2016 registró la tasa más baja desde la crisis financiera mundial con un 3,2%, tuvo bastante fuerza en el año 2017. Hubo una reactivación de la inversión, del comercio internacional y de la producción industrial que fortaleció la recuperación, añadiéndose además la mejora de la confianza de las empresas y consumidores.

En el año 2017 los puertos asiáticos continúan siendo los más destacados, ya que sufrieron en ese año un notable aumento. El puerto de Shanghai (China) es actualmente el puerto más activo del mundo en relación al tráfico de contenedores. El puerto de Singapur está en segundo lugar, seguido del puerto de Shenzhen.

Con respecto al continente europeo el puerto más importante es el de Rotterdam, debido al gran volumen de contenedores que manipula, encontrándose en el listado de los 12 puertos más importantes del mundo.

Haciendo referencia al sistema portuario español en el año 2017, se han movido 15.992.613 TEUs, un 5,07% más que en 2016.

En el mundo existen entre 6000 y 7000 puertos, aunque solo unos pocos centenares tienen realmente una importancia en un contexto global, concentrando la mayor parte del tráfico marítimo. El objetivo del presente trabajo es estudiar la eficiencia técnica de un número determinado de puertos, los que manipulan las mayores cantidades de contenedores, junto con los puertos de Algeciras, Valencia, Barcelona y Tánger, empleando el Análisis Envolvente de Datos (DEA).

El método de Análisis Envolvente de Datos (DEA) es una técnica de programación matemática, no paramétrica y determinista, que permite establecer la estimación de fronteras de producción y evaluación de la eficiencia de un conjunto de muestras de unidades de producción o DMUs. En este tipo de análisis se calcula la eficiencia relativa para cada DMU comparando sus inputs y outputs (grupo de datos de entradas-salidas) respecto a todas las demás DMUs.

Dentro de esta metodología se puede diferenciar dos modelos básicos, como son el modelo DEA-CCR (Charnes, Cooper y Rhodes) y el modelo DEA-BCC (Banker, Charnes y Cooper), que son los modelos que se han empleado concretamente para este estudio.

Para el análisis de la eficiencia se han seleccionado los 12 puertos más importantes del mundo en relación con el tráfico de contenedores anualmente, como se ha dicho anteriormente, junto con los tres puertos más importantes de España, y con el puerto de Tánger. A continuación, se puede ver la clasificación de los puertos más importantes de los años 2017-2018 con su cantidad de TEUs, más los cuatro puertos citados (Tabla 1):

	Puerto	**TEUs 2017**	**TEUs 2018**	**Crecimiento 2017 – 2018**
1	Shanghai	40.233.000	42,010,200	+4.4%
2	Singapore	33.666.600	36,599,300	+8.9%
3	Shenzhen	25.208.700	25,740,000	+2.1%
4	Ningbo & Zhoushan	24.607.000	26,351,000	+7.1%
5	Hong Kong	20.770.000	19,596,000	-5.7%
6	Busan	20.493.475	21,663,000	+5.7%
7	Guangzhou	20.370.000	21,922,100	+7.6%
8	Qingdao	18.262.000	19,315,400	+5.8%
9	Dubai Port	15.368.000	14,954,000	-2.7%
10	Tianjin	15.040.000	15,972,000	+6.2%
11	Rotterdam	13.734.334	14,512,661	+5.7%
12	Port Klang	11.978.466	12,316,003	+2.8%
29	Valencia	4.779.749	5,128,855	+7.3%
34	Algeciras	4.389.836	4,773,079	+8.7%
46	Tánger Med	3.312.409	3,472,451	+4.8%
55	Barcelona	2.972.795	3,422,978	+15.1%

Tabla 1: Posición de los puertos en Lloyd’s List 2017-2018
Fuente: Lloyd’s List 2021

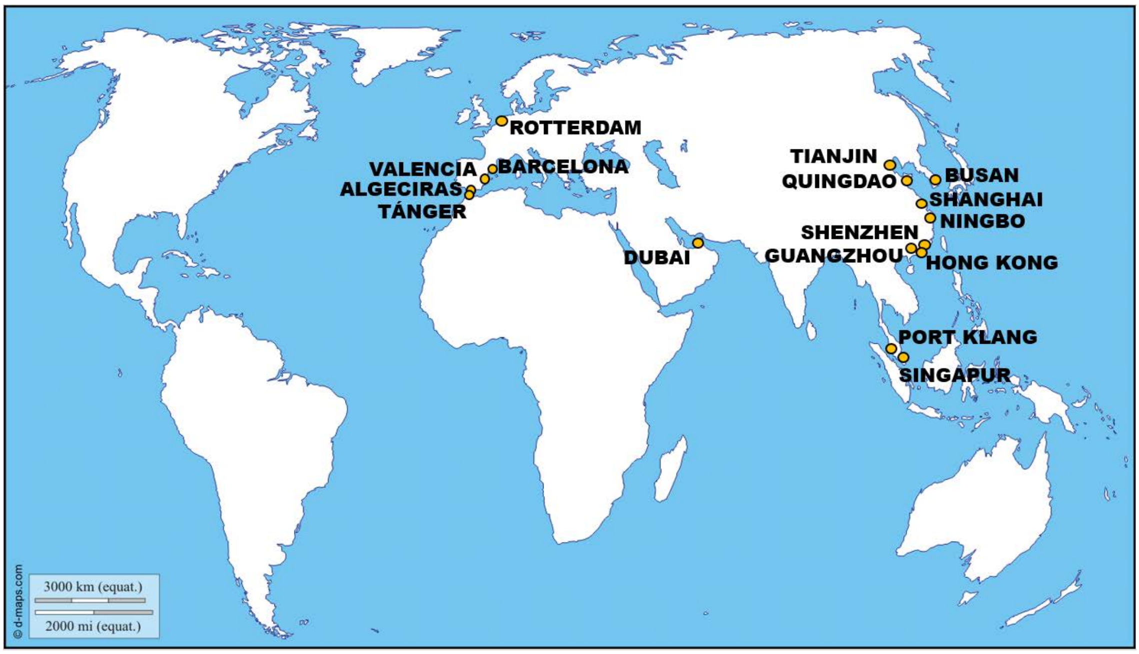

Figura 1. Puertos seleccionados para la elaboración del estudio.
Fuente: Elaboración propia.

Observando el gran número de contenedores que se manipulan en estos principales puertos y habiendo hecho referencia al volumen manipulado en el año anterior en todo el mundo, se entiende que el transporte marítimo por contenedor sea cada vez más importante y una de las principales vías para el desarrollo económico tanto a nivel regional, como nacional e internacional.

2. ESTADO DEL ARTE

La eficiencia portuaria es un tema que se ha ido estudiando a lo largo de los años. La metodología del Análisis Envolvente de Datos (DEA), ha sido tradicionalmente utilizada para la estimación de la eficiencia relativa de un conjunto de unidades productivas por numerosos autores y, en concreto, se ha empleado para estudiar diferentes aspectos de la actividad portuaria.

Farrell (1957) es considerado como el precursor en la medida de la eficiencia técnica, quien hace referencia a tres definiciones de eficiencia, tales como eficiencia técnica, eficiencia en precios y eficiencia global, que se construyen bajo el supuesto de una función de producción eficiente.

La tesis doctoral de Rhodes (1978), que se basó en el trabajo de Farrell (1957), plantea una programación matemática para la construcción de una frontera eficiente, para medir la eficiencia de las unidades evaluadas.

En un principio se contrastan solo entidades comparables, ya que el índice de eficiencia obtenido es relativo, por lo que se debe tener cuidado al definir la unidad de análisis (DMU) y las entradas que a través del proceso se transforman en salidas.

Hay una generación de estudios basada en medidas formales de eficiencia, que tiene como fuente el trabajo de Chang (1978), que se considera como el principio en la estimación de las funciones de producción en el sector portuario. Sin embargo, en los años siguientes no se desarrolla esta línea de investigación y destaca el uso de indicadores.

Dentro de la metodología no paramétrica DEA, los modelos más utilizados para su aplicación son los propuestos por Banker et al. (1984), que admite retornos variables de escala (BCC) y por Charnes et al. (1978), que asume retornos constantes de escala (CCR).
Martínez-Budría et al. (1999) y Pestana (2003) recurren al modelo BCC para las economías de escala y, por otro lado, Bonilla et al. (2002) y Tongzon (2001) utilizan el CCR. Ambos modelos son empleados y comparados por Cullinane et al. (2004), Park y De (2004), Pestana y Athannasiou (2004) y Cullinane et al. (2005).

A mediados de la década de los 90 la literatura sobre eficiencia, que ya se había aplicado a numerosas industrias, se introduce en el sector portuario. Los diferentes enfoques indican un desacuerdo para establecer el método que mejor pueda analizar este sector.

Cullinane et al (2002) analizan la estructura administrativa y de propiedad de las terminales de los 15 principales puertos de contenedores de Asia. Otro estudio que se centra en la relación que existe entre tipo de propiedad y eficiencia es el de Liu (1995), en su análisis se refiere a los puertos británicos, ya que en ellos coexisten varios tipos de propiedad.

Tongzon y Heng (2005) investigan si la privatización portuaria mejora la posición competitiva de los puertos. Para ello miden la eficiencia de terminales portuarias internacionales y estudian la relación que existe entre la eficiencia medida y la estructura de propiedad de las terminales. Cullinane y Song (2003) también analizan la relación entre la estructura de propiedad y eficiencia, siendo este objetivo compartido por Cullinane et al. (2005-a), pero con una muestra internacional de terminales portuarias.

Bichou (2012) realizó un análisis de eficiencia de 420 terminales de contenedores entre los años 2004-2010 a partir de los modelos DEA-CCR y DEA-BCC y, además, analizó la eficiencia de 10 terminales de contenedores con ambos modelos durante el período 2002-2008.

Notteboom et al. (2000) tenía como finalidad analizar la eficiencia de las terminales de contenedores más importantes de Europa, comparándolas con las cuatro terminales más grandes asiáticas.

Una vez tenidos los resultados, investigan los efectos que tienen algunos factores pudiendo afectar a la eficiencia de las operaciones (terminales grandes-pequeñas; puertos hub-feeder; privadas-públicas; norte de Europa-sur europeo).

El objetivo de Pestana (2003) es estudiar si los incentivos que se han introducido por la regulación portuguesa han aumentado la eficiencia. Haciendo uso del análisis DEA, se comprueba la eficiencia de cinco autoridades portuarias portuguesas (1999-2000). A partir de esto, Pestana y Athanassiou (2004) establecen un listado de autoridades portuguesas y griegas, cuyo objetivo es la detección de puertos que son capaces de ofrecer mejoras en su rendimiento dentro de los objetivos de la política portuaria europea.

Martín (2002) centra su estudio en las consecuencias que las reformas del sistema portuario español han tenido sobre la eficiencia y productividad. Para esta evaluación aplica un DEA a las 27 autoridades portuarias españolas (1990-1999).

González (2004) hace un análisis del impacto que tienen algunos factores en el entorno en que operan las principales autoridades portuarias españolas respecto al tráfico de contenedores.

El sistema portuario español es objeto de estudio de otros trabajos como Coto-Millán et al. (2000) que hacen un análisis de la eficiencia económica de las 27 autoridades portuarias en los años 1985-1989 a partir de una frontera de costes.

Martínez-Budría et al. (1999) emplean un DEA a 26 autoridades portuarias (1993-1997), con el fin de analizar su eficiencia. Hacen una comparación separando las autoridades portuarias en cuatro categorías, atendiendo a su dificultad. Bonilla et al. (2002) hacen un estudio con la misma finalidad, con la diferencia que son 23 autoridades portuarias durante los años 1995-1998.

El propósito de Tongzon (2001) es comparar la eficiencia de puertos internacionales de contenedores. Aplica un DEA para obtener los índices de eficiencia de cuatro puertos australianos, que compara con otros 12 puertos internacionales.

Roll y Hayuth (1993) intentan verificar que este método es útil para medir la eficiencia portuaria y la utilidad de los índices de eficiencia con el objetivo de mejorarla y así controlar la actividad de los operadores.

Como algunos estudios más recientes pueden destacar el de Gil Ropero et al. (2015) donde se hace un análisis de la eficiencia de 13 puertos españoles con mayor tráfico de contenedores aplicando DEA durante el período 2008-2011.

Camarero et al. (2016) que, a partir de una serie de indicadores caracterizadores de la actividad portuaria, clasifica los puertos españoles, o Ruiz Aguilar et al. (2016) en cuyo trabajo estudia predecir situaciones de congestión en el tráfico de mercancías, aplicándolo al Puerto de Algeciras.

En base a esto, se puede comprobar que la metodología DEA ha sido empleada por muchos autores a lo largo de los años. En sus estudios relacionados con el sector portuario, aplican este método para poder obtener la eficiencia y ver así la productividad de los puertos o terminales portuarias.

En la amplia revisión bibliográfica enfocada a los artículos que aplican la metodología Bootstrap, Barros et al. analizaron la eficiencia de una muestra representativa de los puertos africanos, durante el período 2004-2006, utilizando un enfoque DEA Bootstrap. Barros et al. (2012) en su estudio nos apuntan que en cuanto al análisis de la productividad y eficiencia portuaria en Brasil entre los años 2004 al 2010, se han utilizados dos técnicas DEA: paramétricas y no paramétricas, obteniendo como resultados que los puertos tuvieron una menor productividad en la eficiencia y reducción de los cambios tecnológicos. En este análisis, nos mencionan que DEA ha identificado las unidades ineficientes, tal como lejanía del puerto, falta de inversión y prácticas de gestión inadecuadas. Indican también que los puertos brasileños, que necesitan mejorar su producción, deberían enfocarse en la mejora de los procedimientos de inversión y nuevos métodos que aumenten el cambio tecnológico. Munisamy y Danxia (2013) analizan a través de la técnica Bootstrap la eficiencia de una manera más fiable a 69 principales puertos asiáticos. Se logró determinar que el 48% de los puertos de contenedores podrían ser considerados para una expansión con acuerdos de cooperación, mientras que el 35% de los puertos deberían considerar la mejora de sus eficiencias por medio de la mejora de sus operaciones.

Uno de los últimos artículos publicados sobre el análisis Bootstrap se ha realizado por Nguyen et al. (2015) que evaluaron la eficiencia de los 43 puertos más grandes de Vietnam. El análisis solucionó la sobreestimación de los índices de eficiencia generados por el DEA tradicional por medio de la técnica Bootstrap, pero a su vez conservando las ventajas del DEA. Wanke y Barros (2006) analizaron la eficiencia de 27 puertos principales de Brasil entre 2007 y 2011, a través de la técnica Bootstrap, utilizando varias estimaciones de DEA. Los resultados arrojaron un grado de deficiencia en la capacidad de dichos puertos, con respecto a las tareas que realizan, pero a su vez demostró tres impactos positivos: a) infraestructura de conectividad en los niveles de eficiencia de escala; b) la administración privada en los niveles de eficiencia de gestión; c) los niveles de eficiencia técnica más altas en los costes de manipulación y gestión en los tiempos de espera. Y más recientemente, Gil Ropero et al. (2018) propusieron un enfoque basado en DEA Bootstrap para evaluar la eficiencia de 16 puertos de la Península Ibérica (España y Portugal).

Este artículo es uno de los primeros estudios en aplicar Bootstrap para medir la eficiencia portuaria en el contexto del caso de España y Portugal. El documento proporciona información útil sobre la aplicación de un DEA Bootstrap como herramienta de modelado y como apoyo para ayudar a la toma de decisiones en la medición de la eficiencia del puerto.

3. OBJETIVOS

El objetivo de este trabajo es la aplicación del Análisis Envolvente de Datos (DEA), que propone la resolución de un programa lineal para cada unidad productiva o DMU observada. Optimiza cada observación individual con el fin de ver la eficiencia de cada puerto estudiado a partir de los datos que se han introducido en el análisis, como son una serie de variables de entrada o inputs y una o varias variables de salida u outputs, y así poder comprobar cuáles son los puertos más eficientes y establecer una comparación entre unos y otros.

En el caso de este estudio, se han establecido como variables de entrada o inputs las siguientes:

- La longitud de los muelles expresada en metros lineales, que es uno de los factores más representativos que tiene un organismo portuario, teniendo como condición en que el calado de los muelles sea mayor de 14 metros.
- El número de grúas muelles que tiene cada entidad portuaria a estudiar, siendo una variable de entrada importante a tener en cuenta.
- La superficie terrestre expresada en metros cuadrados, que viene relacionada con la capacidad que tiene cada terminal portuaria.

Y en cuanto a las variables de salida u outputs, se han considerado el número de contenedores anuales del período 2014-2016 que son manipulados en cada uno de los puertos del estudio.

4. METODOLOGÍA

La eficiencia es uno de los conceptos más importantes en la medición del desempeño. La eficiencia de un puerto, en el desarrollo de su actividad, está relacionada con la utilización de los recursos disponibles. De este modo, desde un punto de vista productivo, la eficiencia trata de describir el proceso de producción que emplea de forma óptima sus recursos, según la tecnología existente. Esta eficiencia en producción ese la conoce como eficiencia técnica.

Para la medición de la eficiencia destacan dos metodologías como son del Análisis Envolvente de Datos (DEA) y del Análisis de frontera estocástica (SFA).

El modelo SFA fue desarrollado por Aigner, Lovell y Schmidt (1977) y Meeusen y Van Den Broeck (1977), quienes exponen el concepto de frontera estocástica, a partir de la que se fundamenta la metodología del estudio sobre eficiencia, en la que se toma como origen la función de comportamiento eficiente, siendo de producción, de costos o de beneficios, según el caso a estudiar.

La metodología DEA, que es la que se ha optado mejor para utilizar en este análisis, se trata de una técnica de programación matemática, no paramétrica, basada en el trabajo seminal de Farrel y que fue propuesta formalmente por Charnes et al. (1978) y se ha seguido empleando a lo largo de los años. Esta metodología permite hacer una evaluación de la eficiencia de un grupo concreto de elementos (puertos, en el caso de este trabajo) a partir de la identificación de una frontera que incluye las que han obtenido el resultado más eficiente. Esta frontera eficiente revela una tecnología de referencia que se elabora a partir de los inputs y outputs de las observaciones de la muestra.

El conjunto de elementos mencionados anteriormente se conoce como unidades de toma de decisión (DMU: Decision Making Unit), utilizándose para hacer la evaluación de entradas y salidas para cada una de las DMUs que se consideren. Estas deben ser comparables, es decir, tanto las entradas como las salidas deben poder medirse en unidades homogéneas para todas ellas. La eficiencia de cualquier DMU siempre será menor o igual que la unidad, siendo aquella que tenga el valor de la eficiencia igual a uno la que se considera eficiente.

Aunque existen múltiples modelos DEA, estos se pueden dividir principalmente en dos alternativas como son la de retornos constantes a escala (DEA-CCR) y de retorno de escala variable (DEA-BCC). Los primeros miden la eficiencia puramente técnica y la ineficiencia de escala, mientras que los segundos solo evalúan la eficiencia puramente técnica. A su vez, cada uno de estos modelos puede tener orientación de entrada (input) o de salida (output).

4.1 Análisis Envolvente de Datos (DEA)

La utilización de la metodología no paramétrica DEA permite cuantificar una medida de eficiencia individual para cada una de las observaciones de la muestra a partir de su distancia respecto a la frontera de eficiencia. Esta frontera refleja una tecnología de referencia que se elabora a partir de los inputs y outputs de las observaciones de la muestra.

En el modelo inicial de Charnes et al. (1978), la medida de eficiencia es la razón entre el sumatorio ponderado de entradas y salidas de cada DMU, con la restricción de que este índice debe ser positivo y menor que la unidad.

En cuanto al modelo DEA-CCR fue el primer modelo DEA desarrollado y recibe el nombre por los que lo llevaron a cabo que fueron Charnes, Cooper y Rhodes (1978).

También se le conoce como modelo CRS o de rendimiento de escala constante.

Se emplea cuando las DMU a evaluar presentan rendimientos constantes a escala tanto para las entradas como para las salidas.

La fórmula orientada a las entradas se puede formular así:

$$Max \qquad h_0 = \sum_{r=1}^{s} u_r y_{r0} \tag{1}$$

Sujeto a:

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \ ; \tag{2}$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \quad \forall j \tag{3}$$

$$u_r; v_i \geq \varepsilon \quad \forall \, r, i \tag{4}$$

Siendo:

j= 1,2,3,…,n

$x_{ij}(x_{ij} \geq 0)$ como la cantidad de entrada i (i= 1,2,3,…,m), consumida por la j-ésima DMU.

$y_{rj}(y_{rj} \geq 0)$ como la cantidad de entrada r (r= 1,2,3,…,s), consumida por la j-ésima DMU.

x_{i0} la cantidad de entrada consumida por la DMU_0.

y_{r0} la cantidad de salida producida por la DMU_0.

Unidad evaluada, *Unidad*$_0$.

u_r y (r= 1,2,3,…,s), v_i (i=1,2,3,…,m) representan los pesos o multiplicadores de salidas y entradas.

La siguiente formulación está orientada a la entrada, una DMU se considera eficiente si cumple dos condiciones: que el valor de θ_0 sea igual a uno y que las variables S^- y S^+ sean cero, en caso contrario la DMU se considera ineficiente.

$$Min \quad \theta_0 - \varepsilon(\sum_{r=1}^{s} S_r^+ + \sum_{i=1}^{m} S_i^-) \tag{5}$$

Sujeto a:

$$\sum_{j=1}^{n} \lambda_j x_{ij} + S_i^- = \theta_0 x_{i0}; \quad \forall \, i \tag{6}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - S_r^+ = y_{r0}; \quad \forall \, r \tag{7}$$

$$\lambda_j, S_i^-, S_r^+ \geq 0 \ ; \quad \forall j \tag{8}$$

Donde:

θ es la eficiencia técnica de la DMU_0
λ es el vector de intensidades (nx1)
S^- es el vector de holgura de las entradas
S^+ es el vector de holgura de las entradas

Para la formulación orientada a las salidas se plantea matemáticamente de la siguiente forma:

$$Max \quad \gamma_0 + \varepsilon(\sum_{r=1}^{s} S_r^+ + \sum_{i=1}^{m} S_i^-) \tag{9}$$

Sujeto a:

$$\sum_{j=1}^{n} \lambda_j x_{ij} + S_i^- = x_{i0}; \quad \forall\, i \tag{10}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - S_i^+ = \gamma_0 y_{r0}; \quad \forall\, r \tag{11}$$

$$\lambda_j, S_i^-, S_r^+ \geq 0\,; \quad \forall j \tag{12}$$

El segundo modelo destacado es el DEA-BCC, que fue desarrollado por Banker, Charnes y Cooper (1984) y lo que añadió a la metodología anteriormente explicada fue la inclusión de retornos variables de escala.

Para considerar esta variación, se incluye una restricción adicional al modelo DEA-CCR que permita que las DMU con rendimientos crecientes, constantes o decrecientes, puedan aparecer en la frontera de eficiencia por ser consideradas técnicamente eficientes. La superficie envolvente se considera representada por una combinación lineal convexa, producto del conjunto de observaciones de las DMU seleccionadas.

Este modelo tiene como origen la siguiente ecuación, que se le añade como restricción a la formulación del modelo DEA-CCR, y el conjunto da lugar a la formulación completa del modelo DEA-BCC:

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{13}$$

4.2 Análisis Bootstrap

El Bootstrap es una herramienta que aporta estimaciones del error estadístico, introducida por Efron (1977), que ofrece una aproximación para el contraste de hipótesis en el modelo DEA. De hecho, es la única aproximación que existe con múltiples inputs y outputs.

La primera utilización dentro de un contexto de frontera fue Simar (1992), el cual en el modelo de datos incorporó la estimación semiparamétrica. Sin embargo, Simar y Wilson (1998) por primera vez adaptaron la técnica Bootstrap a las estimaciones del DEA.

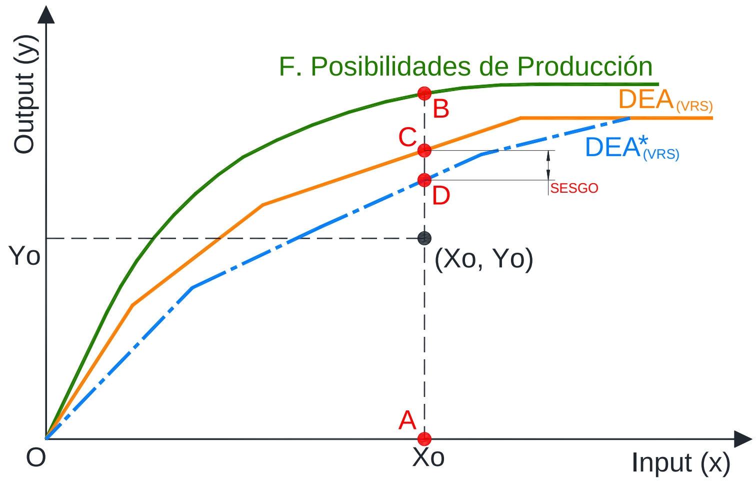

Figura 2. Representación gráfica de Bootstrap Orientación Output.
Fuente: Elaboración propia.

La Figura 1 representa gráficamente Bootstrap consistente en la orientación output. Como puede observarse de dicha representación el sesgo toma un valor negativo en las orientaciones output, debido al desplazamiento de la curva que representa la estimación de la Frontera de Posibilidades de Producción. Cuando el Bootstrap es consistente se cumple la siguiente expresión:

Bootstrap orientación output (BCC) $$\frac{AD-AC}{AY_O} = \frac{AC-AB}{AY_O} \qquad (14)$$

El principio general de la técnica Bootstrap se basa en la idea de que los valores empíricos son una representación de los valores poblacionales desconocidos. Genera una muestra con la que se puede acercar a la función de distribución empírica de los datos y estimar los niveles de confianza de las eficiencias DEA, en la cual se evita el uso de un estimador de sesgo, como es el ruido estadístico; sin embargo, la estimación del sesgo tiene interés por sí misma, que la denominamos como:

$$SESGO[\hat{\theta}(X_0, Y_0)] = E[\hat{\theta}(X_0, Y_0)] - \theta\,(X_0, Y_0) \qquad (15)$$

La estimación Bootstrap del sesgo del estimador original $\hat{\theta}(X_0, Y_0)$ considerando la versión empírica de la expresión anterior:

$$\widehat{SESGO}\;B\;[\hat{\theta}(X_0, Y_0)] = B^{-1}\sum_{b=1}^{B}[\hat{\theta}_b^*(X_0, Y_0)] - \hat{\theta}(X_0, Y_0) \qquad (16)$$

De la misma manera es adecuado elaborar un estimador de $\theta(X_0, Y_0)$ mejorado del sesgo, calculado. Así mismo parece razonable construir un estimador de $\theta(X_0, Y_0)$ corregido del sesgo, calculado.

$$\widehat{\hat{\theta}}(X_0, Y_0) = \hat{\theta}(X_0, Y_0) - \widehat{SESGO}\ B\ [\hat{\theta}(X_0, Y_0)] = 2\hat{\theta}(X_0, Y_0) - B^{-1} \sum_{b=1}^{B} [\ \hat{\theta}_b^*(X_0, Y_0)]$$

Sin embargo, según Eforn y Tibshirani (1993), esta corrección introduce ruido adicional. El error cuadrático medio de $\widehat{\hat{\theta}}(X_0, Y_0)$ puede ser mayor que el de $\hat{\theta}(X_0, Y_0)$.

5. DATOS OBTENIDOS

Este trabajo realiza un estudio de los 12 puertos más importantes del mundo junto con los tres puertos más importantes de España (Algeciras, Valencia y Barcelona) y con el puerto de Tánger. Los datos que se han utilizado para el análisis DEA se han obtenido de las diferentes páginas web de los puertos y de las autoridades portuarias respectivas, así como de las terminales que los conforman, atendiendo a los requisitos expuestos en el apartado *3 conclusiones* del presente trabajo. Para los datos respecto al volumen de contenedores de cada uno de los puertos se han utilizado las páginas web del puerto de Rotterdam y Lloyd's List, como se podrá ver en el apartado *Referencias.*

Como ya se ha mencionado, en los datos de entrada o inputs se introducen el número de grúas, la superficie de la terminal y los metros lineales, y como datos de salida u outputs se toma el número de TEUs anuales de cada uno de los puertos.

Estos datos se pueden apreciar a continuación (Tabla 2):

DMUs	Nº Grúas	S. Terminal (m2)	M Muelle
Shanghai	156	6.730.000	13.000
Singapore	228	7.470.000	19.769
Shenzhen	147	5.800.000	15.809
Hong Kong	99	2.788.500	7.694
Ningbo & Zhoushan	39	1.925.000	3.428
Busan	109	7.012.000	12.023
Guangzhou	79	6.730.000	4.800
Qingdao	37	5.560.000	3.400
Dubai Port	104	5.787.900	10.567
Tianjin	80	5.148.000	8.263
Rotterdam	102	8.340.000	11.300
Port Klang	67	1.870.000	4.900
Algeciras	27	1.043.732	2.591
Barcelona	24	1.594.000	3.000
Valencia	42	2.237.000	4.076
Tánger	16	800.000	1.612
Promedio	84,75	4.427.258	7.889,5
Máximo	228	8.340.000	19.769
Mínimo	16	800.000	1.612
S.D.	57,303	2.585.968,849	5.357,214

Tabla 2: Datos de los puertos analizados y análisis global.
Fuente: Elaboración propia

En el conjunto de datos de la tabla se puede observar que hay puertos en los que algunos de los valores de inputs son mayores que en otros, sin embargo, el volumen de TEUs es inferior, y al igual sucede en el caso contrario. Esto quiere decir que habrá puertos que, aun teniendo buenos resultados a simple vista, su equipamiento les permite ser aún más eficientes y productivos. Estos casos se podrán ver en el siguiente apartado, detallando el grado de eficiencia de cada uno de ellos.

6. RESULTADOS

Una vez introducidos los datos de la tabla del apartado anterior en el programa para realizar el análisis DEA, llamado DEA Frontier y desarrollado por Dr. Joe Zhu, los resultados que se han obtenido de eficiencia para los modelos DEA-CCR y DEA-BCC son los siguientes (Tabla 3):

Puertos	2014		2015		2016		2017		2018		PROMEDIO	
(DMUs)	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC
Shanghai	0,5190	**1,0000**	0,5066	**1,0000**	0,4926	**1,0000**	0,4677	**1,0000**	0,4560	**1,0000**	0,4884	**1,0000**
Singapore	0,4487	0,9597	0,3863	0,8463	0,3694	0,8323	0,3526	0,8368	0,3579	0,8712	0,3830	0,8692
Shenzhen	0,4102	0,7460	0,3893	0,7232	0,3691	0,7028	0,3400	0,6775	0,3242	0,6604	0,3666	0,7020
Hong Kong	0,7879	0,9957	**1,0000**	**1,0000**	**1,0000**	**1,0000**	**1,0000**	**1,0000**	**1,0000**	**1,0000**	0,9576	0,9991
Ningbo & Zhoushan	**1,0000**	**1,0000**	0,6726	0,8557	0,3294	0,6429	0,3020	0,6117	0,2661	0,5486	0,5140	0,7318
Busan	0,3437	0,6459	0,3376	0,6457	0,6344	0,8134	0,5749	0,7475	0,5675	0,7428	0,4916	0,7191
Guangzhou	0,6099	0,7647	0,6089	0,7678	0,6247	0,7926	0,5912	0,7588	0,5941	0,7666	0,6058	0,7701
Qingdao	0,8985	0,9198	0,8906	0,9129	0,8805	0,9031	0,7823	0,8036	0,7726	0,7930	0,8449	0,8665
Dubai Port	0,2931	0,5381	0,2834	0,5290	0,2569	0,4890	0,2342	0,4617	0,2128	0,4266	0,2561	0,4889
Tianjin	0,3524	0,5624	0,3334	0,5384	0,3276	0,5363	0,2980	0,5000	0,2955	0,5017	0,3214	0,5278
Rotterdam	0,2418	0,4395	0,2268	0,4191	0,6288	0,6378	0,5746	0,5832	0,5669	0,5752	0,4478	0,5310
Port Klang	0,5793	0,5869	0,5932	0,6014	0,2196	0,4136	0,1861	0,3628	0,1787	0,3541	0,3514	0,4638
Algeciras	0,4319	0,6874	0,4037	0,6650	0,4073	0,6808	0,3583	0,6240	0,3590	0,6113	0,3920	0,6537
Barcelona	0,1582	0,2159	0,1548	0,2157	0,1686	0,2372	0,2899	0,4182	0,2943	0,4188	0,2132	0,3011
Valencia	0,2121	0,2237	0,2077	0,2194	0,2034	0,2150	0,1250	0,1325	0,1224	0,1298	0,1741	0,1841
Tánger	0,3860	**1,0000**	0,3502	**1,0000**	0,3351	**1,0000**	0,2945	**1,0000**	0,3166	**1,0000**	0,3365	**1,0000**

Tabla 3: Resultados obtenidos del análisis DEA Orientación Output.

Puertos	BOOTSTRAP BCC Orientación OUTPUT					
(DMUs)	2014	2015	2016	2017	2018	PROMEDIO
Shanghai	0,8815	0,8572	0,8576	0,8542	0,8581	0,8617
Singapore	0,8860	0,7561	0,7425	0,7405	0,7739	0,7798
Shenzhen	0,6910	0,6497	0,6303	0,6022	0,5898	0,6326
Hong Kong	0,9306	0,8015	0,8025	0,7801	0,7830	0,8195
Ningbo & Zhoushan	0,8250	0,7803	0,5979	0,5632	0,5076	0,6548
Busan	0,6179	0,6026	0,7390	0,6676	0,6659	0,6586
Guangzhou	0,7130	0,6984	0,7193	0,6789	0,6885	0,6996
Qingdao	0,8212	0,7912	0,7801	0,6767	0,6680	0,7474
Dubai Port	0,5096	0,4883	0,4499	0,4204	0,3907	0,4518
Tianjin	0,5344	0,4988	0,4958	0,4556	0,4589	0,4887
Rotterdam	0,4245	0,3952	0,5518	0,4939	0,4885	0,4708
Port Klang	0,5246	0,5225	0,3888	0,3375	0,3309	0,4209
Algeciras	0,6111	0,5774	0,5889	0,5317	0,5215	0,5661
Barcelona	0,1923	0,1870	0,2059	0,3534	0,3544	0,2586
Valencia	0,1963	0,1876	0,1842	0,1101	0,1082	0,1573
Tánger	0,7666	0,7613	0,7559	0,7442	0,7359	0,7528

Tabla 4: Resultados obtenidos del análisis BOOTSTRAP BCC Orientación Output.

Se puede comprobar que el puerto de Ningbo-Zhoushan es el más eficiente durante los años que se han tomado para el estudio y para los dos modelos analizados. Y concretamente para el modelo BCC, que es el más significativo, también serían eficientes los puertos de Shanghai y Tánger, junto con el de Ningbo-Zhoushan como se ha comentado anteriormente.

El puerto de Hong Kong en el año 2014 es también bastante eficiente, teniendo un valor de eficiencia para el modelo CCR de 0.7879 y para el modelo BCC de 0.9957. En los años siguientes del estudio (2015 y 2016) la eficiencia se ve reducida debido a un descenso del volumen de TEUs de unos 2.000.000, lo que equivale a una diferencia del 10.75 % con respecto al volumen obtenido en 2014.

Con el puerto de Singapur ocurre lo mismo que en el caso del puerto de Hong Kong. Tiene una eficiencia con el modelo CCR de 0.4487 y con el modelo BCC de 0.9597 siendo en este caso bastante buena para el año 2014, pero sufre un notable descenso de la eficiencia en el 2015 ya que hay una bajada del número de TEUs de casi 3.000.000 y se mantiene prácticamente el mismo volumen en el año 2016.

El puerto de Qingdao es otro de los puertos que presenta mejor eficiencia en los dos modelos y para los tres años estudiados, con una eficiencia que va manteniendo entre los valores de 0.88 y 0.91 y el volumen de TEUs va incrementándose del 2014 al 2016.

Centrándonos en el modelo DEA-CCR, los puertos que tienen una eficiencia media, a parte de los puertos de Shanghai y Singapur anteriormente analizados, son el puerto de Shenzhen con 0.4102 en 2014 y se va reduciendo en los dos años siguientes, el puerto de Guangzhou con 0.6099 en 2014, que se mantiene constante en el siguiente año y aumenta en el último, ya que este puerto tiene un aumento en el volumen de TEUs de unos 2.000.000. En el caso de Port Klang tiene una eficiencia en el primer año del estudio de 0.5793 y se produce un aumento progresivo hasta llegar a una eficiencia en el año 2016 de 0.6288, por lo que el aumento en TEUs fue de un 16.89 %. Otro puerto que se puede considerar como eficiencia media es el puerto de Algeciras, el cual se va manteniendo más o menos constante durante los tres años.

Como podemos comprobar los puertos que tienen menos eficiencia en este método son los puertos de Busan, Dubai, Tianjin, Rotterdam, Barcelona, Valencia y Tánger, destacando el puerto de Barcelona como el que tiene la eficiencia más baja en los tres años estudiados.

En cuanto a las eficiencias obtenidas a partir del modelo DEA-BCC se puede comprobar que son mayores que las obtenidas por el anterior modelo, siendo este más significativo.

Los puertos que tienen eficiencia media son Shenzhen, Busan, Guangzhou y Algeciras, estando entre 0.64 y 0.79 a lo largo de los tres años. El puerto que experimenta cambios más relevantes es el puerto de Guangzhou, ya que aumenta su volumen de TEUs en algo más de 2.000.000.

En los puertos con menor eficiencia en este método se encuentran el puerto de Dubai, Tianjin, Rotterdam Port Klang, Barcelona y Valencia, siendo el puerto de Barcelona el que presentar menor eficiencia, como en el caso del modelo CCR.

Como complemento al análisis anterior, y únicamente con el objetivo de clasificar los puertos según sus resultados en los distintos modelos DEA y Bootstrap, se han agrupado según los valores promedios obtenidos de eficiencias.

Se han clasificado los puertos en cuatro categorías (Tabla 5). En primer lugar, aquellos puertos cuyo valor promedio de la eficiencia corregida Bootstrap es igual o superior a 0,90, a los que podemos considerar Puertos Eficientes (I). En segundo lugar, puertos cuya eficiencia está en valores comprendidos entre 0,70 y 0,90, a cuyos puertos denominaremos

Puertos con Eficiencia Media (II). Un tercer grupo es el formado por los puertos con valores de eficiencia entre 0,50 y 0,70, Puertos con Eficiencia Baja (III), y por último, aquellos puertos cuyas eficiencias corregidas son inferiores a 0,50, a los que consideraremos como Puertos Ineficientes (IV). Cada una de estas categorías está clasificada en la Tabla 5.

Grupo	Puertos (DMUs)	Valor Promedio Efic. DEA-BCC	Puertos (DMUs)	Valor Promedio Efic. BOOT-BCC
I (> 0,90)	Shanghai	1,00000		
	Tánger	1,00000		
	Hong Kong	0,99913		
II (0,70 - 0,90)	Singapore	0,86924	Shanghai	0,86173
	Qingdao	0,86646	Hong Kong	0,81953
	Guangzhou	0,77010	Singapore	0,77979
	Ningbo & Zhoushan	0,73177	Tánger	0,75276
	Busan	0,71905	Qingdao	0,74744
	Shenzhen	0,70198	Guangzhou	0,69963
III (0,50 - 0,70)	Algeciras	0,65369	Busan	0,65859
	Rotterdam	0,53095	Ningbo & Zhoushan	0,65477
	Tianjin	0,52775	Shenzhen	0,63259
			Algeciras	0,56613
IV (< 0,50)	Dubai Port	0,48887	Tianjin	0,48871
	Port Klang	0,46375	Rotterdam	0,47077
	Barcelona	0,30114	Dubai Port	0,45175
	Valencia	0,18407	Port Klang	0,42088
			Barcelona	0,25862
			Valencia	0,15729

Tabla 5: Agrupación de puertos según valores promedio DEA-BCC y DEA-BOOTSTRAP.

En el análisis del modelo DEA-BCC se comprueba que existen tres puertos en el primer grupo. Los puertos de Shanghai y Tánger MED con valores de eficiencia del cien por cien.

El puerto de Hong Kong obtiene un valor muy próximo a la unidad. Todo esto es debido a la capacidad técnica que poseen estas tres terminales.

En el grupo de Puertos con Eficiencia Media (II) se clasifican encuentran los puertos de Singapore y Qinddao, con valores casi idénticos y por encima del ochenta y cinco por ciento. En el mismo grupo, pero tampoco muy distanciados, nos encontramos con los puertos de Guangzhou, Ningbo & Zhoushan, Busan y Shenzhen con valores inferiores a los anteriores, aunque bien es cierto qué obtienen un valor por encima del setenta por ciento. Esto nos indica que todos los puertos de este grupo podrán estar muy cerca de conseguir el objetivo de ser puerto Eficiente.

En el tercer grupo formado por aquellos Puertos con Eficiencia Baja (III) se clasifican a los puertos de: Algeciras (0,65369), Rotterdam (0,53095) y Tianjin (0,52775). Valores muy discretos para puertos de esta entidad en el escenario mundial de tráfico de contenedores.

Por último, los puertos de Dubai Port, Port Klang, Barcelona y Valencia obtienen la clasificación de Puerto Ineficiente (IV). Resulta muy llamativas las posiciones última y penúltima de los puertos de Baercelona y Valencia, con un valor de apenas el dieciocho porciento el puerto levantino.

Los resultados muestran una importante homogeneidad en los valores de Eficiencia DEA dentro de cada uno de los grupos definidos, sin apenas diferencias entre ellos, siendo algo mayor en el grupo I y IV y apenas insignificante en los grupos II y III.

Si nos centramos ahora en el análisis de los valores obtenidos para la Eficiencia corregida Bootstrap, comprobamos que no hay ningún puerto que consiga superar la barrera del noventa por ciento de eficiencia y por consiguiente no se podría clasificar como puerto eficiente a ningún puerto de la nuestra. Con respecto al siguiente escalón, hay tres puertos que se mantienen en el grupo II, como es el caso de Singapore (0,77979), Qingdao (0,74744) y Guangzhou (0,69963). Sin embargo, los tres puertos que conformaban el grupo I en el análisis DEA, bajan a este grupo II cuando optimizamos los resultados aplicando la técnica estadística Bootstrap. Es el caso de los puertos de Shanghai (0,86173), Hong Kong (0,81953) y Tánger (0,75276). Hay que destacar que el ajuste producido entre los valores de Eficiencia DEA y los de Eficiencia Bootstrap es pequeño, del orden de un valor medio del 10%. Esto puede ser un indicador de que estos puertos se encuentran trabajado en un escenario muy próximo a su tamaño máximo productivo.

Hay que destacar que el puerto de Algeciras (0,56613), se mantiene constante en el grupo III, Puertos con Eficiencia Baja, y prácticamente en el mismo orden que se ha obtenido en el análisis DEA, y con un ajuste del 9%.

Por último, el cuarto grupo al que hemos denominado puertos Ineficientes, está formado por seis puertos, y entre ellos encontramos a puertos de la entidad de Rotterdam (0,47077), Barcelona (0,25862) y Valencia con un muy discreto valor de 0,15729.

7. CONCLUSIONES

Una vez comprobada la eficiencia técnica global de escala y la eficiencia técnica pura, se observa que los puertos asiáticos son bastantes eficientes, destacando el puerto de Shanghai que moviendo más de 42 millones de TEUs ocupa el primer puesto en la clasificación mundial. Tánger MED (puesto 46) y Hong Kong (puesto 5) se mantienen en la parte alta de los valores de eficiencia. Los puertos asiáticos deben estos valores de eficiencia a su posición estratégica y a las dimensiones de las terminales y muelles, así como al número de grúas. Por consiguiente, manipulan un número muy elevado de contenedores en comparación con otros puertos.

Las condiciones geoestratégicas de estos puertos y sus condiciones técnicas les permitiría atraer aún más volumen de tráfico. Del mismo modo, y debido a su situación en el Estrecho de Gibraltar, en los próximos años asistiremos a un crecimiento considerable del puerto de Tanger MED. Está aumentando su volumen de contenedores progresivamente y en los próximos años se prevé que con las nuevas terminales, el tráfico de contenedores sea bastante más elevado, pudiendo ser una fuerte competencia para el puerto de Algeciras con el que comparte posición estratégica.

Los puertos de Singapur y Shenzhen presentan características similares al de Shangai, pese a encontrarse entre los tres principales puertos, tienen una eficiencia baja con respecto a otros, lo que significa que sus puertos no son totalmente productivos, sino que podrían mejorar.

Centrándonos en los puertos europeos, se puede ver que siendo el puerto de Rotterdam el más importante del continente, al compararlos con los puertos más importantes del mundo, su eficiencia es bastante baja.

Esto que no quiere decir que obtenga malos resultados, sino que podrían ser bastantes mejores, pudiendo llegar a ser una fuerte competencia para los puertos asiáticos por su novedoso y gran equipamiento, aparte de por la localización en la que se encuentra, siendo la principal entrada de mercancía de toda Europa y debido a sus buenas conexiones con otros países.

Se puede comprobar que entre los puertos españoles el que presenta mayor eficiencia en los dos modelos estudiados es el puerto de Algeciras, que pese a tener menor volumen de equipamiento y capacidad que el puerto de Valencia, su volumen de TEUs es muy similar entre ambos puertos, teniendo años que está por encima y otros ligeramente por debajo del puerto valenciano.

En verano de 2018, se han introducción tres nuevas grúas en la terminal APM Terminals de Algeciras, lo que ha supuesto un aumento del número de contenedores manipulados en esa terminal, que beneficiará al rendimiento y eficiencia del puerto.

En definitiva, los puertos y las cadenas logísticas tienen como objetivo el crecimiento a partir de la inclusión de tecnologías y prácticas innovadoras para los procesos de organización, administración y de servicios. Los puertos están en continuo avance, intentado automatizar las terminales que les sean posibles para así poder incrementar la eficiencia y que sean más productivos, con el fin de llegar a ser de los principales puertos de contenedores del mundo.

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ECOFLOTA: BUSINESS INTELLIGENCE SYSTEM FOR THE TRANSITION TOWARDS SUSTAINABLE MOBILITY FLEETS

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ABSTRACT

The lack of knowledge about the possibilities of switching to sustainable fleets and their costs lead companies to prolong the life of their fleets as much as possible. Therefore, the overall objective of ECOFLOTA is to provide arguments for companies to decide to migrate their fleets towards new ones that provide more sustainable mobility.

Within this framework, this project proposes the development of an automated analysis, planning and forecasting system consisting of i) a support tool for the optimised migration towards cleaner vehicles to achieve the objectives of zero emissions and green transport; ii) a predictive model of the useful life of these new sustainable vehicles and iii) the development of an eco-driving model to optimise the performance of these new sustainable vehicles. Hence, the project proposes the design and development of a global system at all levels for the upgrade of fleets with low emission vehicles.

The project was developed over a period of 15 months, during which time last mile delivery companies were involved in the definition, design, development and validation of the system, in order to meet the technical specifications and functional requirements of their operations. As a result, 61 use cases were simulated considering three types of routes (urban, short distance and interurban), as well as three types of low emission vehicles (electric, gas and hybrid)

1. INTRODUCTION

In recent years, local governments have adopted several urban traffic and mobility management measures based on energy efficiency and environmental sustainability. The aim is to create a more liveable and friendly environment. Simultaneously, cities face this challenge while trying to increase the operational efficiency of urban goods distribution.

In many studies, low emission vehicles are considered the right solution to meet both needs. However, currently logistics operators do not have clear information about the advantages offered by these new sustainable vehicles. Likewise, it is difficult for them to calculate the costs of replacing their current fleet with these types of vehicles and to estimate the profitability that this fact could generate in the long term.

In this context, the ECOFLOTA tool is an automated system of analysis, planning and forecasting of sustainable mobility fleets. It comprises a support module for optimised migration to low emission fleets, a predictive life model of these new sustainable vehicles and an eco-driving model to optimise the performance of these type of vehicles.

Specifically, the migration module involves a multi-objective optimisation model that allows to determine, for an established time horizon, a fleet replacement plan that minimizes the total cost to invest considering all the economic, technical, operational, environmental, and regulatory restrictions.

In addition, the predictive maintenance model is based on a genetic algorithm that allows monthly maintenance of the new fleet to be planned considering both economic and technical criteria.

Finally, the system includes an eco-driving module that contemplates and quantifies the savings in fuel consumption, pollutant emissions and maintenance costs in vehicles, derived from a more efficient and safe driving.

For its validation, more than sixty use cases were simulated taking into account different types of routes (urban, short distance and interurban), as well as low emission vehicles (electric, gas and hybrid)

2 TECHNICAL AND FUNCTIONAL REQUIREMENTS OF THE SYSTEM

The first of the tasks carried out focuses on identifying the technical requirements of the project and its functionalities. Based on this, the system architecture and all associated components were designed.

2.1 System architecture

The following figure shows the general architecture of ECOFLOTA, which identifies the three components that interact within the tool, as well as the actors involved in it:

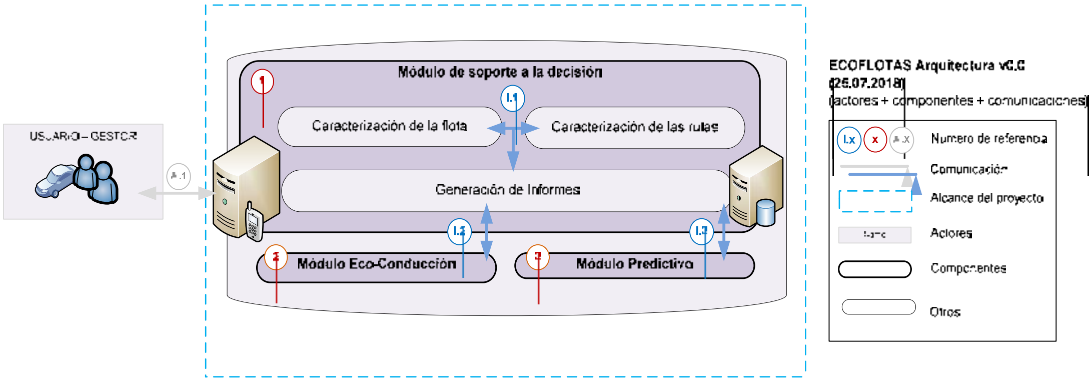

Fig. 1: ECOFLOTA architecture.

The table below identifies all system components, the communications between them and the graphical interfaces involved:

#	ECOFLOTA component	HMI	Communications
1	Decision Support module	User (Web)	I.1
2	Eco-driving Module	User (Web)	I.2
3	Predictive Module	User (Web)	I.3

Table 1: System components.

Considering both technical and economic feasibility, the aim is to obtain optimised solutions that demonstrate the benefits of the company's competitive, ecological, and sustainable development. With the use of predictive models, local regulations and standards in force or planned to be implemented, mobility patterns on historical routes, eco-driving models, among others, it will be possible to establish for the most common delivery routes where low-emission vehicles can be incorporated as a priority. This information, from the point of view of planning and logistics, is an added value of high performance of the tool.

The starting point for the definition and design of the tool, as well as its operation, is the characterisation of the company's operations, mainly related to the services provided (routes used and vehicles used). To complement the basic information of the data on its current operation and to provide a result more aligned with the company's needs, the user will also provide additional information, such as the city where it operates (to know municipal restrictions), critical mass of nearby recharging points, investment capacity and amortisation.

In order to propose an optimal development of the tool, some working sessions were held on Business Design and Lean Start-up, with the participation of companies, and in which the following objectives on their operation were identified:

- Minimising costs
- Optimising routes with mixed fleets
- Avoiding service incidents (breakdowns, accidents...)

Furthermore, some barriers relating to the different low emission vehicle typologies considered were also identified:

- Electric vehicles: high price; less autonomy; and limited recharging points
- Gas vehicles: less space and reduced power; greener, but polluting, vehicles; and limited refuelling stations
- Hybrid vehicles: high price; and not-definitive (transition to electric vehicle)

2.2 Decision Support Module

This is a support tool for logistics operators, vehicle dealerships or, in short, any company with a vehicle fleet. Its objective is to analyse the feasibility of migrating their fleets to less polluting vehicles, achieving the objectives of low emissions and green transport.

To this end, a multi-objective optimisation model has been developed that is capable of defining the optimal plan for replacing a current fleet, made up of conventional petrol or diesel vehicles, for a given time horizon of 5 to 10 years, or whatever the user estimates.

Thus, the optimisation model can define which vehicles of the current conventional fleet should be replaced by which type of more sustainable vehicle (that includes electric, hybrid or gas types)

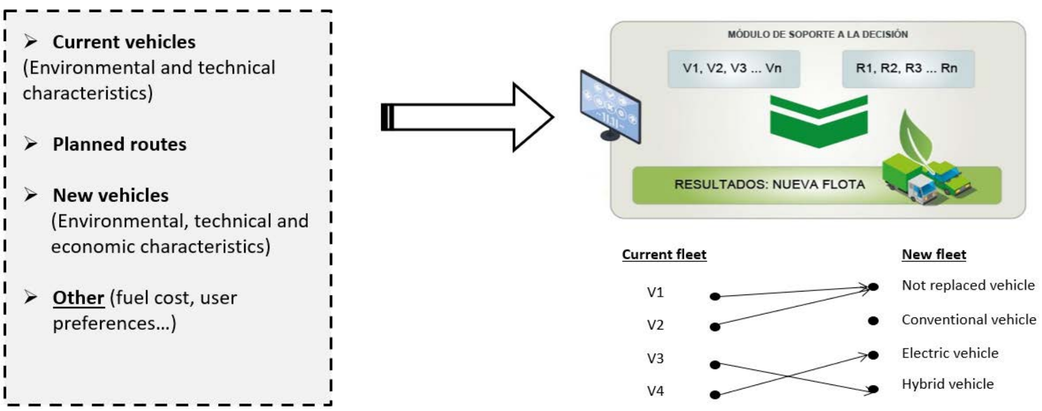

Fig. 2: Decision Support Module architecture.

With a view to define the replacement plan, the optimisation model developed considers all aspects or factors that may affect this decision to a greater or lesser extent. Specifically, all the technical, environmental, and economic characteristics of the current and new vehicles (sustainable and conventional) and the technical characteristics of the scheduled service routes. In addition, other non-economic and non-technical aspects have also been considered, such as user preferences in relation to the type of car they are willing to purchase, budget constraints, among other considerations. The table below shows all these technical, economic, and environmental aspects considered.

Current fleet	**Routes**	**New fleet**	**Other**
- Cost and maintenance - Fuel consumption - CO2 emissions	- Type - Km - Frequency - Cargo to be transported - Restriction on diesel?	- Age and km - Acquisition cost - Maximum permissible load - Range (km) - Fuel consumption - CO2 emissions	- Fuel costs - Bonuses for the purchase of sustainable vehicles - Reduction in maintenance operating cost and emissions by eco-driving - Maintenance cost - User preferences: > Car type > Car size (small, medium, and large) > Type of range (basic, mid-range and luxury)

Table 2. Economic, technical and environmental aspects considered in the substitution module.

Two different criteria, one economic and one environmental, have been considered for the optimisation model. This model seeks to minimise both the environmental impact of the new fleet and the total replacement cost. To define this cost, not only the acquisition cost but also the maintenance cost and the operating cost over the proposed horizon have been considered. The operating cost corresponds to the cost of charging the battery for hybrid and electric cars, or filling the tank in the case of gas, diesel or petrol vehicles. These two optimisation criteria can be completely opposite, i.e., the vehicle that pollutes the least, i.e., the electric vehicle, can be much more expensive than, for example, a hybrid that pollutes a little more. In this type of situation, the optimisation model will seek to minimise both criteria, but always giving greater priority to the environmental criterion, since the replacement module aims to replace the current fleet with a more sustainable one.

Through the optimisation model, the decision tool will be able to determine for each vehicle, i, in the fleet whether it needs to be replaced and if so, the type of sustainable vehicle, x, (electric, hybrid, or gas) and the corresponding range, g, (high, low and medium) by which it should be replaced.

Therefore, the decision variables of the model are the binary variables $n_{i, x, g}$ y n_i^{co}. More specifically, $n_{i, x, g}$ is a binary variable that will be equal to 1 if the vehicle i in the fleet is to be replaced by a sustainable vehicle of type x and range g:

$$n_{i, x, g} \begin{cases} 0 & \text{Vehicle i not replaced} \\ 1 & \text{Vehicle i replaced by a sustainable one of x type and g} \end{cases} \quad (1)$$

While the binary variable n_i^{co} will be equal to 1 if the vehicle i is not to be replaced and remains as a conventional type vehicle:

$$n_{i,}^{co} \begin{cases} 0 & \text{Vehicle i replaced by a sustainable one} \\ 1 & \text{Vehicle i not replaced} \end{cases} \quad (2)$$

For clarity, the following table specifies the indexes used in the nomenclature for the definition of both parameters and variables.

Indexes	**Description**
x $\{c, e, h, g\}$	Vehicle types {conventional, electric, hybrid, and gas}
k	Time period
i	Vehicles
r	Routes
$g =\{a ,m ,b \}$	Car type range {High, medium, low}

Table 3. Indexes used for the variables and parameters of the optimisation model.

The table below summarises all input parameters required for the development of the optimisation model:

Data	**Description**
T	Planning horizon
NC	Fleet size
B_x	Bonus for purchase of type *x* sustainable vehicle
β	Normalisation parameter
P	Vehicle procurement budget
$UL_{x,g}$	Lifetime (years) of type *x* vehicle and range *g*
UL_i^{co}	Useful life (years) of vehicle *i* of the original fleet
RUL_i^{co}	Remaining useful life (years) of vehicle *i* of the original fleet
Q_r	Average route load *r*
$Q_{x,g}$	Load that can be carried by type *x* vehicle and range *g*
$C_{x,g}^a$	Acquisition/replacement cost of type *x* vehicle and range *g*
$C_i^{a,co}$	Replacement cost of fleet *i* vehicle
$C_{x,g}^m$	Maintenance cost of type *x* vehicle and range *g*
$C_i^{m,co}$	Maintenance cost of fleet vehicle type *i*
$D_{i,x,g}$	Eco-driving discount factor for vehicle *i* when it is of type *x* vehicle and range *g*
D_i^{co}	Eco-driving discount factor for vehicle *i* when vehicle *i* is not replaced
l_r	Average route length *r*
$l_{x,g}$	Maximum km of type *x* vehicle and range *g*
fr_r	Route *r* frequency
$C_{k,x,g}^f$	Cost fuel of type *x* vehicle and range *g*
$C_i^{f,co}$	Fuel cost of fleet *i* vehicle
f_i^{co}	Fuel per km of fleet *i* vehicle
$f_{x,g,k}$	Fuel per km of car type *x* and range *g*
$E_{x,g}$	CO2 emission per km of vehicle type *x* and range *g*
E_i^{co}	CO2 emission per km of fleet i vehicle

Table 4. Required parameters for the optimisation model.

Finally, the following table describes parameters that are necessary for the optimisation model and that are calculated from the data defined in Table 3, i.e., fixed data, specified by the user or that can be collected from the database.

Parameter	**Description**
eco	Total emissions from existing vehicles
G	Total operating cost over the entire time horizon
$C_{i,k}^{co}$	Operational cost for original fleet vehicle *i* in period *k*
$C_{i,x,g,k}$	Operational cost of sustainable vehicle *x* of range *g* in period *k*
$k_{i,x,g}$	Total consumption on the routes by vehicle *i* of vehicle type *x* and range *g*
k_i^{co}	Total consumption on the routes by original fleet *i* vehicle

Table 5. Calculated parameters.

With the aim of defining the optimal fleet replacement plan, the optimisation model must consider the acquisition and maintenance costs of the different types of vehicles (current and those that could be acquired) as well as the future operational costs due to the energy consumption of the vehicles. Thus, the objective function of the optimisation model seeks to minimise all these costs according to the given replacement plan as well as to minimise the total emissions of the new fleet, but always giving higher priority to emission reduction. This priority is achieved by defining a very high emission cost, c.

Meanwhile the overall restrictions affecting the fleet are as follows:

- Avoiding of allocating more than one type of vehicle, sustainable or conventional (non-substituted), per vehicle.
- The total number of vehicles must be equal to that of the initial fleet
- Replacement of the current vehicle with sustainable vehicles based on the minimum weight they have be able to carry
- Replacement of the current vehicle by sustainable vehicles with the minimum autonomy required to carry out the assigned routes
- Limitation of access in certain areas due to regulations
- Load limitation for safety or danger reasons or due to regulations
- User requirements/preferences (e.g., user only wants electric and gas vehicles)
- Limitation in the budget for the acquisition of new sustainable vehicles

Additionally, another term can be added to the objective function to penalise the number of times the new fleet vehicles (sustainable and non-replaced) should be replaced over the time horizon according to their useful life. For example, if the lifetime of an electric vehicle is 8 years and the considered time horizon of the replacement plan is 10 years, the objective function should consider the cost of replacing this vehicle twice over the time horizon, in order to keep the number of vehicles in the fleet.

Many of the parameters that are considered within the optimisation model are user-defined, which can lead to infeasible solutions. In this case, the optimisation model will result in an infeasible solution. To warn the user about this type of error, in addition to the optimisation module, an error detection program has been developed to identify inconsistencies in the input parameters.

2.3 Maintenance module

The maintenance module is based on the development of the predictive maintenance tool. This consists of a genetic algorithm that allows monthly maintenance planning of the new fleet based on both economic and technical criteria of the new sustainable fleet.

For the development of the decision tool, a genetic algorithm based on metaheuristic techniques has been developed which can establish the monthly maintenance planning for the cars that make up the current sustainable fleet based on economic and technical criteria.

To do this, it has been necessary to identify, for each of the types of cars (electric, petrol, diesel, gas, hybrid), the critical elements, i.e. the elements whose breakdowns are the most frequent, most complex and, above all, most costly. In the case of petrol and diesel vehicles, the injection system and the steering system have been identified as critical elements. In the case of the injection system, its breakdowns are not the most frequent.

Specifically, it accounts for 16% of car breakdowns, but changing the injectors involves a large outlay of money. In the case of hybrid and electric cars, the car battery has been considered as a critical element, and in the case of hybrids, as an additional element, the injection system. Finally, for gas cars, only the injection system has been considered.

Based on the types of cars that make up the fleet, the genetic algorithm defines which months the user should perform the maintenance of its critical elements so that the total cost of preventive and corrective maintenance of the entire fleet over a predefined time horizon is minimal. Preventive maintenance refers to the maintenance of the element before its breakage and makes it possible to reduce the failure rate of the critical element, and therefore to avoid its replacement due to breakage, which could entail a high cost.

The only parameter defined by the user in the genetic algorithm is the time horizon (in years) to be analysed, the rest of the parameters will either be given by the substitution module or will be collected from the database. The parameters obtained from the previous module define some of the technical characteristics of the cars that make up the new sustainable fleet. In particular, the maintenance model only needs to know the type of car involved and the lifetime of the car, as it is not the same to plan the maintenance of a 10-year-old car with 1,000 km as a newly acquired one. In turn, the parameters defined in the database are those that characterise from an economic and technical point of view the critical elements of each of the types of car that may exist within the fleet.

More specifically, these parameters define the failure rate of each of the critical elements, and their corresponding preventive and corrective maintenance costs. In summary, the parameters considered are indicated in the following table.

Source	Description
User-defined	Number of years to be considered for planning purposes
Replacement module	Vehicle type
	Vehicle lifetime
Database	Failure rate of critical element of a vehicle depending on its type (petrol, diesel, gas, hybrid, or gas)
	Preventive maintenance cost of a critical element of a vehicle
	Corrective maintenance cost of a critical element of a vehicle

Table 6. Inputs to the genetic algorithm

The genetic algorithm aims to define the months of maintenance of each of the critical elements of the cars that make up the fleet given by the substitution module. In this sense, the only decision variables of the algorithm, i.e., the genomes that would compose everyone, are binary variables that will take the value equal to 1 when maintenance is scheduled for a specific critical element of a given car in a given month, and 0 otherwise.

In order to model the time evolution of the failure rate $\lambda_i^d(t)$of the critical element d of a car i, which is of petrol, diesel, electric, hybrid, gas or hybrid-electric type, based on what is suggested in the technical literature, the two-parameter Weibull function has been used, which adopts the following expression:

$$\lambda_i^d(t) = \left(\frac{\beta_i^d}{\alpha_i^d}\right)\left(\frac{t}{\alpha_i^d}\right)^{\beta_i^d - 1} \quad (2)$$

$\lambda_i^d(t)$: Failure rate of equipment i by critical element d at time t
β_i^d, α_i^d: Weibull function coefficients

2.4 Eco-driving module

The Institute for Energy Diversification and Saving (IDAE) points out that efficient or ecological driving, compared to aggressive driving, reduces emissions of carbon dioxide (CO2), one of the main gases involved in climate change, as well as other pollutant emissions: up to 78% of carbon monoxide (CO), 63% of hydrocarbons and 50% of nitrogen oxides (NOx). Noise pollution is also reduced: one car at 4,000 revolutions per minute (rpm) makes the same noise as 32 cars at 2,000 rpm.

In this context, eco-driving is a concept associated with the new way of driving, which focuses on achieving a more economical and safer way of driving, reducing environmental pollution, and improving comfort. To this end, the concept defines and sets out a series of rules and modes of behaviour that seek to take advantage of the possibilities offered by current car engine technologies.

Driving style is influenced by a complex mix of social, psychological and cultural factors that directly affect the driver. At the same time, eco-driving is also influenced by technical factors related to the vehicle. In this area, the main driving parameters affecting the emission of pollutants are speed, engine speed, idling time, power take-off time, acceleration breaking, tyres and air-conditioning use.

In line with the above, the following are a number of guidelines and driving behaviours that can save fuel while driving, and therefore also help to reduce emissions.
With simple changes in driving habits, most drivers can save 10-15% on fuel.

- Reduce speed: For every 10 km/h over 100 km/h, fuel efficiency is reduced by 10%. Driving at 120 km/h on the highway instead of 100 km/h is equivalent to a 20% saving on fuel. In addition, maintaining a constant speed means lower fuel consumption. Using the accelerator and brake pedals smoothly: Hard starts between traffic lights can save 2.5 minutes on a one-hour journey, but it increases fuel consumption by 37%.
- Reducing idling times: As noted above, 10 seconds at idle speed means higher fuel consumption than when starting the engine. In this context, 10 minutes at idle means a consumption of half a litre of fuel
- Warming up the engine on the move: today's vehicles do not require periods of idling to warm up the engine. Gentle driving for the first few minutes after starting allows the transmission, steering and engine to warm up at the same time.
- Combining journeys: Journeys of less than 5 km are the most polluting, as the engine and pollution control system never reach maximum operating temperature. Combining several trips into one can reduce fuel use and emissions by 20-50%.
- Avoid overloading: every additional 100 kg of load reduces fuel efficiency by up to 2%, so it is recommended not to carry unnecessary items
- Make the most of your transmission: using overdrive at high speeds saves fuel and reduces engine wear. With a manual transmission, smooth but quick shifting at higher speeds allows the engine to operate more efficiently.
- Consult the vehicle's on-board computer (if available): such devices provide real-time fuel consumption information. In general, drivers who learn to adjust their driving habits according to the information available can save up to 10% in fuel consumption
- Proper maintenance of the different elements of the vehicle: Aditionally to being a safety factor, also results in lower fuel consumption.

Eco-driving offers numerous benefits: it not only saves fuel and costs, but also improves road safety and the quality of the local and global environment. In addition, eco-driving provides direct benefits to drivers and passengers, i.e., more comfort and a more relaxed environment. All of this is associated with equal or shorter travel times.

In short, the eco-driving module aims to be a tool that complements the decision module, with the objective of, on the one hand, making recommendations on the way of driving, both sustainable and conventional vehicles, and on the other hand, estimating the effects that the practice of this driving style (savings) will have on the operational scenarios of the fleet. To do this, it is based on both the type of vehicle and the type of routes that the vehicle will carry out.

Thus, and as a synthesis of the possible benefits of this driving style, the following table is taken into account, depending on the different types of vehicles (propulsion):

SAVINGS	**CONVENTIONAL**	**GAS**	**HYBRID**	**ELECTRIC**
Fuel	15%	15%	18%	20%
Emissions	15%	15%	18%	N/A
Maintenance	5%	5%	5%	5%

Table 7. Percentage savings as a result of eco-driving by vehicle type

2.5 System validation

For the validation of the integrated system, 61 different tests were proposed, whose fleet was made up of three combustion vehicles (2 petrol and 1 diesel), and their operation included three different types of routes (Urban, Interurban and Short distance).. The results showed that:

- 7 of the cases did not result in a change of fleet. In other words, there was no substitution necessary in the scenario proposed. The specific cases were:
    - Only sustainable vehicles with a current full diesel fleet and with a budget constraint of €17,000
    - No sustainable selection with no vehicle selection. At least one sustainable vehicle must be selected, when only sustainable vehicles are selected
    - No range selection. The range must be selected
    - No size selection. The size must be selected
    - With a higher bonus than the budget for electric vehicles.
    - Routes currently undertaken are not viable for sustainable vehicles (1,000,000 km)
    - The weight of the current routes cannot be covered by the current sustainable vehicles.

- 38 replacement cases 1 fleet vehicle
    - 23 electric
    - 6 gas
    - 3 hybrids
    - 3 new diesel
    - 3 new petrol
- 10 replacement cases 2 fleet vehicles
    - 5 new diesel
    - 3 new petrol
    - 1 gas
    - 1 hybrid
- 6 replacement cases all 3 vehicles in the fleet
    - 3 new diesel
    - 3 new petrol

3. WEB INTERFACE DESIGN

The web platform is designed in such a way that any user can use it intuitively following good web design practices. In addition, it is designed to be "responsive" so that no matter what device is used to view it, whether mobile, tablet or monitor, the content of the page will adapt to the resolutions of each of these screens.

In order to access the platform, registration is required. Once registered, you can log in to access the platform. It contains different sections, which are always available in a fixed sidebar. Among the sections are some designed to create and visualise the initial fleet situation, both vehicles and route types. Also, a section to perform simulations, being able to vary different input parameters to generate different results.

Finally, a screen to visualise these simulations, and to generate the prediction of the maintenance module with respect to the associated simulation.
Below are a series of screenshots of all the screens mentioned above.

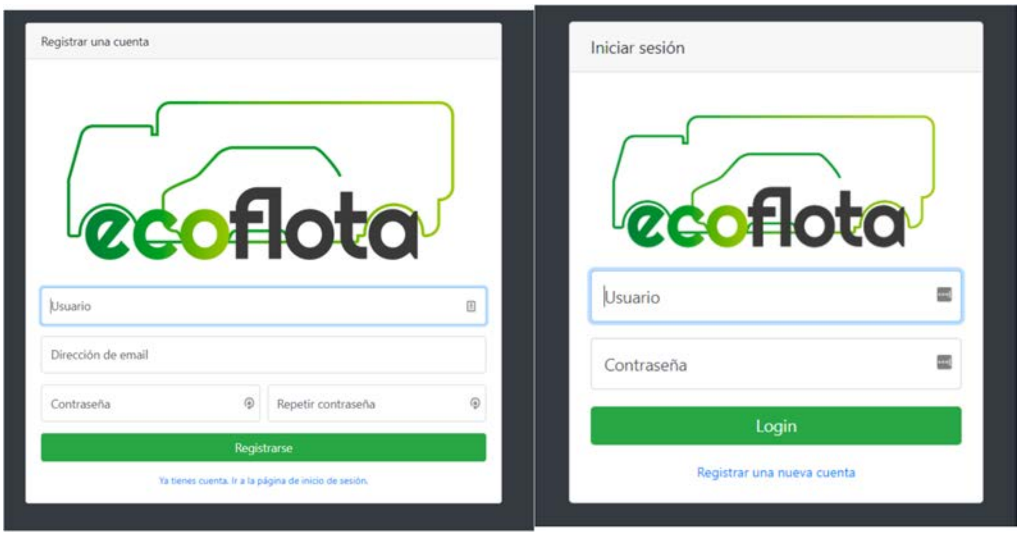

Fig. 3: Registering on the platform and logging in.

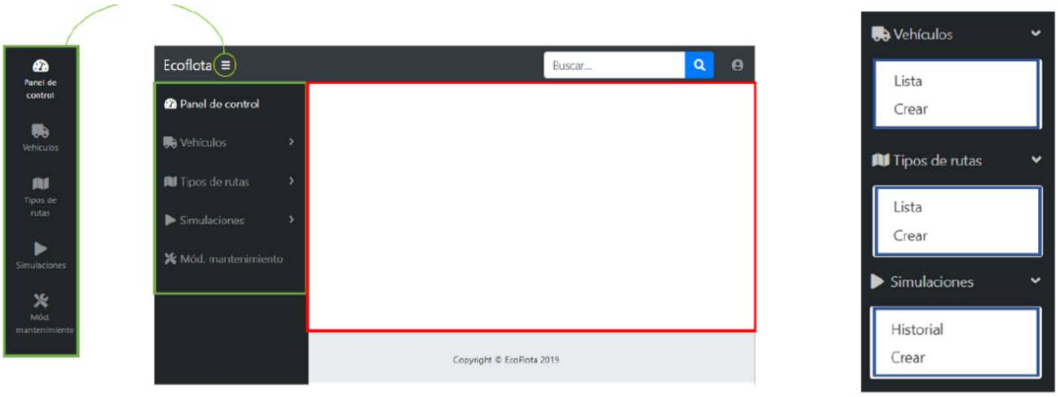

Fig. 4: Basic structure of the web platform.

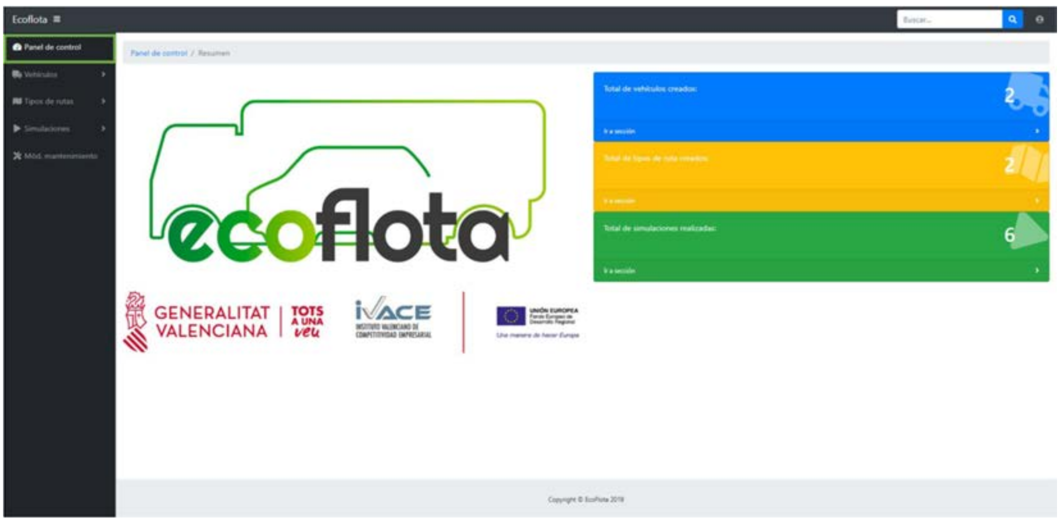

Fig. 5: Control pannel.

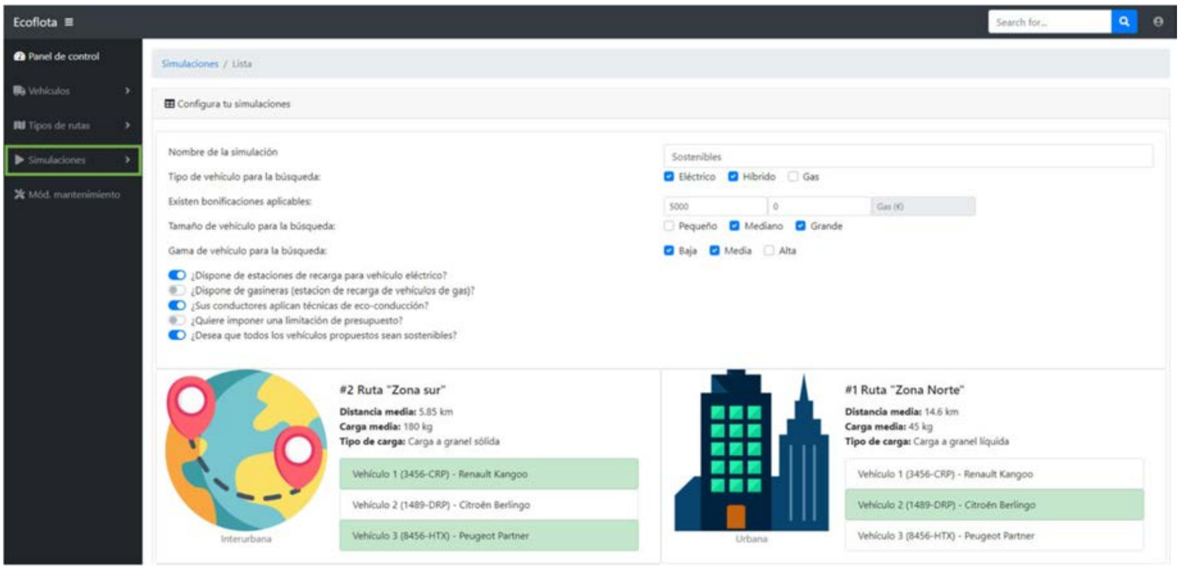

Fig. 6: Simulation creation.

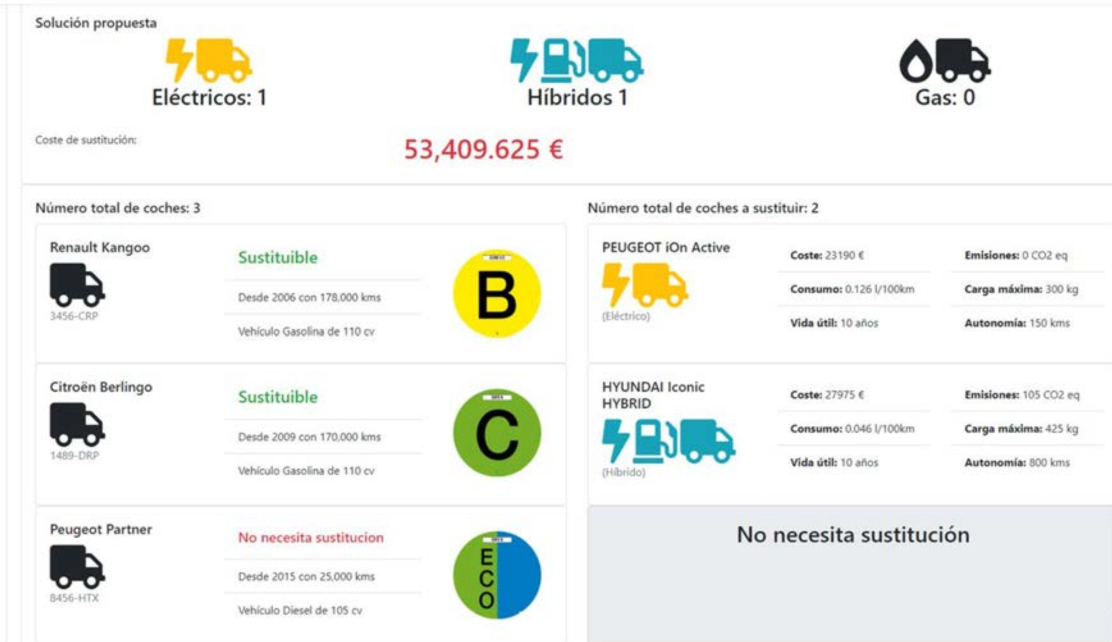

Fig. 7: Example simulation output.

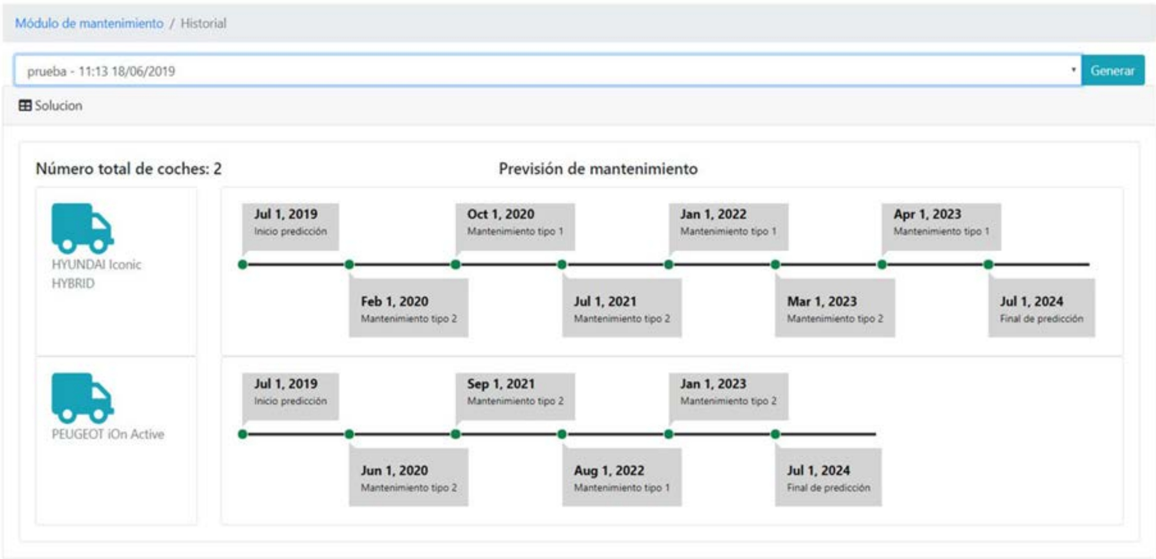

Fig. 8: Maintenance module simulation output.

4. CONCLUSION

To help the transition to a sustainable mobility model, ECOFLOTA has developed an intelligent decision support system, capable of interpreting the needs of both routes and vehicles, to provide the optimal result. In other words, the main objective is to facilitate the change from conventional fleets to sustainable fleets.

The decision has been based on the needs of the companies transferred directly to the architecture and design of the system. To this end, it has been obtained:

- Automated system for analysis, planning and forecasting of sustainable mobility fleets.
- Aimed at transport and logistics companies
- Contributes to reducing pollution and noise in cities.
-

It mainly consists of:

- A support tool for logistics companies for the optimised migration of their fleets towards cleaner vehicles to achieve zero emission and green transport objectives.
- A predictive model for the lifetime of these new sustainable vehicles.

In view of the results and feedback obtained, the tool could be further improved with:

- Include leasing and carsharing modalities in the model
- Extending the catalogue of vehicles
- Extend the topology of the vehicles. (Bicycles, motorbikes, scooters...)

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EFECTOS DE LA CONDUCCIÓN EFICIENTE EN LA DISTRIBUCIÓN DE MERCANCÍAS

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RESUMEN

El sector del transporte es uno de los mayores causantes de las emisiones de contaminantes y de los gases de efecto invernadero (GEI). La conducción eficiente en los últimos años ha demostrado ser una herramienta eficaz para reducir el consumo de carburante y las emisiones de GEI a la atmosfera. Hasta ahora la mayor parte de investigaciones realizadas se han centrado en aplicar las técnicas de conducción eficiente a conductores corrientes en sus itinerarios habituales, sin embargo, existe muy poca investigación en la distribución de mercancías sobre conductores profesionales. Parece por tanto necesario analizar los efectos que la conducción eficiente produce sobre el consumo de combustible y emisiones de GEI de la distribución de mercancías de una ciudad pequeña como Cáceres. Para ello se han realizado un experimento en tiempo real con conductores profesionales conduciendo furgonetas de la empresa pública Correos. En un primer periodo se ha realizado una conducción en condiciones normales (non eco) donde se han registrado segundo a segundo mediante un dispositivo instalado en los vehículos (OBDKEY), distintos parámetros de la conducción (posición, velocidad, rpm, aceleración, deceleración, paradas, etc.). Después de un periodo de formación teórica en conducción eficiente, se ha realizado un segundo periodo de conducción (eco) donde se han vuelto a registrar los mismos parámetros y se han evaluado los efectos que produce sobre los mismos esta conducción. Esta investigación analiza los consumos y emisiones de GEI según la zona de reparto en la ciudad de Cáceres (urbanas, suburbanas y extrarradio) para ambos tipos de conducción (eco y non eco). A partir de este análisis se evalúa la reducción de consumos de combustible y emisiones a la atmósfera con la conducción eficiente y se comparan los resultados obtenidos con conductores no profesionales.

1. INTRODUCCION

El sector transporte representa el 25% de las emisiones totales de gases de efecto invernadero y casi el 40% de las emisiones de los sectores difusos.

Por modos de transporte, la carretera representa casi el 95% de las emisiones, mientras que la contribución de otros modos de transporte es bastante más minoritaria (EEA, 2019). Los turismos y furgonetas representaban el 73 % de las emisiones de GEI del transporte por carretera en 2015 (NU, 2019a).

El acuerdo de Paris (NU, 2015) marcó el objetivo de reducir las emisiones de los gases de efecto invernadero (GEI) un 40% en 2030 con respecto a las emisiones de 1990. Para poder alcanzar este objetivo, la ONU (NU, 2019b) ha advertido que a partir de 2020 las emisiones de carbono tendrán que reducirse a un ritmo de 7,6% al año para cumplir con la meta de un calentamiento global limitado a 1,5 grados.

En la COP-25 de Madrid (Conference of Parties of the United Nations Framework Convention on Climate Change) (NU, 2019b), 73 Estados se han comprometido a ser neutros en carbono en 2050, entre ellos, España. Para lograrlo, España se ha fijado reducir una de cada tres toneladas de CO_2 en la próxima década, duplicando el consumo final de energía renovable en 2030.

En España el modo mayoritario de transporte es sin duda el transporte por carretera, tanto en pasajeros como en mercancías, representado más del 80% de la movilidad total a nivel nacional (MITECO, 2020a). Existen circunstancias propiamente nacionales que han supuesto un incremento de la cuota modal de la carretera, como el modelo de crecimiento urbanístico disperso en el caso de la movilidad de pasajeros y el hecho de ser un país periférico en el caso de la movilidad de mercancías. Además, se caracteriza por el uso preferente de combustibles derivados del petróleo que representan más de 90% del total de energía consumida en el sector transporte en España (Pérez y Monzón, 2008).

Las emisiones de gases de efecto invernadero correspondientes al sector del transporte en España en el año 2014 fueron de 77,2 MtCO2-eq (MITECO, 2020b), habiéndose incrementado casi en un 50% desde 1990 como consecuencia del incremento en la demanda de movilidad de pasajeros y mercancías.

La búsqueda por tanto de medidas de reducción de emisiones de GEI es uno de los objetivos de cualquier país que persiga la neutralidad en carbono para el año 2050. En el caso del transporte de mercancías existen las siguientes medidas para reducir las emisiones de GEI:

1. Sistema de gestión de flotas. Las herramientas informáticas disponibles permiten organizar mejor el tráfico de mercancías y limitar el consumo de combustible y, en consecuencia, de emisiones de CO_2. Cada vez más empresas apuestan por estos sistemas para reducir los kilómetros en vacío y controlar la distribución de cada camión. Las empresas que los han utilizado han reducido las emisiones de sus procesos logísticos hasta en un 2% cada año (Demir et al., 2014).

2. Vehículos a gas natural. El gas natural se ha considerado durante muchos años como la energía de transición, hasta que la eléctrica consiga la autonomía suficiente. Jugará un papel destacado en la descarbonización de la economía mundial y cada vez tiene más aplicaciones en transporte terrestre y marítimo. En 2017 el consumo de gas creció un 9% en España y se espera que despegue a partir del 2020. En el transporte de mercancías por carretera, con cada vez más gasolineras de gas, el gas natural gana confianza para viajes de larga distancia. Los fabricantes de camiones también aumentan su apuesta por este combustible (NGVA, 2017).

3. Megacamiones. El megacamión (o camión euromodular) mide 25,25 metros de largo, pesa 60 toneladas y tiene una capacidad de 51 palés. El llenado pasa de un 54% a un 57,5%, lo que reduce el número de viajes, kilómetros y el consumo de combustible. Según un estudio de la Comisión Europea (CE, 2017), los megacamiones pueden ahorrar hasta un 20% de combustible, un 20% de las emisiones de CO_2 y un 40% de las emisiones de otros contaminantes como NOx (óxidos de nitrógeno).

4. Conducción eficiente. Cómo arrancar, cuándo empezar a frenar, mantener una velocidad adecuada… son conceptos que reducen el consumo de carburante y, por tanto, las emisiones de CO_2. Además, suponen ahorro económico y de energía, menos mantenimiento, mejora de la velocidad media, menos riesgo de accidentes y mejora del confort. La conducción eficiente permite ahorros medios del 10% en carburante, según la guía de conducción eficiente de vehículos industriales del Instituto para la Diversificación y Ahorro de la Energía de España (IDAE, 2011). Los programas de formación en conducción eficiente realizados a conductores de forma individual, suelen estar compuestos de dos partes, una teórica y otra práctica. En la parte práctica se hace hincapié en conducir de forma suave manteniendo una velocidad constante, cambiando de marchas a bajas revoluciones y evitando en la medida de lo posible las repentinas aceleraciones/deceleraciones (Wang y Boggio-Marzet, 2018).

En la literatura, las técnicas de conducción eficiente (Sivak y Schoettle, 2012) han demostrado distinta eficacia en el ahorro de combustible y emisiones de GEI en función de diversos factores externos y métodos de aprendizaje empleados. Los valores de reducción de emisiones de CO_2 oscilan entre el 0,5% y 10% en función del tipo de carretera -carreteras urbanas o autovías- (Alam y McNabola, 2014). La intensidad de tráfico o las pendientes por las que se circula el vehículo son factores que tienen una incidencia directa en el consumo (Kamal et al, 2012). Por tanto, las técnicas de conducción eficiente que se deben emplear son distintas en función del tamaño de la ciudad (Coloma et al., 2020), o el tipo de carretera recorrida (Coloma et al, 2019).

Las investigaciones realizadas hasta ahora sobre conducción eficiente se han centrado normalmente en conductores no profesionales, conduciendo turismos en distintos tipos de carretera, vehículo o ciudad, pero no se ha visto el efecto de la conducción eficiente en empresas de mensajería cuyos conductores son profesionales y tienen como objetivo realizar un reparto en el menor tiempo posible. Conocido este vacío en la literatura los objetivos de esta investigación serán:

1. Consumos y emisiones emitidas a la atmósfera por los vehículos de reparto de mercancías durante una conducción normal y posteriormente con una conducción eficiente.
2. Evaluación de la reducción de consumos de combustible y emisiones a la atmósfera en la conducción eficiente.
3. Comparación de los resultados obtenidos en esta investigación con los de conductores no profesionales que no tienen las obligaciones y exigencias del reparto.

Para cumplir estos objetivos se cuenta con la colaboración de la empresa pública de mensajería española Correos. La ciudad elegida ha sido Cáceres (España) ya que se en ella se ha llevado a cabo un experimento similar con conductores noveles (Coloma, et al, 2017) y puede servir para comparar la eficacia de estas técnicas de conducción en conductores profesionales.

Después de esta introducción el apartado 2 hace una descripción de la metodología seguía para realizar los ensayos con conductores profesionales antes y después de recibir formación en conducción eficiente, el apartado 3 describe los resultados y realiza un análisis de los mismos comparándolos con conductores noveles en Cáceres y con otras investigaciones publicadas en la literatura. Finalmente se adjunta un apartado con las conclusiones más sobresalientes de esta investigación aportando nuevas ideas para futuras investigaciones.

2. MATERIALES Y MÉTODOS

Los resultados favorables de anteriores investigaciones en el campo de la conducción eficiente animan a llevar a cabo un experimento de conducción “eco” en el sector de los vehículos pertenecientes a entidades profesionales donde el consumo de combustible tiene un impacto directo en el rendimiento económico de la empresa. Para ello se lleva a cabo un ensayo en cuatro vehículos pertenecientes a la empresa “Sociedad Estatal Correos y Telégrafos, S.A., S.M.E. (Correos)” en la ciudad de Cáceres (España).

La investigación consta de dos partes, unas pruebas de campo y un posterior estudio y análisis. En las pruebas de campo los vehículos realizan sus respectivas rutas con conducción normal la primera semana y con conducción eficiente en una semana posterior.

En ambas conducciones se realiza un almacenamiento y registro de los principales datos de conducción del vehículo (posicionamiento GPS, velocidad, aceleraciones/deceleraciones, etc). En la segunda parte, se elabora un análisis y estudio de los datos recogidos para poder analizar la eficacia de la conducción eficiente en conductores profesionales.

2.1. Primera fase: Recolección de datos de la actividad de los vehículos en carretera

El génesis de la investigación se sitúa a mediados del mes de septiembre de 2019 y se desarrolla hasta mediados de octubre, consistiendo en la recolección de datos a través de un dispositivo OBD (OBD-KEY, 2020) implementado en los vehículos, el cual almacenaba diferentes parámetros sobre la actividad de los automóviles en sus respectivas jornadas de reparto. En un primer lugar, los conductores ejercieron el tipo de conducción habitual que venían practicando hasta la fecha, después de esta primera extracción de datos, los conductores asistieron a una jornada de instrucción sobre conducción eficiente, con el fin de implementar en su sistemática de manejo del vehículo, actitudes típicas de este modo de conducción. Una vez adquiridos estos conocimientos, los conductores comenzaron a conducir en modo "eco" registrándose también los mismos parámetros de conducción que fueron extraídos en la fase anterior para poder llevar a cabo su comparación. Al final de estas jornadas, se recogieron las sensaciones al respecto en una encuesta realizada a los conductores participantes.

En este tipo de experimentos es necesario el compromiso de los conductores para realizar el ensayo, es decir, el factor humano tiene un peso muy importante en los resultados y eficacia de aplicación de estas técnicas. Adicionalmente, es necesario aclarar que en esta ocasión, las rutas no eran predefinidas, lo que si se hace en otros estudios (Zarkadoula, 2007), sino que estaban sujetas a los itinerarios que marcaban los repartos o bien a la metodología de distribución que los conductores consideraran oportuna. Por tanto, los conductores se enfrentaron a multitud de situaciones de tráfico, lo que afectó a variables que inciden en la investigación como pueden ser la velocidad, tiempos de espera por congestión de tráfico o el confort. No obstante, estos factores son necesarios para evitar sesgos en los resultados que, si son positivos, demostrarían la fácil implementación de la conducción eficiente en los sectores profesionales y lo beneficioso a nivel económico y ambiental que es este tipo de conducción con independencia de la tipología de la distribución de los repartos.

2.1.1. Caso de estudio: Cáceres, España

Cáceres es una ciudad localizada en el oeste de España, con una población de aproximada de 96.000 habitantes y que cuenta con una superficie de 30 km^2. La ciudad posee un significativo pasado histórico, contando con una densidad importante de monumentos y con una morfología urbanística característica de la Edad Media que resulta única, lo que le ha llevado a ser nombrada Patrimonio de la Humanidad por la UNESCO en el año 1986 (UNESCO, 1986).

Cáceres posee una Ciudad Monumental, situada en el centro, de carácter urbano peatonal protegido, a la que perimetralmente se han añadido, tras diversas actuaciones urbanísticas, nuevas zonas de ámbito civil que han ido desarrollándose de forma paulatina a lo largo del tiempo. Sin duda, el modo de transporte principal es el automóvil, representando un 55% de los movimientos dentro de la ciudad.

La orografía de carácter montañoso que posee el emplazamiento de la ciudad y sus dimensiones, no impiden que el desplazamiento peatonal suponga un tercio de los movimientos, a costa de los medios públicos que solo representan un 10% del total (AYUNTAMIENTO DE CACERES, 2014). La ciudad de Cáceres tiene tres franjas horarias punta en cuanto a los movimientos de transporte para acceso a la ciudad: entre las 8 y las 9h, entrada a los trabajos y los centros de enseñanza (10% por encima de la media), y entre las 18 y 19h, donde se produce el regreso a los hogares (15% superior a la media). Como ejemplo, la Avenida de España, situada en el centro de la ciudad, cuenta con un promedio de 1000 vehículos/hora por cada sentido, creciendo dicho valor hasta 1300v/h a las 14h (AYUNTAMIENTO DE CACERES, 2010).

El crecimiento sostenible de la ciudad pasa por implementar medidas que fomenten el uso del transporte público y la movilidad peatonal. A pesar de que ya se han estado aplicando políticas de protección del medio ambiente y reducción de las emisiones en el centro histórico de Cáceres, que en gran parte está dedicado a los peatones, se ve necesario aumentar el número de zonas con estas características, que excluyan los movimientos de automóviles para alcanzar nuevas y mejores metas de sostenibilidad.

2.1.2. Rutas y condiciones de tráfico

Cáceres es una ciudad pequeña que puede ser atravesada de lado a lado en tan solo 15 minutos. Como se ha dicho anteriormente, las rutas no siguen itinerarios definidos, se trata de rutas típicas de una jornada de transporte de repartos de un conductor profesional que se distribuyen por casi toda la ciudad y recorren diferentes tipos de vías urbanas.

Se definen cinco tipos de vías (USDT, 2013), para poder caracterizar los distintos tramos y analizar las rutas específicas de tamaño menor (micro-rutas).

1. Calle local (Local). Este tipo de vía urbana se dispone en el interior de la ciudad. La calzada tiene un carril por sentido de circulación, sin mediana ni aparcamientos. La velocidad máxima de la vía es de 50 km/h.
2. Colector urbano (Colector). Carretera que rodea el centro de la ciudad y conecta puntos neurálgicos de esta. Su calzada está compuesta por dos carriles en cada dirección, dispone de mediana y aparcamiento a cada lado. La velocidad está limitada a 30 km/h y en ocasiones está congestionada.
3. Carretera perimetral (Perimetral). Antigua circunvalación de la ciudad integrada ahora en la red urbana. Tiene doble calzada con dos carriles para cada dirección separados con doble línea continua o mediana, su límite de velocidad es 50 km/h y apenas crea congestión de tráfico.
4. Variante de población (variante). Se sitúa como circunvalación exterior rodeando las afueras de la ciudad. Las intersecciones se ejecutan por medio de glorietas y los pasos para peatones, en su mayoría, se regulan por medio de semáforos. Los límites de velocidad se sitúan en una horquilla de entre 40 y 80 km/h.

5. Vía interurbana (Interurbana). Carreteras situadas fuera de los límites del casco urbano que conectan puntos exteriores a este, ya sean núcleos poblacionales de menor entidad, núcleos industriales como puede ser polígonos o con otras carreteras nacionales o autovías. Sus límites de circulación varían entre 50 y 90 km/h.

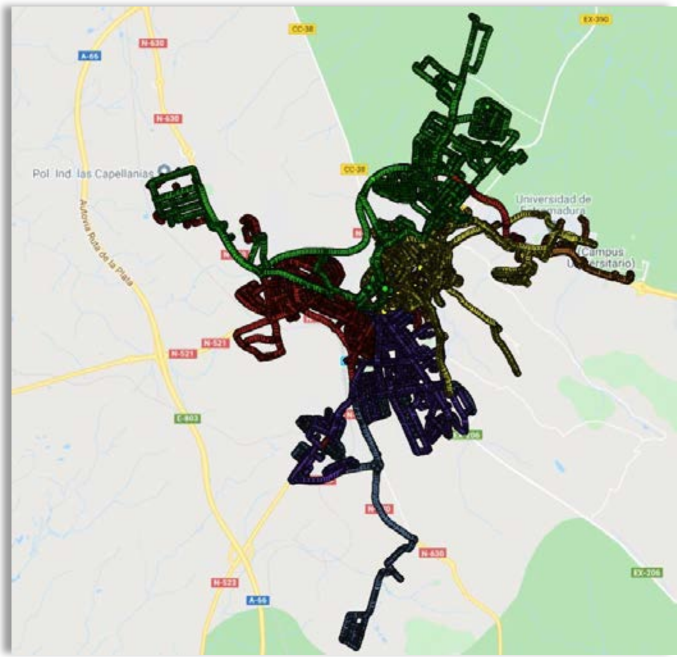

Figura 1. Visión global de las rutas de los vehículos que participan en la investigación.

2.1.3. Selección de conductores, entrenamiento en eco-driving y fechas

Para la realización del experimento fueron seleccionados cinco conductores de la sección de repartos de la empresa Correos en la ciudad de Cáceres. Todos los conductores eran varones con edades comprendidas entre los 35 y 60 años, por lo que la muestra es representativa en cuanto a la edad, pero no en cuanto al género. Durante la primera semana se registraron los viajes de estos conductores durante sus repartos con su conducción habitual.

Posteriormente, los conductores seleccionados recibieron un curso teórico acerca de las técnicas de conducción eficiente para poderlas implementar la semana siguiente en sus repartos diarios. Todos los viajes realizados con conducción “eco” fueron registrados de la misma forma que lo fueron los de la primera semana con conducción habitual.

El horario de las jornadas laborales se divide en dos franjas horarias correspondientes a los turnos de trabajo de mañana y tarde, un primer turno de 7:00 a 14:00 h y un segundo turno comprendido entre las 14:00 y las 21:00 h.

Cuatro de los conductores desarrollaron la experiencia en el primer turno, mientras que un solo individuo realizó el ejercicio en el turno de tarde.

El experimento tuvo lugar entre el 23 de septiembre y 2 de octubre de 2019 para la conducción habitual (non eco) y entre el 9 y 18 de octubre del mismo año para la conducción eficiente (eco). Entre ambos periodos se imparte la formación eco-driving a los conductores de la entidad pública.

2.1.4. Recolección de datos experimentales

Para el ejercicio de campo de la investigación se emplearon vehículos de tipo comercial, en este caso furgonetas diésel, con similitudes en sus características técnicas, tres de ellas pertenecientes a la gama Kangoo de la marca automovilística Renault y la cuarta correspondía a la gama Partner de la marca Peugeot (tabla 1). Los vehículos comerciales representan aproximadamente el 20% de los automóviles activos en la ciudad de Cáceres (DGT,2019).

CARACTERÍSTICAS	PEUGEOT	RENAULT
Clasificación comercial	PARTNER 1.6 HDi 75	KANGOO 1.5 DCi 70 CV
Tipo de cambio de marchas	Manual (5)	Manual (5)
Masa máxima autorizada	1960	2956
Potencia (CV)	75	70
Dimensiones (LxWxH) (mm)	4380 x 2890 x 1801	4213 x 2133 x 1799
Asientos	2 – 5	2 – 5
Emisiones (g de CO2/km)	143	147
Clasificación por consumo relativo	C	D

Tabla 1. Características técnicas de los vehículos utilizados en la investigación

2.1.5. Medición de variables

Para la obtención y almacenamiento de los parámetros necesarios para el posterior estudio, se dispuso a bordo de los vehículos el dispositivito ODB-Key, de esta manera se pudo obtener un perfil de conducción para cada automóvil. Se registró en todo momento la ubicación geográfica de los vehículos, de modo que se pudiera sintetizar de manera digital en el posterior análisis de datos. El proceso que sigue el sistema se representa a continuación:

Figura 2. Esquematización del proceso del sistema de obtención y almacenamiento de datos.

La obtención y almacenamiento de datos se resume en la tabla 2.

PROCESO	OPERADOR	FUNCIÓN
1	OBD-Key	Instalación en vehículo
2	OBD-Key	Obtención de datos
3	OBD-Key	Envío de datos a la aplicación
4	App	Almacenamiento y geolocalización
5	PC	Tratamiento de datos

Tabla 2. Características técnicas de los vehículos utilizados en la investigación

Los efectos de la conducción eficiente se evaluarán por un lado comparando el consumo de combustible y emisiones de CO_2 a la atmósfera y por otro, analizando los parámetros de conducción que tienen mayor influencia en el consumo. Según Coloma et al. (2018) y posteriormente Lois et al. (2019), los parámetros que tienen una mayor influencia en el consumo y que son capaces de representar más del 80% del consumo de fuel son la velocidad media, las revoluciones por minuto (rpm) medias y las aceleraciones y deceleraciones superiores e inferiores a 0,83 m/s2 respectivamente. Además de estos valores que justifican el consumo se registran otros parámetros que se consideran de interés para caracterizar las distintas rutas por su ubicación (posicionamiento GPS) y situación del tráfico (tiempos de recorrido y número de paradas). La siguiente lista muestra los parámetros que finalmente fueron utilizados para el análisis antes y después de que los conductores recibieran la formación sobre conducción eficiente:

Posición GPS (longitud y latitud) y distancia recorrida (km).
Tiempo de viaje (h) y número de paradas.
Velocidad media (km/h).
Rpm medias, aceleraciones y deceleraciones medias (m/s^2).
Consumo de combustible (l/100 km).

2.2. Segunda fase: Análisis y estudio de los datos recolectados.

En la fase de gabinete se reciben los datos almacenados que se procesan a partir de hojas de cálculo. Estos datos se filtran para eliminar los registros erróneos y las paradas para realizar los repartos. Posteriormente, es necesario llevar a cabo una discretización de los distintos parámetros seleccionados y organizarlos de modo que se puedan realizar sobre ellos cálculos como sumatorios, promedios, ponderaciones o cambios de unidades que nos permitan obtener resultados equiparables unos con otros y que nos faciliten la obtención de conclusiones fiables.

A la hora de enfrentarte al tratamiento de datos, en primera instancia nos encontramos con varios documentos pertenecientes a cada conductor, donde se registran por cada segundo de tiempo cada uno de los parámetros que monitoriza el OBD-Key.

Para poder sintetizar esta cantidad de información, se hace necesario obtener los resultados representativos de cada jornada de trabajo, de modo que obtengamos los resultados de los parámetros correspondientes a cada día de trabajo de cada conductor.

Una vez generadas estas hojas de cálculo, se comienza a realizar comparaciones entre las conducciones no ecológicas y las ecológicas entre los mismos vehículos, para ello, los datos más relevantes son el consumo de combustible y las emisiones de CO_2 a la atmósfera. Como cada conductor recorrió distancias diferentes y manejó el vehículo a velocidad también diferente, se hace necesario obtener los parámetros de consumo y emisiones de manera ponderada respecto al tiempo de trayecto de cada jornada. Así, los resultados se comparan con conducciones llevadas a cabo por el mismo conductor antes y después de la formación eco.

El compendio de datos obtenidos también permitió analizar pequeños tramos de rutas realizadas por los automóviles (microtrips). Para ello se obtenían los tiempos iniciales y finales en puntos truncados de los itinerarios de distribución, utilizando en este caso un software de almacenamiento y análisis de geolocalización (QGis, 2020), en el cual se podía apreciar gráficamente los recorridos realizados por los conductores y obtener datos de cada punto de trayecto. Este proceso permitía investigar sobre los beneficios del eco-driving en trayectos más pequeños.

Finalmente se realiza una encuesta a los conductores que permite valorar el estado de ánimo y actitud del conductor a aplicar las técnicas de conducción eficiente. Con los puntos descritos en este apartado sobre la metodología con la que se gestionó el proceso de obtención y análisis de datos, se pueden obtener resultados que nos permitan establecer conclusiones satisfactorias acerca de esta investigación.

3. RESULTADOS Y DISCUSIÓN

Los datos estadísticos del experimento han sido los incluidos en la tabla 3:

VEHÍCULO	MODO DE CONDUCCIÓN	DISTANCIA RECORRIDA (km)	TIEMPO DE CONDUCCIÓN (h)	Nº REPARTOS REALIZADOS
4121KDW	NON-ECO	195,241	46,938	379
	ECO-DRIVING	346,600	68,014	584
4414JKD	NON-ECO	123,100	33,144	266
	ECO-DRIVING	167,247	34,463	340
2790KRG	NON-ECO	96,840	31,665	328
	ECO-DRIVING	43,940	11,180	133
4118KDW	NON-ECO	176,766	24,782	245
	ECO-DRIVING	139,166	23,411	277
SUMA PARCIAL	NON-ECO	591,947	136,529	1218
	ECO-DRIVING	696,953	137,068	1334
TOTALES	NECO+ECO	1288,900	273,597	2552

Tabla 3. Distancias recorridas, tiempos de conducción y repartos realizados

Los repartos por tipo de zona (residencial o industrial) y por edad (mayores o menos de 45 años) se representan en la tabla nº4

REPARTOS POR ZONA			REPARTOS POR EDAD		
USOS	Nº REPARTOS	%	EDAD	Nº REPARTOS	%
Residencial	2424	95,28	Mayores de 45	1150	47,44
Industrial	120	4,72	Menos de 45	1274	52,56
TOTAL	2544*	100	TOTAL	2424*	100

*No se tiene registro del destino de todos los repartos realizados

Tabla 4. Distribución de los repartos por tipo de zona y edad.

3.1. Parámetros de conducción

En la tabla 5 se recogen por vehículo cada uno de los parámetros de conducción registrados en ambos tipos de conducción eco y non eco.

	MODO CONDUCCIÓN	VEHÍCULOS 4121KDW	4414JKD	2790KRG	4118KDW
VELOCIDAD MÁXIMA (km/h)	NON-ECO	40,619	47,069	31,696	61,122
	ECO-DRIVING	50,061	74,933	29,963	49,195
V95 (km/h)	NON-ECO	37,199	42,545	28,930	55,642
	ECO-DRIVING	44,566	68,072	28,288	44,692
VELOCIDAD MEDIA (km/h)	NON-ECO	17,008	19,947	15,305	30,288
	ECO-DRIVING	19,156	34,239	15,354	25,802
RPM MEDIAS	NON-ECO	1335,843	1224,952	1208,728	1744,645
	ECO-DRIVING	1451,565	1834,372	1286,472	1412,045
RPM MÁXIMAS	NON-ECO	2532,164	2849,191	1956,477	3004,262
	ECO-DRIVING	2802,280	3792,467	2012,363	2365,704
ACEL. MEDIA POSITIVA (m/s2)	NON-ECO	0,503	0,720	0,417	0,9120
	ECO-DRIVING	2,613	1,041	0,358	0,8100
ACEL. MEDIA NEGATIVA (m/s2)	NON-ECO	-0,518	-0,678	-0,434	-0,920
	ECO-DRIVING	-2,648	-1,013	-0,386	-0,782
ACEL. MÁXIMA POSITIVA (m/s2)	NON-ECO	2,013	2,906	1,503	4,072
	ECO-DRIVING	0,611	4,153	1,327	3,217
ACEL. MÁXIMA NEGATIVA (m/s2)	NON-ECO	-0,518	-2,515	0,417	-4,007
	ECO-DRIVING	-0,632	-3,730	-1,380	-3,469

Tabla 5. Parámetros de conducción para los distintos tipos de vehículo y conducción.

Eco-driving produce reducciones de rpm, velocidad y aceleraciones / desaceleraciones (Huang et al., 2018 y Saito el at., 2008). De los resultados obtenidos se puede concluir que solo el conductor 5 mejora sus parámetros de conducción con la conducción ecológica. Las velocidades, rpm y aceleraciones máximas y medias aumentan con la conducción ecológica en los parámetros de conducción de los otros 4 conductores.

La congestión o el estrés que implica la entrega de paquetes en el menor tiempo posible, hace que la mayoría de los conductores profesionales en el experimento no hayan obtenido mejoras en los parámetros de conducción al conducir eco.

3.2. Consumo y emisiones

La tabla 6 recoge los consumos y emisiones de CO_2 estimadas para cada uno de los vehículos y tipos de conducción.

	MODO CONDUCCIÓN	VEHÍCULOS 4121KDW	4414JKD	2790KRG	4118KDW
CONSUMO (l/100km)	NON-ECO	6,955	4,930	6,756	5,010
	ECO-DRIVING	4,918	4,005	6,807	5,071
EMISIONES DE CO2 (g/km)	NON-ECO	217,8500	150,186	205,201	157,891
	ECO-DRIVING	151,838	121,676	208,033	160,444

Tabla 6. Consumo y estimación de emisiones para los distintos tipos de vehículo y conducción.

El consumo de combustible y las emisiones de CO_2 muestran que la conducción ecológica en las ciudades pequeñas no es eficiente. El único conductor con parámetros de conducción ecológica ha obtenido un mayor consumo medio de combustible y mayores emisiones de CO_2. Tres de los otros cuatro conductores sin parámetros de conducción ecológica reducen el consumo de combustible y las emisiones. Esto muestra que en las ciudades pequeñas, las altas velocidades significan tiempos de viaje cortos que a su vez reducen el consumo medio de combustible (l/100 km) y, por tanto, las emisiones medias. La conducción ecológica reduce velocidades y aceleraciones, pero en ciudades pequeñas donde los recorridos son muy cortos, no reduce suficientemente el consumo instantáneo y esto provoca que los tiempos de conducción más largos produzcan un mayor consumo medio de combustible (l/100 km) y como consecuencia, mayor Emisiones de CO_2 a la atmósfera.

Esta afirmación coincide con Schall et al (2016), ya que no observaron mejoras en la reducción del consumo de combustible con conducción ecológica en una empresa de mensajería en Munich (Alemania). Sin embargo, estos resultados van en contra de la mayoría de las investigaciones realizadas hasta ahora con conductores no profesionales, ya que muestran resultados favorables en el consumo con conducción ecológica tanto en ciudades grandes como pequeñas, por ejemplo Dhaou (2011) logró un ahorro de combustible de aproximadamente un 20% con la conducción ecológica en 10 ciudades de Túnez y Andrieu et al. (2012) obtuvo un 11,3% de ahorro de combustible en una pequeña ciudad francesa llamada Pontchartrain.

3.2. Microtrips

Se ha realizado también un análisis por tipo carretera recorrida (local, colectora, perimetral, variante e interurbana) para ver si se pueden sacar conclusiones sobre la conducción eficiente de los conductores profesionales por tipo de ruta. Las características de las micro rutas seleccionadas (micro trips) se adjuntan en la tabla 7.

TIPO DE VÍA	Nº RUTA	ASIGNACIÓN DEL TRAMO	DESCRIPCIÓN	LONG. TRAMO	LÍMITES VELOC.
LOCAL	1	RONDA MARQUES DE VADILLO	UN CARRIL POR CADA SENTIDO, ARCÉN A AMBOS LADOS	550 m	50 km/h
COLEC-TORA	2	AV. HISPANIDAD – INTERSECCIÓN ANTONIO HURTADO	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA, APARCAMIENTOS A AMBOS LADOS	600 m	30 – 50 km/h
	3	AV. RUTA DE LA PLATA	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA CON VEGETACIÓN	900 m	30 – 50 km/h
PERIME-TRAL	4	ROT. HERNÁN CORTÉS – PLAZA DE TOROS	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA, APARCAMIENTOS A AMBOS LADOS	950 m	50 km/h
	5	ROT. C. DIOCESANO – ROT. UNIV. LABORAL	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA, UNA PARTE CON APARCAMIENTOS A AMBOS LADOS	1200 m	50 km/h

TIPO DE VÍA	Nº RUTA	ASIGNACIÓN DEL TRAMO	DESCRIPCIÓN	LONG. TRAMO	LÍMITES VELOC.
VARIAN-TE	6	ROT. CASAR DE CÁCERES – GLORIETA G. CORDEL MERINAS	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA CON VEGETACIÓN, LATERALES PROTEGIDOS CON GUARDARAÍLES	1000 m	50 – 80 km/h
	7	RONDA NORTE	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA CON VEGETACIÓN, LATERALES PROTEGIDOS CON GUARDARAÍLES	2200 m	50 – 80 km/h
INTER-URBANA	8	ROTONDA CABEZARRUBIA – POL. CAPELLANÍAS	DOS CARRILES POR CADA SENTIDO SEPARADOS POR MEDIANA CON VEGETACIÓN	950 m	80 km/h

Tabla 7. Características de las micro rutas seleccionadas.

Las distancias de conducción, tiempos de recorrido y repartos realizados en las micro rutas seleccionadas se adjuntan en la tabla 8.

TIPO DE VÍA	Nº RUTA	MODO	DISTANCIA (km)	TIEMPO (h)	Nº
LOCAL	RUTA 1	NON-ECO	1,196	0,047	4
		ECO-DRIVING	3,322	0,147	10
COLECTOR	RUTA 2	NON-ECO	1,514	0,185	9
		ECO-DRIVING	0,788	0,118	5
	RUTA 3	NON-ECO	6,287	0,304	13
		ECO-DRIVING	1,52	0,09	2
PERIMETRAL	RUTA 4	NON-ECO	7,181	0,632	18
		ECO-DRIVING	11,622	1,323	18
	RUTA 5	NON-ECO	3,003	0,13	5
		ECO-DRIVING	1,892	0,103	5
VARIANTE	RUTA 6	NON-ECO	4,502	0,121	6
		ECO-DRIVING	2,822	0,084	5
	RUTA 7	NON-ECO	2,286	0,092	6
		ECO-DRIVING	5,512	0,139	11
INTER-URBANA	RUTA 8	NON-ECO	9,796	0,168	13
		ECO-DRIVING	4,506	0,085	6
SUMA PARCIAL		NON-ECO	35,766	1,679	74
		ECO-DRIVING	31,983	2,088	62
SUMATORIO		EC+NE	67,749	3,767	136

Tabla 8. Distancias recorridas, tiempos de conducción y número de repartos realizados en las micro rutas seleccionadas.

Los parámetros de conducción registrados en las micro rutas antes y después de la formación en conducción eficiente se incluyen en la tabla 9.

	MODO	LOC.	COLECTOR		PERIMET.		VARIANTE		INT. URB.
		R 1	R 2	R 3	R 4	R 5	R 6	R 7	R 8
VELOC. MÁXIMA (km/h)	NON-ECO	51,40	43,21	65,89	51,92	76,91	83,37	60,43	87,99
	ECO	67,82	44,36	41,67	52,85	70,58	80,71	84,52	51,37
V95 (km/h)	NON-ECO	50,48	40,76	63,61	47,79	75,44	81,29	58,04	86,79
	ECO	66,42	42,66	41,06	47,15	69,37	79,04	81,64	50,96
VELOC. MEDIA (km/h)	NON-ECO	39,61	26,57	37,19	13,42	57,04	57,59	38,95	73,59
	ECO	44,85	25,86	26,87	27,73	42,81	64,73	56,63	45,48
RPM MÁXIMAS	NON-ECO	2520	2461	2296	2409	2372	3057	2776	2859
	ECO	3205	2233	2159	2481	2426	2592	3077	2234
RPM MEDIAS	NON-ECO	1869	1326	1522	1365	1745	2049	1962	2154
	ECO	2428	1231	1423	1483	1479	1882	2293	1833
ACEL. MÁXIMA POSITIVA (m/s2)	NON-ECO	1,716	2,124	2,407	2,631	1,894	1,696	2,601	1,764
	ECO	2,215	2,796	1,067	4,944	1,871	1,629	2,619	0,806
ACEL. MÁXIMA NEGATIVA (m/s2)	NON-ECO	-1,182	-1,621	-2,683	-2,66	-2,69	-2,939	-3,42	-2,69
	ECO	-1,768	-2,249	-1,493	-3,337	-2,366	-1,725	-3,392	-1,31
ACEL. MEDIA POSITIVA (m/s2)	NON-ECO	0,608	0,615	0,638	0,825	0,652	0,575	0,775	0,558
	ECO	0,662	0,729	0,292	0,899	0,689	0,551	0,905	0,290
ACEL. MEDIA NEGATIVA (m/s2)	NON-ECO	-0,496	-0,553	-0,697	-0,748	-0,793	-0,767	-0,855	-0,85
	ECO	-0,59	-0,651	-0,338	-0,817	-0,711	-0,566	-1,094	-0,29

Tabla 9. Parámetros de conducción en las micro rutas seleccionadas.

Las investigaciones realizadas en diferentes tipos de carreteras normalmente reducen la velocidad, las rpm y las aceleraciones en la conducción ecológica (Beusen et al., 2009), sin embargo, hay otros estudios que muestran que en carreteras congestionadas, la conducción ecológica no reduce estos parámetros (Garcia-Castro y Monzón, 2014).

La tabla 10 incluye los consumos y la estimación de emisiones para las micro rutas seleccionadas.

	MODO	LOC.	COLECTOR		PERIMET.		VARIANTE		INT. URB.
		R 1	R 2	R3	R 4	R 5	R 6	R 7	R 8
CONSUMO (l/100 km)	NON-ECO	3,251	7,608	8,819	11,49	8,417	7,573	6,977	4,534
	ECO	5,844	13,73	9,931	17,27	8,474	8,545	4,497	4,191
EMISIONES DE CO_2 (g/km)	NON-ECO	97,49	236,2	270,6	361,2	259,2	227,8	218,1	139,8
	ECO	177,7	424,9	307,2	534,0	261,5	268,2	140,4	128,2

Tabla 10. Consumos y estimación de emisiones en las micro rutas seleccionadas

Los resultados de los micro viajes muestran que la conducción ecológica es más eficaz en carreteras menos congestionadas y con mayor capacidad (variante e interurbana). Las vías urbanas que sufren más congestión de tráfico (local y colector) no son efectivas para ahorrar consumo de combustible y emisiones de CO_2 en modo eco. La perimetral por su carácter mixto urbano y periurbano no deja claro el beneficio de la conducción ecológica sobre ella. Por lo tanto, sería bueno que el conductor profesional eligiera las rutas menos congestionadas y de mayor capacidad para que la conducción ecológica sea más efectiva.

Coloma et al en Cáceres (2017) y posteriormente Yang et al en Madrid (2018), obtuvieron resultados similares a los encontrados en esta investigación, ya que el ahorro de combustible aumentó con la capacidad de la carretera. Sin embargo, también hay otros estudios (Perez-Prada y Monzón, 2017) que muestran que las carreteras de alta capacidad pero congestionadas no son eficientes con la conducción ecológica.

3.3. Encuestas

La tabla 11 recoge el resultado de las encuestas realizadas después de la conducción.

PREGUNTAS	MODO	Nº	RESPUESTAS						
			1	2	3	4	5	6	7
EL MANEJO LE HA RESULTADO: FÁCIL (1) – DIFÍCIL (7)	NON-ECO	18	15	1	1	1	0	0	0
	ECO	15	15	0	0	0	0	0	0
EL ENTORNO DE CONDUCCIÓN ERA: FÁCIL (1) – DIFÍCIL (7)	NON-ECO	18	12	2	3	1	0	0	0
	ECO	15	10	4	1	0	0	0	0
DURANTE LA CONDUCCIÓN ESTABAS: ABURRIDO (1) - ENTRETENIDO (7)	NON-ECO	18	3	1	1	1	2	8	2
	ECO	15	3	0	1	0	0	6	5
DURANTE LA CONDUCCIÓN ESTABAS: RELAJADO (1) - ESTRESADO (7)	NON-ECO	18	5	8	1	3	1	0	0
	ECO	15	6	5	1	0	0	1	2

Tabla 11. Encuesta realizada a los conductores en todos los viajes registrados

La mayoría de los conductores (15 de 18) consideran que conducir es fácil. Esto es lógico ya que son conductores profesionales. Por otro lado, las condiciones de conducción también han sido “fáciles”, lo que significa que la congestión del tráfico y otros agentes externos no han afectado la forma de conducir de los conductores profesionales.

Finalmente, se ha aclarado si el modo de conducción estresa al conductor profesional. Los resultados muestran que la mayoría de los conductores (13 de 15) estaban relajados durante ambos modos de conducción, lo que significa que la conducción ecológica no aumenta su estrés. Sin embargo, la necesidad de realizar una entrega en un tiempo determinado hace estresar al conductor profesional y es muy difícil modificar su estilo de conducción para aplicar técnicas de conducción ecológica. García et al (2018) en su experimento observaron que los conductores no profesionales tampoco aumentaban su nivel de estrés cuando conducían en modo eco. No obstante, la conducción era más eficiente (en ahorro de combustible y emisiones de CO_2) cuando el conductor era más joven, por lo que sería necesario enseñar estas técnicas de conducción desde las escuelas de conducción (Stromberg, 2015).

4. CONCLUSIONES

Los países desarrollados intentan promover una gestión vial eficiente mediante el uso de tecnologías que reducen las emisiones de GEI en las ciudades, implementando modos de conducción para los conductores y decisiones de viaje sostenibles. Las ciudades tienen diferentes métodos para lograr estos objetivos ambientales, pero ninguno puede alcanzarse con éxito sin la cooperación de los conductores. Las políticas medioambientales deben ser aceptadas por el público en general, y algunas de ellas dependen fundamentalmente de su forma de conducir (eco-driving) y de cómo planifican sus viajes (eco-routing). La investigación hasta la fecha sobre conducción ecológica se ha centrado generalmente en las grandes ciudades debido a sus graves problemas de congestión. Sin embargo, las ciudades pequeñas también enfrentan estos problemas y deben ayudar a reducir las emisiones de GEI, que es un objetivo mundial.

En esta investigación se realizó un estudio sobre la efectividad de la conducción ecológica con conductores profesionales en una ciudad pequeña y poco congestionada como es Cáceres. Los resultados obtenidos confirmaron que la conducción ecológica con entrega por mensajería no suele generar ahorro de combustible. Un análisis de micro viajes refleja una tendencia en el ahorro de combustible a medida que aumenta la capacidad de las carreteras. La figura 12 resume las principales conclusiones de esta investigación.

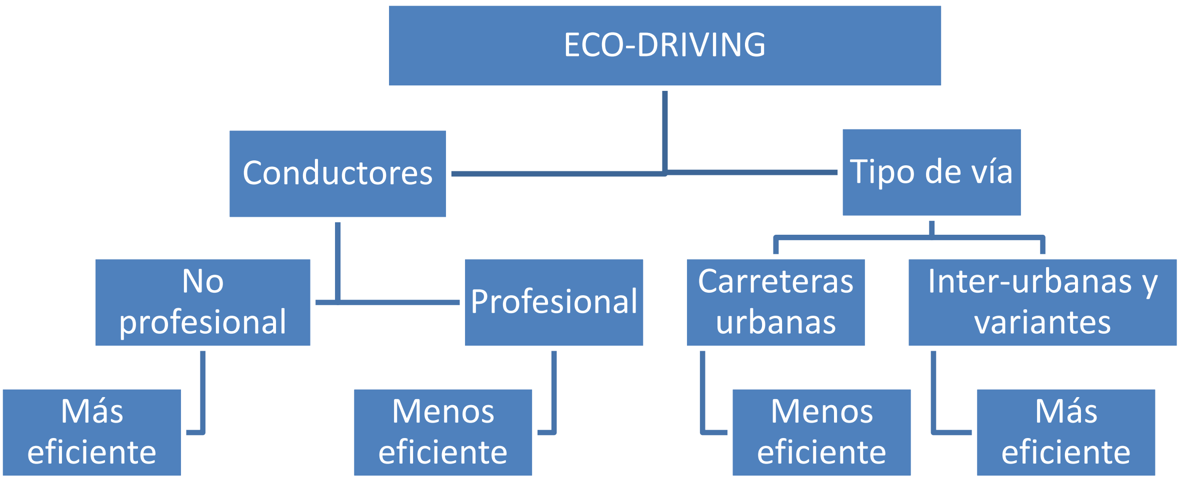

Figure 12. Conclusiones principales de la investigación.

En investigaciones futuras, los efectos de la conducción ecológica en los conductores profesionales podrían estudiarse con incentivos (monetarios y no monetarios), ya que Schall y Mohnen (2015) lograron ahorros de combustible de alrededor del 5% con los conductores de una empresa de flotas que había recibido incentivos. También podrían estudiarse otros tipos de vehículos ampliamente utilizados en el reparto por mensajería, como las motos (Seedam et al., 2017).

Además, también es necesario observar el efecto de la conducción ecológica en los vehículos eléctricos.
Este tipo de estudios requieren modelos teóricos de consumo de energía como la Potencia específica del vehículo (VSP) (Pitanuwat et al., 2020).

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PREDICTING ON-TIME DELIVERIES IN TRUCKING: A MODEL BASED ON THE WORKING CONDITIONS OF DRIVERS

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ABSTRACT

Over a period of two years, 26.3 thousand road freight shipments were recorded. The records include information about truckload companies, drivers, and the causes of non-compliance and delays in deliveries. Logistic regression based in working conditions as independent variables was used to predict non-compliance deliveries attributed to cargo drivers. Results show that vehicle type, medical coverage and social security, level of stress, work dissatisfaction, and transit time were strongly associated with out-of-time-delays in deliveries. The proposed model is a promising tool to improve the performance of truckload companies and it may motivate to benefit working conditions of truckers.

1. INTRODUCTION

On-Time Delivery (OTD) is one of the key performance indicators in transportation service companies. Failure to comply with OTDs can lead to breakdowns in supply chains, loss of customers and, in general, high costs for transportation that are assumed both in the short and long term. Consequently, leading companies in the supply chain use data analysis to optimize their operations and prevent disruptions in their processes (Sanders, 2016); however, identifying the causes of deviations and preventing non-compliance in deliveries are an obligated task for companies involved in the transport of goods, since it is a highly competitive market with increasingly narrow profit margins.

In this regard, in the international literature there are studies to predict the arrival time and delays of trucks. Van der Spoel, Amrit, and Van Hillegersberg (2017) carried out a review of the literature in which they found 82 investigations related to predictors for arrival time.

In this investigation, a classification of the factors found in thirteen categories was made: congestion, weather, speed, distance, type of cargo, type of truck, time of day (week, month, and year), cumulative previous deviation, accidents, road work, traffic signal failures, road condition, and driving style.

The authors conclude that congestion, time of day, and accidents are the most frequently mentioned factors and that, in a negative way, they are the ones that most influence travel time. However, it stands out that, despite the relationship with the human factor, no variable refers directly to the working conditions of drivers.

Despite the fact people have a crucial effect in determining a successful supply chain (awcett, Magnan, & McCarter, 2005), the absence of the working conditions of truck drivers in the prediction models of on-time deliveries appears to be the predominant situation. It is undeniable that drivers are a decisive link in transport chains; and it has been established (Kemp, Kopp, & Kemp, 2013) that some working conditions of drivers lead to emotional exhaustion and, therefore, reduce commitment to the organization, negatively affect the service that drivers provide to the customer and, therefore, cause delays and non-compliance in deliveries on time.

Furthermore, previous studies have indicated that late deliveries are one of the main repercussions of drivers' working conditions in the supply chain (Berrones, González, Lámbarry, & Rocha, 2020). The driving activity subjects workers to risks and demands, derived from the organization and technical division of labor, which implies strenuous work rhythms, intense working hours, market structures and lifestyles that determine the health / illness of drivers and affect their physical and mental health (Berrones, 2017; Berrones & González, 2018). Likewise, these investigations focused on Mexican truck drivers have stated that drivers are in precarious working conditions, do not have social security, are prone to diseases, have high stress levels, are dissatisfied with their work, and are subjected to derived workloads work organization, which include the area where they work, the type of vehicle, the size of the company and the type of relationship they have with it (Berrones, 2017; Berrones et al., 2020; Berrones & González, 2018).

Then, the questioning arises of how the working conditions of the drivers of the freight transport are related in their performance, specifically, in the deliveries on time. In this way, this study aims to explore the relationship between work and drivers' performance, under the assertion that working conditions can explain out-of-time deliveries. Thus, a case study was carried out in a manufacturing company that seeks to reduce non-compliance in deliveries caused by causes attributed to drivers and, based on the availability of variables that determine their working conditions, the binary logistic regression was used to model and predict truckers' on-time deliveries.

2. METHODS

2.1 Description of variables

For two years, data of 26,312 shipments were kept track, that of a company which manufactures lightweight construction systems in Mexico. Variables such as the labor relationship (employee or owner-operator), access to social security, age and the results of subjective assessment of stress and the satisfaction of the truck drivers were used to determine the factors that affect the performance in the goods deliveries.

The variables considered in the study were determined according to previous studies on working conditions of trucks in Mexico (Berrones, 2017; Berrones & González, 2018), and with the availability of information from the company in the case study. Finally, eleven independent variables, which are shown in figures 1 and 2, were considered.

After examining the characteristics of the statistical distribution of the variables involved in the analysis, the bivariate and multivariate relationships, and the analysis of the differences between groups the data were tested in several models of multivariate type.

Finally, given that the dependent variable, which was named non-compliance of deliveries (Y_{ncd}) has the characteristic of being dichotomous (correct or incorrect delivery) a logistic regression approach was found adequate. In this way, to examine the contribution of the independent variables (figures 1 and 2) logistic regression based in working conditions as independent variables was used to predict on-time deliveries attributed to cargo drivers, its significance was verified, and a model of the parsimonious type was constructed.

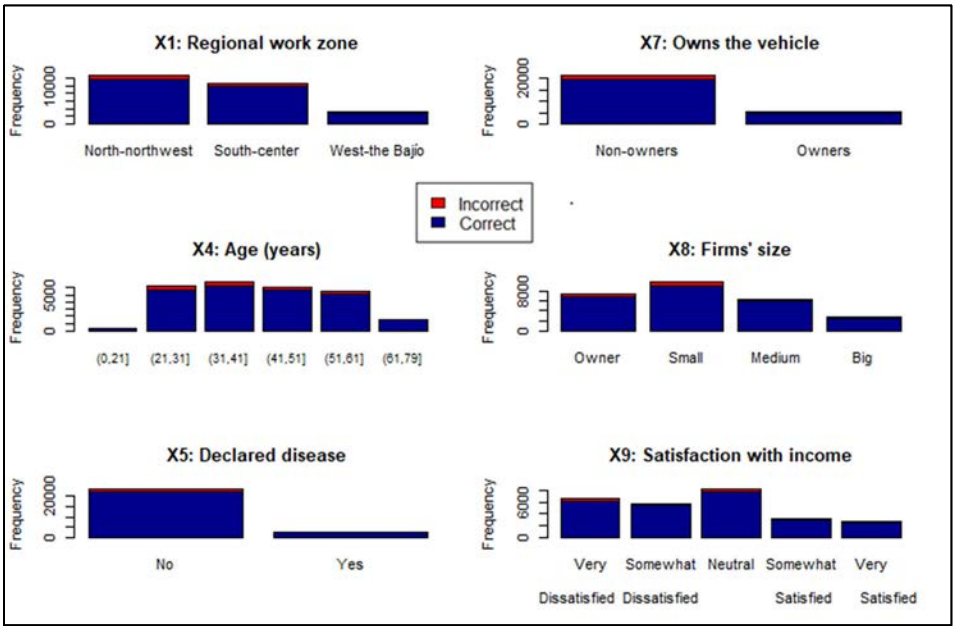

Fig. 1 Considered variables that are not in the final equation

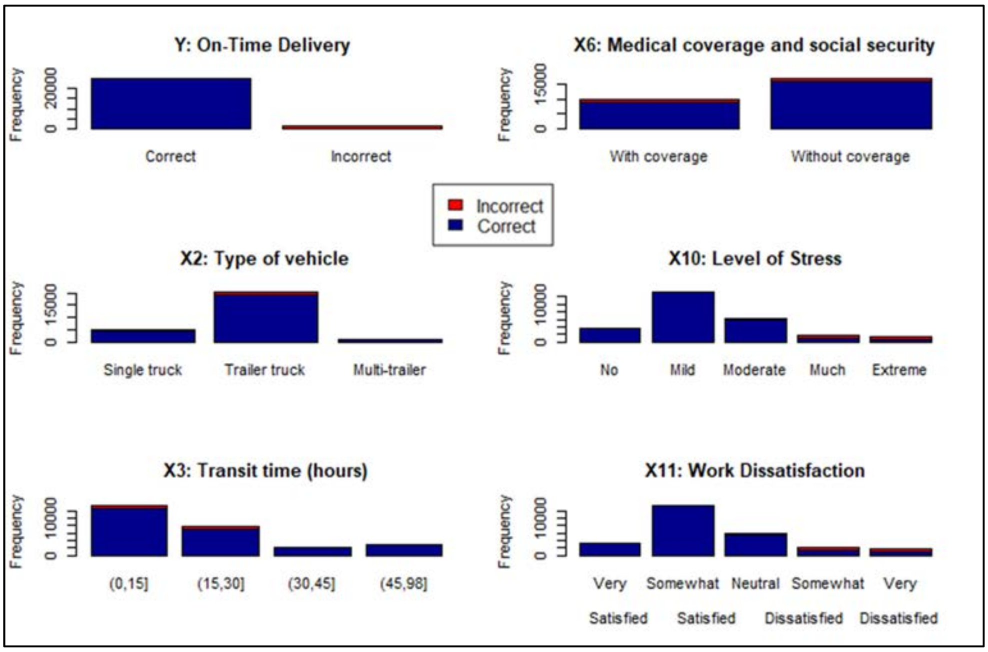

Fig. 2 Variables in the equation

2.2 The sending company

The manufacturing company, which produces approximately 80% of the total lightweight construction systems that are marketed in Mexico, makes its shipments in heavy vehicles that are loaded in three plants, located in the north, east and west of the country. The different locations manufacture the same products, with the same quality standards, and are shipped, to be distributed throughout the national territory under the same process in three types of vehicles: single trailer 6-axle truck (77.37%), single unit 3-axle trucks (18.17%) and multi-trailer 9-axle trucks (4.46%), with a capacity of 19, 30 and 56 tons of payload, respectively.

2.3 Truckload Trucking companies

The manufacturing company does not have its own vehicle fleet, so all the transportation of the goods is carried out as an outsourced activity. In total, 52 truck companies were used and were classified by the number and type of vehicles available (company size), the location or work area in which they provide the service (north-northwest, south-center and west-The Bajío), the access to social security, and vehicle ownership (is or not owner-operator).

2.4 Systematization of data

The information used in this study was obtained through systematic data recording, from a module named Shipment System -programmed and adapted as a complement to a system of Enterprise Resource Planning (ERP)- and whose main objective is creating indicators for transport services, that the sending company subcontracts. The data were divided into three components: shipment tracking, delivery information, and perception of the driver.

The shipment tracking module records the timetable the driver arrives at the loading point and is available to load, the time it is positioned on the loading platform, the start and end time of the loading process, and the departure time in which drivers start the trip to the final destination. In all these processes, several users use different computers and record the schedules by selecting a checkbox, which cannot be manipulated by the users, and where the schedules are captured in real time. These data are compared with the planned schedules and the fulfillment of time of the truck companies and loading dock personnel is verified.

The delivery information is verified through global positioning systems (if the carrier has the service) or telephone reports made by the drivers. Subsequently, they are verified through the delivery documentation (delivery note), in which the client signs the receipt, reports missing or apparent damage to the materials and establishes the date and time at which the carrier arrived, same that is contrasted with the date in which the delivery was promised.

Finally, to assess the perception of the driver, the documents included three mandatory Likert-type questions, with a scale of one to five, which assessed the level of work stress, dissatisfaction at work and satisfaction with income. Other information about drivers, such as the name, age and if he has social security or medical coverage, was previously entered in the drivers register and during the planning of the shipments.

For the logistic regression, R software and glm function (Fitting Generalized Linear Models) were used, and it was used as a dependent variable and it was coded with a one (Y=1) to shipments that were delivered incorrectly, that is, with damages, out of time, or any cause of non-compliance; and with a zero (Y=0) for the shipments that were delivered in a timely manner (on-time-delivery). This classification includes only the shipments whose causes of non-compliance were attributed to the carriers, and the derivatives for any other reason, such as programming errors or problems in the loading areas are excluded.

Finally, the logistic regression coefficients were used to elaborate an equation that allows calculating the probability of non-compliance in the timely deliveries of truck drivers. In this way, the categories or values taken by the variables that generate both the lowest and the highest probability of non-compliance were identified and, therefore, can be considered protective or risk factors for fulfillment of on-time deliveries.

3. RESULTS

De Of the 26,312 shipments, almost 14% (3,635) were registered as inaccurate deliveries that included any cause and not just transportation issues; that is, they were delivered with some missing, wrong materials, damaged or the promised delivery schedule was not met.

Of the non-compliances, 1,790 (6.81%) were attributed to causes related to the carriers; represent the event of interest and were coded with *Y*=1. The rest of the shipments were considered correct or on-time and were coded with *Y*=0.

The shipments frequency classified by correct or incorrect delivery is shown in figures 1 and 2. It can be seen that the highest percentage of incorrect deliveries occurs in small (2.6%) and owner-operators (2.4%) firms, in the south-center area (3.9%) and in the 6-axle truck type vehicle (5.1%). As for trucks drivers, just over a quarter (25.5%) are owners of the vehicle (owner-operator), a fifth (20.6%) have no social benefits or medical coverage, on average they have an age of 40.7 ± 12.99 years, and 8.4% indicated having a permanent disease; mainly of cardiovascular or chronic degenerative type. In addition, it can be seen that drivers who indicated an extreme level of stress got a higher frequency in inaccurate deliveries, whereas this does not seem to be related to drivers who were very dissatisfied with work or very dissatisfied with income.

3.1 Logistic regression and the probability model of non-compliance

Using R software, the parameters associated to Logistics Regression were calculated. In this way, Omnibus tests of model coefficients showed the probability of obtaining chi-square statistic (7,867.237), so that there is no effect of the independent variables, taken together, on the dependent variable ($p<.001$).

Meanwhile, the Hosmer-Lemeshow test of the goodness of fit suggested the model is a good fit to the data as $p=0.075$ and the hypothesis null was not rejected ($p>.05$). Thus, in general, the model has a high specificity (98.5%) and an average sensitivity (65.6%), so that the model generated through logistic regression offers an overall sample accuracy of 96.3% in the prediction of the event of out-of-time deliveries.

Table 1 provides variables in the equation in the final step; it contains estimated coefficients, standard error, the Wald statistic (*z* value), statistical significance and the Odds Ratio of the variables involved. Only five variables (figure 2) had statistical significance ($p<.05$); these are named: Transit time (X_3), Type of vehicle ($X_{2,j}$), Medical coverage (X_6), Level of stress ($X_{10,j}$), and Work dissatisfaction ($X_{11,j}$), strongly associated with the out-of-time deliveries.

Variable $X_{i,j}$	Estimate ($\beta_{i,j}$)	Std. Error	z value	Pr(>|z|)	Exp($\beta_{i,j}$)	95% C.I. for EXP($\beta_{i,j}$) Lower	Upper
βo	-5.42863	0.25954	-20.92	0.00	0.0044	0.0030	0.0070
$X_{2,2}$	0.43417	0.11673	3.72	0.00	1.5437	1.2280	1.9410
$X_{2,3}$	1.18485	0.21412	5.53	0.00	3.2702	2.1490	4.9750
$X_{3,Sc}$	-0.00659	0.00263	-2.51	0.01	0.9934	0.9880	0.9990
$X_{6,Di}$	-0.57919	0.09040	-6.41	0.00	0.5604	0.4690	0.6690
$X_{10,2}$	0.04556	0.25473	0.18	0.86	1.0466	0.6350	1.7240
$X_{10,3}$	1.43868	0.24363	5.91	0.00	4.2151	2.6150	6.7950
$X_{10,4}$	4.88311	0.23592	20.70	0.00	132.0407	83.1550	209.6650
$X_{10,5}$	5.73594	0.23803	24.10	0.00	309.8039	194.3030	493.9630
$X_{11,2}$	-1.44191	0.12298	-11.72	0.00	0.2365	0.1860	0.3010
$X_{11,3}$	0.25132	0.11734	2.14	0.03	1.2857	1.0220	1.6180
$X_{11,4}$	1.72793	0.13054	13.24	0.00	5.6290	4.3580	7.2700
$X_{11,5}$	2.29704	0.13718	16.75	0.00	9.9447	7.6000	13.0120

Otherwise = 0

Table 1. Variables in the Equation.

With the coefficients of regression β_i, which were significant, the model is formed to calculate the probability of non-compliance of deliveries (Y_{ncd}) it is presented below:

$$P(Y_{ncd}) = \left[1 + e^{5.42863 - \sum_{i=1}^{n}\sum_{j=1}^{m} x_{i,j}\cdot\beta_{i,j}}\right]^{-1} \quad (1)$$

Tabla 2 shows the codes for each of its explanatory variables in the final equation and shows the codes for each of its explanatory variables in the final equation.

Variable $X_{i,j}$	Variable name	Code
βo	(Intercept)	1: always
$X_{2,2}$	Single unit 3-axel truck	1: present, 0: otherwise
$X_{2,3}$	Trailer 6-axel truck	1: present, 0: otherwise
$X_{3,Sc}$	Transit time (hours)	Continuos
$X_{6,Di}$	Medical coverage and social security	1: present, 0: otherwise
$X_{10,2}$	Mild Stress	1: present, 0: otherwise
$X_{10,3}$	Moderate Stress	1: present, 0: otherwise
$X_{10,4}$	Much Stress	1: present, 0: otherwise
$X_{10,5}$	Extreme Stress	1: present, 0: otherwise
$X_{11,2}$	Work: Somewhat Satisfied	1: present, 0: otherwise
$X_{11,3}$	Work: Neither Satisfied nor Dissatisfied	1: present, 0: otherwise
$X_{11,4}$	Work: Somewhat Dissatisfied	1: present, 0: otherwise
$X_{11,5}$	Work: Very Dissatisfied	1: present, 0: otherwise

Di: Dichotomous variable
Sc: Scale variable

Table 2. Variables coding.

4. DISCUSSION

Some research about drivers has demonstrated that stress affects the performance of workers (Kemp et al., 2013; Lámbarry, Trujillo, & Cumbres, 2016). Thus, it is not surprising that stress has been included as one of the factors in the model and that, to the extent that it increases, the probability of non-compliance of on-time-delivery also increases.

However, given that the stress is caused by labor journeys that do not adequately meet the needs of rest, the lack of training to drive their vehicles or other job demands (Lámbarry et al., 2016); trying to reduce the level of stress is a complicated task, because it already includes practically all the categories of working conditions.

However, it is well-known that an important part of the working conditions of drivers is determined by the characteristics of the vehicle in which they carry out their activities and which has an important influence on their satisfaction (Ordaz & Maqueda, 2014). Thus, given that in Mexico 88% of the vehicle fleet is more than twenty years old (DGAF, 2018); delays are evident in terms of ergonomics, comfort, noise, safety and technological devices that facilitate driving; so the old vehicles not only affect the working conditions and the satisfaction of the drivers, but also put in constant disadvantage the competitiveness of the companies.

In addition to the concerns about the characteristics of vehicles, the satisfaction comprises other dimensions such as job demands, organizational issues, work environment, remuneration, the nature of the tasks performed and even personal situations. In this study, satisfaction was evaluated from two perspectives: 1) subjective work dissatisfaction, which evaluates in a general way the feelings and emotions of the drivers (variable $X_{11,j}$); and 2)

Satisfaction with income (variable $X_{9,j}$) which assesses wellness or pleasure in relation to the money that drivers receive for their work. However, only the subjective dissatisfaction was included in the model as it was significant (p<0.01), and the variable related to satisfaction with income was excluded (p=0.735). For these reasons, it is deduced that the drivers are satisfied with their income, although not with other working conditions that are directly related to the inaccuracy of on-time deliveries, so it can be said that the higher levels of work dissatisfaction are related to the risk of out-of-time deliveries.

On the other hand, although the income satisfaction variable was not significant and therefore was not included in the model, it is known that the drivers' income is related to experience and the ability to drive larger vehicles.

For example, a driver of vehicles with multi-trailers obtains more income than that of trailer trucks and, in turn, higher income than those of a single unit truck. However, the model shows that vehicles that move more cargo (Multi-trailer 9-axle trucks) are more likely to fail on deliveries.

Other studies indicate that the relative odds of death in road accident increases with the size of the vehicle, and it increases up to 3.42 times for heavier vehicles (Berrones, 2019). Although the model does not delve into accidents, vehicle crashes are considered as non-compliance of deliveries, and the results agree on the risk that the size of vehicles (variable $X_{2,j}$) imposes on the flow of the transport chain.

Given that larger vehicles are more efficient in terms of costs and using the different vehicle configurations depends on the planning and specific needs -such as order size or market conditions- it is not feasible, only to use smaller vehicles. Therefore, training and promotion of road safety must be promoted, so that progressively, drivers have new skills that compensate the dimensions of vehicles and reduce risks in the supply chain.

As for work time, although the proposed model does not directly contemplate the workday, days worked per week or resting time; it incorporates within the variables with statistical significance the programed transit time, which is part of the work time. Transit time is related with to out-of-time deliveries and calculates its highest probability of default (97.18%) in the scheduled deliveries of 36 hours (X_3=36). During that time, a worker drives from the origin to the destination, is present during loading and unloading, he feeds, rests, sleeps, and travels about one thousand kilometers. In Mexico, it is common for truck drivers to work by piecework and under a lax regulation of driving hours, which also does not include working hours outside the wheel.

Although many hours worked per day can lead bad temper, physical and mental fatigue, excessive drowsiness or anxiety, inattention at work and road fatalities (Kemp et al., 2013), it is known that, a common practice for Mexican drivers is to work up to 76 hours per week and without a proper rest (Berrones & González, 2018). Consequently, the effects of transit time and long hours of work, not only put the logistics processes at risk through the inaccurate deliveries, but are associated with adverse health effects, such as chronic diseases, or permanent physical and psychological injuries(Beek, 2012).

Also, despite the fact that several studies around the world indicate that driving is among the professions that have the greatest suffering and risk factors associated with their occupation (Tse, Flin, & Mearns, 2006), the subjective condition of disease (Variable X_5) did not show statistical significance (p=0.276) and was not considered for the final model.

While in the opposite way, the medical coverage and social security (Variable X_6) had statistical significance (p<0.01) and are considered for the calculation of probability of non-compliance. However, the percentage of drivers who have medical coverage is high compared to the national total of land transit workers, 63.12% for the case study versus 42.09% of the registered drivers in the National Survey of Occupation and Employment (Instituto Nacional de Estadística y Geografía, 2020).

It is important to note that, for this case study, the amount is influenced by the number of companies with more than thirty vehicles, 17.31% against 2.2% in the national total (DGAF, 2018); since, on the contrary of the companies of type owner-operator, greater-sized companies provide these benefits to its employees.

Consequently, having the benefit of social security (X_6), represents that the driver is entitled to several privileges, which include access to health services, vacation, bonuses, pension systems, among others; that guarantee certain compliance in working conditions.

Thus, in spite of the fact that in many cases, as a strategy of evasion of labor taxes, the companies register only minimum wage and not the real remuneration of the driver, and so that in case of temporary or definitive disability, or retirement, they only perceive a minimum part of the usual income; the lack of social security is a factor that participates in the calculation of the highest probability of default on deliveries.

Finally, in comparison with other logistic regression models, and even though they have different objectives, it can be observed that these have some similar variables. Martínez, Oviedo, and Luna (2015) to explain the quality of working life, included variables of job stability, physical load, income, and some other stressors.

It highlights the similarity of the variables related to stress and physical load which are also considered in the proposed model through variables like X11,j and X3. In addition, in the same way as in the proposed model, neither Martínez et al. (2015) nor Villar, Delgado, and Barrilao (2015) had a statistical significance for the variable income despite the fact that income correlates positively with subjective work conditions; so you can say that income is not as important as other working conditions for the behavior of workers.

Likewise, Villar et al. (2015) did not find statistical significance in the region where employees work but indicates that the autonomy of workers influences their satisfaction. Given that in the inaccurate deliveries model the vehicle ownership variable ($X_{7,j}$) represents work autonomy, it is possible to consider some contradiction between the two studies. However, the comparison study refers to administrative employees, while the current is based on drivers; and the driving activity already implies a certain autonomy in the work.

For that reason, despite the different objectives of this research, the multi-variant analysis with logistic regression models seem to be a good alternative to explain and predict the relationships between working conditions and workers' behavior.

5. CONCLUSIONS

Si Although the different groups of drivers share risks and demands derived from their labor process, their working conditions vary according to different factors determined by technological, social, cultural, economic and regulatory aspects, including labor laws and traffic regulations; so, some other variables not included in the model could be relevant.

However, the five variables used to calculate the probability of non-compliance of deliveries can be considered as dimensions that encompass other factors, and these are related to other working and health conditions, both physical and mental. Thus, for example, the variable $X_{8,j}$ (firms' size) is associated with the longevity of the vehicle fleet, given the larger companies have vehicles with models under six years, while those of the owner-operators are over twenty years.

Briefly, to extrapolate the model to other types of industries, it is necessary to include a greater number of variables (demographic, health, work and organizational, among others), to rule omissions of factors or relevant characteristics, typical of certain industries or products, which may affect the inaccurate deliveries and, therefore, the competitiveness of companies.

In addition, data considered subjective variables. It is recommended that objective methods, as validated tests, are used to measure and reduce the level of stress, job dissatisfaction and the other subjective variables.

However, this study shows the relevance of the working conditions of truckers in terms of how they affect non-compliance in the delivery of goods by road.

The results will be used to create a conceptual model that generalizes, in any type of industry, the effect of labor conditions on inaccurate deliveries. And, finally, despite the limitations of the model, the results show that proposed model is a promising tool to improve the performance of truckload companies and it may motivate to benefit working conditions of cargo drivers.

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EFFICIENCY OF SCALE OF LOGISTICS IN THE PRODUCTION OF THE WORLD'S COUNTRIES (2007-2018)

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ABSTRACT

Logistics is an important factor in global production. However, this does not mean that we know the impact of logistics on production and its efficiency in the short and long term.

The content of the paper reflects the results of research conducted on the contribution of logistics to the scale efficiency of the world's countries.

This research uses a production function of the type proposed by Mankiw et al. (1992) to study the effect of logistics on scale efficiency through data envelopment analysis (DEA) for one hundred and thirty-three countries in the world during the period 2007-2018. This research establishes that logistics is an important channel for improving scale efficiency for the countries of the world in view of the estimation results.

This research contributes to the literature by estimating the contribution of each of the components of the Logistics

Performance Index (LPI), developed by the World Bank, to scale efficiency.

The results highlight the significant impact of logistics on global efficiency. Available World Bank data show that a 1% increase in the logistics performance index increases the current global level of the efficiency scale by 0.42%.

1. INTRODUCTION: EFFICIENCY AND ECONOMIC GROWTH

Today, there is no doubt that logistics is an important factor in global production.

However, this fact does not mean that the impact of logistics on production and its efficiency in the short and long term is known. There is even some controversy about the extent to which logistics affects production and efficiency. Ultimately, this is what Stiglitz (2014) calls a puzzle about the nature of the comparative advantage of technologies and logistics.

There are very few studies that analyze the contribution of logistics, there are only two works, Coto-Millán et al. (2013) and Coto-Millán et al. (2016), both of which provide an approximation of the contribution of logistics to economic growth and global technical efficiency. Even more striking is the lack of studies and research on the impact of logistics since the crisis of recent years.

An important question is how to accurately describe the aggregate production function.

Output growth is typically explained as the accumulation of factor inputs and growth in total factor productivity. Apart from the basic factors of production, growth accounting looks for additional determinants that can explain growth and efficiency. This leads to a regression that treats all determinants of output growth as inputs, which is conceptually incorrect, as many determinants that can be included can only indirectly affect output production (Miller and Upadhyay (2000)). However, using Data Envelopment Analysis (hereafter DEA) we can detect additional determinants of output growth (beyond the input factors) that affect the efficiency of real inputs, physical capital, human capital and employment, and thus directly affect the productivity factor.

First, by estimating the overall scale efficiency through DEA techniques, taking as a starting point the growth model proposed by Mankiw et al. (1992).

Secondly, by assessing the impact of global logistics and its components as explanatory variables of the global scale efficiency of the different countries. The objective is to analyse the impact, at least in part, of logistics on the overall scale efficiency of world production.

This question is considered of great interest, given that progress in logistics is one of the most significant social and economic issues in recent decades, to the extent that it has created what some call a new revolution in production, storage, distribution and transport.

For this purpose, and given data limitations, a panel of data from the years 2007-2010-2012-2014-2016-2018 for 133 countries has been studied.

According to Farrel's (1957) classical definition, an economy is considered technically efficient if it obtains the maximum achievable output (outputs) with the resources (inputs) used and the technology available. Graphically, this can be understood by viewing output growth from the perspective of a production possibilities frontier where countries may be operating within and, where the distance to the frontier reflects technical inefficiency (Ghosh and Mastromarco 2013).

The frontier literature is quite extensive and can be roughly divided into two groups according to the method chosen to estimate the production function frontier, namely deterministic versus stochastic frontiers (SFA) .

It is well known that the first work applying SFA and data envelopment analysis (DEA) to economic growth was by Rao and Coelli (1998). The authors conducted an updated analysis of productivity convergence and inequality around the world. Their finding showed that transition to thrift achieves inefficiency reduction in planned economies.

Following the analysis of Technical Efficiency (hereafter TE), Delgado and Álvarez (2003) conducted a study for the EU-15. The authors used the SFA to explore the determinants of TE in European economies.

The results of this research, estimating a translog function, show that larger endowments of public capital and education can facilitate access to productive activity at efficient levels for their members.

Deliktas and Balcilar (2005), using DEA, conducted a production frontier for one hundred and thirty countries over the period 1991 to 2000; however, they eventually focused on estimating TE for twenty-five transition countries. Their results revealed that public capital had a positive impact on private sector efficiency.

Lam (2010) used SFA methods to conduct a cross-sectional analysis of the role of institutions in TE in countries around the world. This research concluded that institutions play a positive role.

Alonso and Aubyn (2010) estimated a panel-based TE frontier for the output of the nineteen EU countries for the years 1970, 1980, 1990 and 2000. The authors used stochastic frontiers and semi-parametric approaches with the calculation of Malmquist productivity indices. The main conclusion was that inefficiency could be explained by government efficiency in investing in net capital stock with a positive coefficient.

Oliveira-Pires and Garcia (2012) estimated a world production function as well as its frontier for the period 1965 -2000, concluding that there was a set of explanatory variables that determined that of each country. Using a similar methodological approach, Ghosh and Mastromarco (2013) showed that the impact of human capital was important in increasing efficiency through trade flows and foreign direct investment flows, while immigration to countries richer in human capital improved their efficiency relatively more than immigration to countries with lower human capital.

2. INFORMATION AND COMMUNICATION TECHNOLOGIES, EFFICIENCY AND ECONOMIC GROWTH

Stiglitz (2014) stresses that the current situation is analogous to the developments that took place in the 1980s with the use of personal computers. Solow (1987) wrote: "What this means is that I, like everyone else, am a little embarrassed by the fact that what everyone feels has been a technological revolution, a dramatic change in our productive lives, has been accompanied for everyone, including Japan, by a slowdown in productivity growth, not a step forward. You can see the computer age everywhere, but not in productivity statistics.

The study of the effects of ICT on output and productivity growth was initiated by Bauer (1990), who decomposed the contribution to total factor and productivity growth of the world's countries in the presence of cost inefficiency, technological progress and no constant returns to scale. A few years later, Fereetal (1994) has analyzed the contribution of productivity, technological progress and efficiency to industrial growth across countries.

Most studies analyzing the relationship between ICT productivity and economic growth find positive correlations between the variables, although there are also some studies in which this relationship is not found or is negative.

In the context of findings of negative effects or spillovers, Berndt et al. (1992) examined the contribution of ICT capital to US industries, productivity growth and found a positive relationship. Another approach in the US, Olinery Sichel (1994) studied whether the positive impact of innovation in terms of ICT can leave a macroeconomic trace. He concluded that the macroeconomic impact on the productivity factor was minimal. Olinery Sichel (2000) incorporated ICT as a productive input in the overall production function and, as in his earlier work, found no positive macroeconomic impact for any variable proxy with ICTs.

Some of the studies have found a positive and significant relationship between ICT and economic growth. Brynjolfsson and Hitt (1996, 2002) find signs of a positive impact of ICTs on the microeconomic level of productivity. For a sample of US firms during the period 1987-1991, the authors found a positive correlation between ICT investments and changes in productive organization, process decentralization and the incorporation of skilled people. Schreyer (2000) has studied the contribution of ICTs to economic growth in the most developed OECD countries in 1996. His main result was that ICTs had a significant impact on economic growth in the United States, leading the ranking.

Meanwhile, Pilat and Lee (2001) studied OECD countries and concluded that the contribution of ICTs to labour productivity growth was high, with countries such as Finland, Ireland and the United States standing out.

The complexity of international logistics systems in many sectors has grown as a result of product variation and differentiation. Recent economic developments are thus linked to the creation of complex production networks (Ducruet and Beauguitte, 2013).

There is a relationship between the level of development of an economy and logistics costs. While logistics costs can be as high as 25% of shipping costs in some developing economies, they reach 8% to 9% in advanced economies (Roberts 2003).

Consequently, logistics costs in international trade directly affect international trade. If logistics costs are so high, they may outweigh the benefit derived from the price differential, so that international trade would not gain a positive economic benefit.

However, as Lin et al. (2014) have pointed out, there is also an environmental cost of traffic networks that needs to be considered.

There is a large literature assessing the spillover effect of transport and its external impact generated by transport infrastructure on economic development. Evidence from different countries (e.g. Munnell 1990; Aguas2004; Xiushan et al. 2015) as well as theoretical evidence (Illenberger et al. 2013; Batabyal and Nijkamp2014) supports the existence and importance of spillover effects. Other studies have focused on the relationships between the spatial structure of networks and their vulnerability and resilience in critical situations (e.g. Reggiani et al. 2002; Griffith and Chun 2014; Caschiliet al. 2015).

However, despite the importance of logistics, there are few papers assessing its impact on the growth of the global economy, and there are no studies considering the impact of logistics on the Scale Efficiency of global production.

Yang (2007) studied the relationship between logistics and economic development. Based on data from North America, Japan and Europe, he found that logistics and economic growth are cause and effect of each other by cointegration techniques.

Using an instrumental variable model, Czernich et al.(2011) estimates the effect of broadband infrastructure on economic growth. The author concludes that a 10 % increase in broadband penetration leads to an annual per capita growth of 0.9-1.5 %.

While some have argued that ICTs have been the main technological enabler of economic globalization, bringing about a 'death at a distance' (Cairncross 1997) in a 'flat world' (Friedman 2005), this perspective does not fully appreciate the role of transport innovation (Levinson, 2006).

It is precisely the combination of logistics and ICT that led to the reduction of transport costs and the growing importance of networks in the evolution of the global economy.

Moreover, Coto-Millán et al. (2013) have studied the impact of logistics on economic growth, focusing on the long-run equilibrium solution of a growth model and estimated that a 1 % increase in synthetic LPI could generate economic growth in a range of 0.011 and 0.034 %. Coto-Millán et al. (2016) estimate synthetic LPI efficiency for a sample of 34 developed countries. Finally, Tang and Abosedra (2019) estimate the influence of LPI for a model of export-led economic growth in Asia for the period 2010 to 2016 for 23 countries.

3. DEA METHODOLOGY

Statistical and econometric approaches can be used to assess efficiency. The measurement of efficiency in empirical research has myriad applications. The most commonly used methodological approaches are the parametric stochastic frontier analysis (SFA) method (Aigner et al., 1977) and the non-parametric approach of Data Envelopment Analysis (DEA) (Charnes et al., 1978). The latter methodology can be applied to obtain technical and scale efficiency. In addition, DEA measures the relative performance of organizational units presented by multiple inputs and outputs. In the method, if the output appears within the production set, the unit is considered technically inefficient. The Decision Making Unit (DMU) measure assesses inefficiency by the distance from its observed input and output values to the production frontier (Coelli et al., 2005).

The DEA model can be either input-oriented or output-oriented. In the study of global production efficiency, the choice is an output-oriented specification rather than an input-oriented model. The reason for this is that countries' economic policy is generally directed towards the growth of the country's output or income. Thus, for the j-n countries, the output-oriented technical efficiency with constant returns to scale (CRS) is obtained by solving the following linear programming problem.

$$\underset{\theta_j^{CRS},\lambda}{Máx} \quad \theta_j^{CRS}$$
$$sujeto\ a: \begin{cases} \theta Y_j \leq Y\lambda \\ X_j \geq X\lambda \\ \lambda \geq 0 \end{cases} \tag{1}$$

Where X is the vector of inputs and Y is the vector of outputs, and where $\varphi_j^{CRS} = 1/\theta_j^{CRS}$ is the technical efficiency (TE) of countries in the world under CRS and λ is an n x 1 vector of weights.

The efficiency contribution of the countries of the world as measured by non-negative weights λ is selected as a determinant of a benchmark for the world's countries. Generally, if the countries of the world are on the production frontier and within $0 \leq \varphi_j^{CRS} \leq 1$where

$\varphi_J^{CRS} = 1$is the maximum technical efficiency. Where $\varphi_J^{CRS} < 1$indicates that the country is technically inefficient.

In the case of variable returns to scale (VRS), the technical efficiency φ_J^{VRS} has the convexity constraint $\sum_{j=1}^{n} \lambda_j = 1$ for the linear program expressed in (1). All this can be seen in detail in Banker et al. (1984).

The estimation of the effect of the synthetic LPI and its six efficiency components will be carried out through the second stage method of a truncated regression with the application of Simar and Wilson (2007). It is performed by a process of data generation under a method consisting of two stages. An advantage that drives the method of Simar and Wilson (2007) is that it allows for obtaining unbiased coefficients in valid confidence intervals. The discriminatory power of the first stage is not affected as the explanatory variables are not included in the first stage (Liebert and Niemeier, 2013).

The second stage regression to explain efficiency levels is presented as follows:

$$\varphi_j = a + \delta\, z_j + \varepsilon_j \qquad (2)$$

Where a is a constant term, ε_j is the error term, z_j is a vector (row) of possible variables that are expected to explain the efficiency levels of each decision unit, φ. We will apply the homogeneous approach with 2000 iterations to overcome the potential problem of biased results in our second stage regressions, for further discussion see Simar and Wilson (2000) and Simar Wilson (2008).

The impact of the LPI and its six components on each country's production efficiency can now be measured from the estimation results of equation (2).

4. DATA

The Logistics Performance Index or LPI is an indicator defined by the World Bank, with the aim of assessing trends in logistics in the countries of the world. Data is available for the years 2007, 2010, 2012, 2014, 2016 and 2018.

The LPI was designed to measure the components of the supply chain, such as transportation, customs, timeliness of shipments, tracking, etc.. It measures the efficiency of each country's supply chain and how it performs in international trade with other countries around the world.

Figure 1 shows a representation of the components of the LPI. The components of the Logistics Performance Index (LPI) are:

1.- Customs: efficiency in customs processes and formalities.
2.- Infrastructure: related to trade and transport.
3.- Quality and logistics competences: in logistics services.
4.- Punctuality (Timeliness): shipments within the scheduled delivery times.
5.- International shipments: international trade transactions.
6.- Traceability and tracking: real-time location of shipments and their traceability throughout the logistics chain.

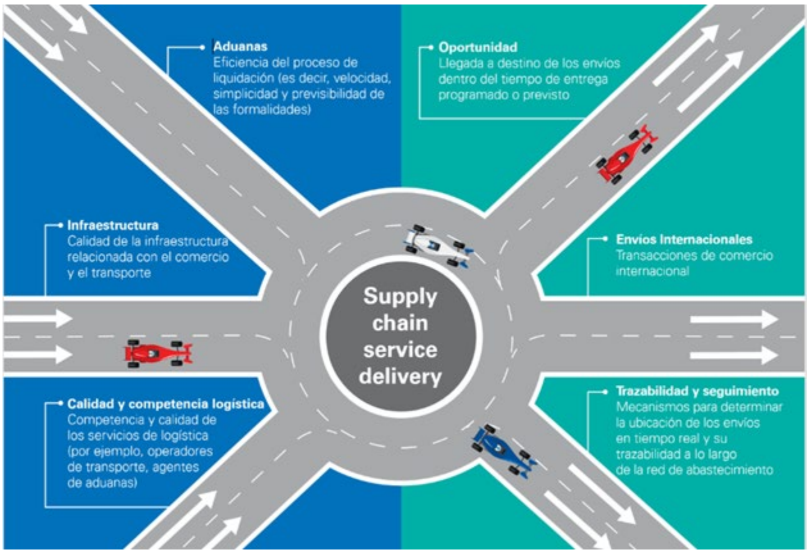

Figure 1 - Representation of the components of the Logistics Performance Index
Source: KPMG

The first three correspond to areas of regulatory policy and the last three to time, cost, and reliability.

The World Bank publication (2018) includes the LPIs in its sixth edition, which facilitates this research work from a scientific approach, and which, as will be seen, allows us to verify the theses that I am maintaining in this chair competition with coherence in the teaching and research aspects; adapting to the emerging reality as a result of digital transformation, sustainability and inclusion.

The LPIs for 2018 are shown at the world map level in Figure 2.

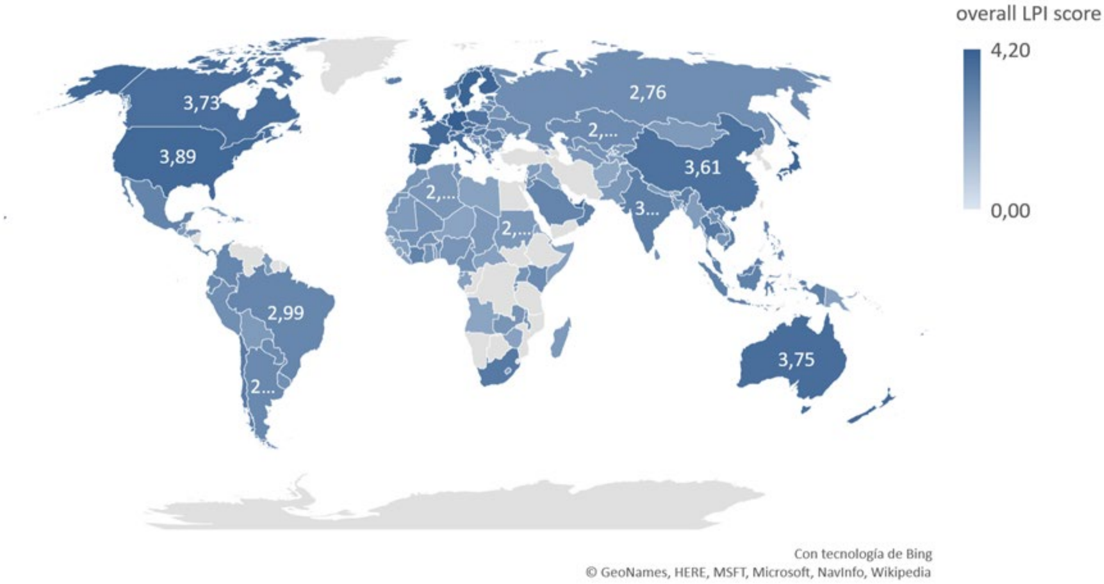

Figure 2. Logistics Performance Index (LPI) rankings by country in 2018

Figure 3 shows the top ten countries in the world with the highest LPI, as of 2018.

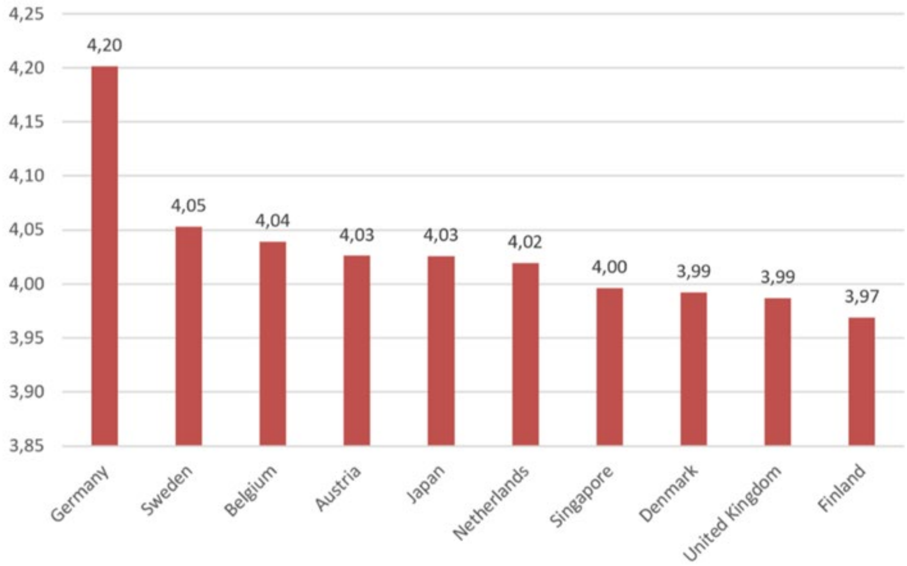

Figure 3 - Top ten countries in the world with the highest LPI in 2018

Figure 4 shows the ten countries in the world with the lowest LPI, for the year 2018.

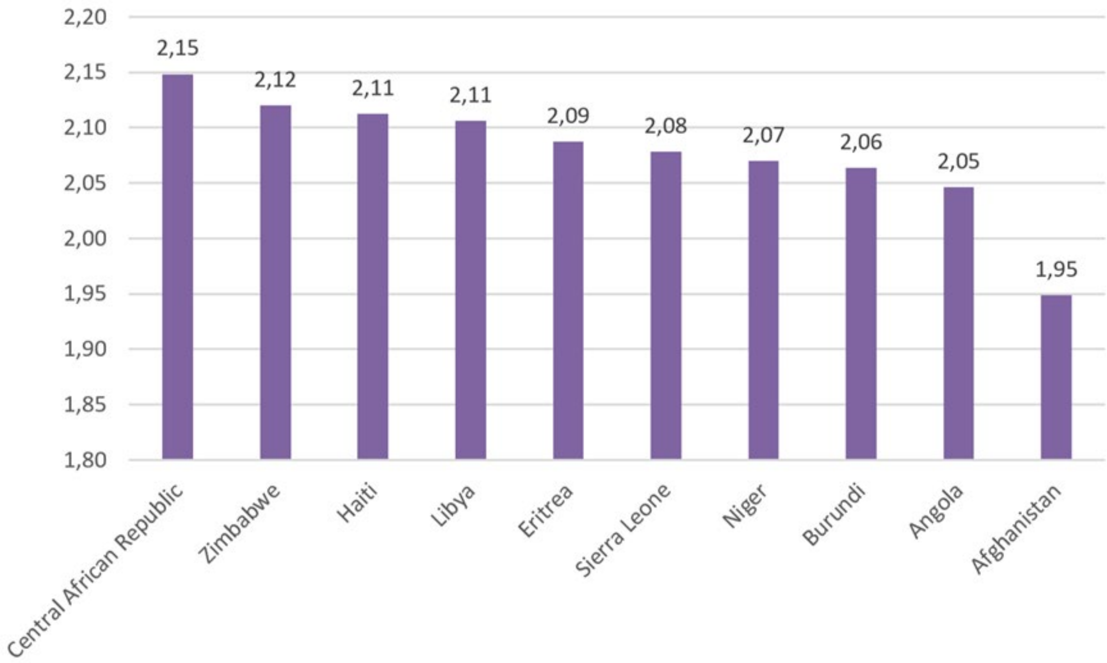

Figure 4 - Top ten countries in the world with the lowest LPI in 2018

An empirical test of the proposed model has been carried out with the indicators included in the World Economic Indicators (WDI) database created by the World Bank. The World Bank is an international organization with several objectives, most of which are closely related to poverty and economic development in all countries. Since its creation in 1944, it has devoted an increasing share of its resources to the collection of statistics and indicators, which are organized in databases.

For the empirical analysis, a sample of 133 countries has been used, for which complete logistics data is available for the years 2007, 2010, 2012, 2014, 2016 and 2018 .

Table 1 provides a detailed description of the variables included in the estimation of the production function and those as determinants in the Technical Inefficiency Effects Frontier model (hereafter TIE model).

Variable definition data		
Production function		
GDP	(in $)	WDI
EDU	% secondary school working age population.	WDI
EMP	% employed population	WDI
GBF	% of GDP of fixed capital in dollars.	WDI
For the efficiency explanatory stage of the production function, the following are used:		
LPI	logistics performance index	WDI
LPI1	infrastructures	WDI
LPI2	Customs	WDI
LPI3	Quality and Logistics Competence	WDI
LPI4	Tracking and Tracing	WDI
LPI5	Punctuality	WDI
LPI6	International Shipments	WDI

Source: Own elaboration based on World Bank WDI data.

Table 1 - Structure of the variables used

Table 2 shows the main statistics for the variables used.

Variable	Media	Medium	D. T.	Minimum	Maximum
GDP	8.67e+005	1.76e+005	2.46e+006	1.83e+003	2.05e+007
EDU	86.8	93.7	26.7	10.7	100
EMP	57.4	57.7	10.1	35.4	87.8
GBF	24.89	23.22	7.74	11.91	67.91
LPI	2.98	2.86	0.53	1.61	4.18
LPI1	2.82	2.66	0.66	1.40	4.34
LPI2	2.76	2.63	0.57	1.63	4.21
LPI3	2.93	2.83	0.58	1.43	4.32
LPI4	3.00	2.93	0.59	1.67	4.27
LPI5	3.41	3.38	0.54	1.67	4.71
LPI6	2.94	2.89	0.46	1.57	4.05

Table 2 - Principal statistics
Source: Own elaboration based on World Bank data.

The dependent variable is real GDP per capita and the independent variables are capital stock per capita for each country and human capital (which measures the percentage of the working-age population in secondary school).

To assess the efficiency of Logistics and Innovation in TE of global production we include the LPI variables. The Logistics Performance Index, as defined by the World Bank, is an interactive benchmarking tool.

To obtain the LPIs the World Bank conducted a worldwide survey of land operators (global freight forwarders and express carriers), providing feedback on the logistics co-modality of the countries in which they operate and those with which they trade. They combine in-depth knowledge of the countries in which they operate with qualitative assessments of other countries where they trade and operate in global logistics environments.

Operators' comments are complemented by quantitative data on the performance of key components of the logistics chain in the country. It is expected that an increase in LPI will decrease technical inefficiency. Similarly, we expect that each of the disaggregated indices, if functioning properly, will promote technical efficiency.

5. RESULTS

We will use the model of Mankiw, Romer and Weill (1992) to estimate the world production function. In essence it is to explain the world output measured by GDP, by the following world inputs: Human Capital (EDUC), Physical Capital (GFB) and Employment (EMP).

Once the variables have been defined and the main statistics for them have been provided, we proceed to estimate the world production function incorporating the indices relating to the different components of the LPI. This estimation is given in Table 3.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	-0.0251427	0.400771	-0.06274	0.9500	
l_EDU	1.40084	0.0915710	15.30	<0.0001	***
l_GFB	0.0461570	0.0235357	1.961	0.0512	*
LPI1	0.0406124	0.194689	0.2086	0.8350	
LPI2	0.617081	0.182377	3.384	0.0009	***
LPI3	-0.0334662	0.146374	-0.2286	0.8194	
LPI4	-0.0450878	0.230131	-0.1959	0.8449	
LPI5	-0.219594	0.167897	-1.308	0.1923	
LPI6	0.470041	0.141023	3.333	0.0010	***

Mean of variable. dep.	9.411849	D.T. of the vble. dep.	1.091432
Sum of waste squares	44.95717	T.D. of the regression	0.460502
R-squared	0.885288	Unbiased' R-squared	0.846043
F(117, 212)	13.98378	p-value (of F)	1.47e-58
Log-likelihood	-139.3416	Akaike criterion	514.6832
Schwarz Criterion	962.9762	Hannan-Quinn Crit.	693.5008
rho		Durbin-Watson	2.195793

statistically significant at 99% ** statistically significant at 95% *** statistically significant at 99% ** statistically significant at 95% *** statistically significant at 99% ** statistically significant at 95% ** statistically significant at 95% statistically significant at 90%. Joint contrast of regressors (except for the constant) -
Contrast statistic: F (8, 212) = 145.626 with p-value = P (F (8, 212) > 145.626) = 9.34981e-082. Contrast of different intercepts by groups Null hypothesis: The groups have a common intercept. Contrast statistic: F (109, 212) = 0.715557 with p-value = P(F(109, 212) > 0.715557) = 0.974277.
Source: Own elaboration. Estimated with GRETL software.

Table 3 - Estimation of a panel World Production Function 2007-2018 by the Fixed Effects Method Dependent variable: l_GDP_pc

As can be seen, the only indices that are significant are those corresponding to Infrastructure and Punctuality. The other four are not significant. The following question arises: Why these results? To answer this question we will carry out an analysis of efficiency in world production using the DEA methodology.

In the production function, from which the efficiency scores are obtained, the specification of the Cobb-Douglas function is used and therefore constant and unit elasticity of substitution between inputs is required.

The question now is to analyse why some countries have high levels of efficiency while others have low levels.

That is, what is the cause of scale efficiency in the countries of the world?

To answer this question we will use the information on logistics and its components provided by the World Bank. As explained above, the model of Simar and Wilson (2007) will be used to study how LPI and its components influence the efficiency of global production.

Table 4 shows the estimated efficiency explained by the LPI synthetic index for 133 countries in the period for which LPI is available, i.e. 2007, 2009 and 2012, 2014, 2016 and 2018.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	-0.9918894	0.062191	-15.95	0.000	***
LPI	0.3693917	0.0176201	20.96	0.000	***

Table 4 - Efficiency Estimation with CRS, Simar and Wilson (2007).
Source: Own elaboration based on World Bank data, with STATA.

As can be seen in Table 2 the variable LPI (overallLPI-e) is significant and positive with a value of 0.369. This is when we assume that there are Constant Returns to Scale (CRS).

Table 5 presents an estimate in which the LPI is broken down into its components.

In the following table, the component indices of the LPI are very significant and positive: Infrastructure (LPI1) and Opportunity (LPI4). It can be observed that some component indices of the LPI are not significant such as Customs (LPI2), International Shipping (LPI6) and Tracking (LPI4). In addition the logistics quality index contributes to inefficiency (LPI3).

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	-0.851728	0.400771	-0.06274	0.9500	
LPI1	0.310270	0.041805	7.42	0.000	***
LPI2	0.000745	0.037201	0.02	0.984	
LPI3	-0.169600	0.048583	-3.49	0.000	***
LPI4	0.027368	0.039388	0.69	0.487	
LPI5	0.137383	0.030776	4.46	0.000	***
LPI6	0.011185	0.031561	0.35	0.723	

Table 5 - Efficiency Estimation with CRS, Simar and Wilson (2007): Components
Source: Own elaboration based on World Bank data, with STATA.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	0.76879	0.019816	38.80	0.000	***
LPI	-0.00468	0.006652	- 0.70	0.481	

Table 6- VRS Efficiency Estimation, Simar and Wilson (2007): LPI.
Source: Own elaboration based on World Bank data, with STATA.

Table 6 presents an estimate in which we assume Variable Returns to Scale for the synthetic LPI.

As can be seen in Table 6 when we assume variable returns to scale, the contribution of synthetic LPI is not significant.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	0.812954	0.025753	31.57	0.000	***
LPI1	0.052526	0.021072	2.49	0.013	***
LPI2	-0.383546	0.020884	-1.84	0.066	
LPI3	0.043975	0.026048	1.69	0.091	
LPI4	-0.040080	0.0200177	-2.00	0.045	***
LPI5	-0.022385	0.0150446	-1.49	0.137	
LPI6	-0.011638	0.0169149	-0.69	0.491	

Table 7- Efficiency Estimation with VRS, Simar and Wilson (2007): Components
Source: Own elaboration based on World Bank data, with STATA.

Table 7 shows that only the infrastructure index (LPI1) has a significant and positive contribution. On the other hand, Tracking(LPI4) has a significant and negative contribution to efficiency. Finally, the remaining indices are not significant at the required levels.

Table 8 shows that the results for Scale Efficiency are very similar to those obtained in Table 5. The explanation is similar.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	-1.084573	0.061704	-17.70	0.000	***
LPI	0.427494	0.017901	23.88	0.000	***

Table 8 - Estimation of Scale Efficiency, Simar and Wilson (2007): LPI.

Variable	Coefficient	Standard deviation	Statistic t	p-value	Sig.
const	-0.913269	0.068212	-13.39	0.000	***
LPI1	0.328735	0.043929	7.48	0.000	***
LPI2	0.034905	0.038692	0.90	0.367	
LPI3	-0.165906	0.051516	-3.22	0.001	***
LPI4	0.029209	0.039352	0.74	0.458	
LPI5	0.133755	0.031214	4.29	0.000	***
LPI6	0.007969	0.033503	0.24	0.811	

Table 9 - Estimation of Scale Efficiency, Simar and Wilson (2007): Components
Source: Own elaboration based on World Bank data, with STATA.

Table 9 shows that the results for Scale Efficiency are very similar to those obtained in Table 5. The explanation is similar.

Figure 5 presents the Efficiency of Scale results for countries around the world.

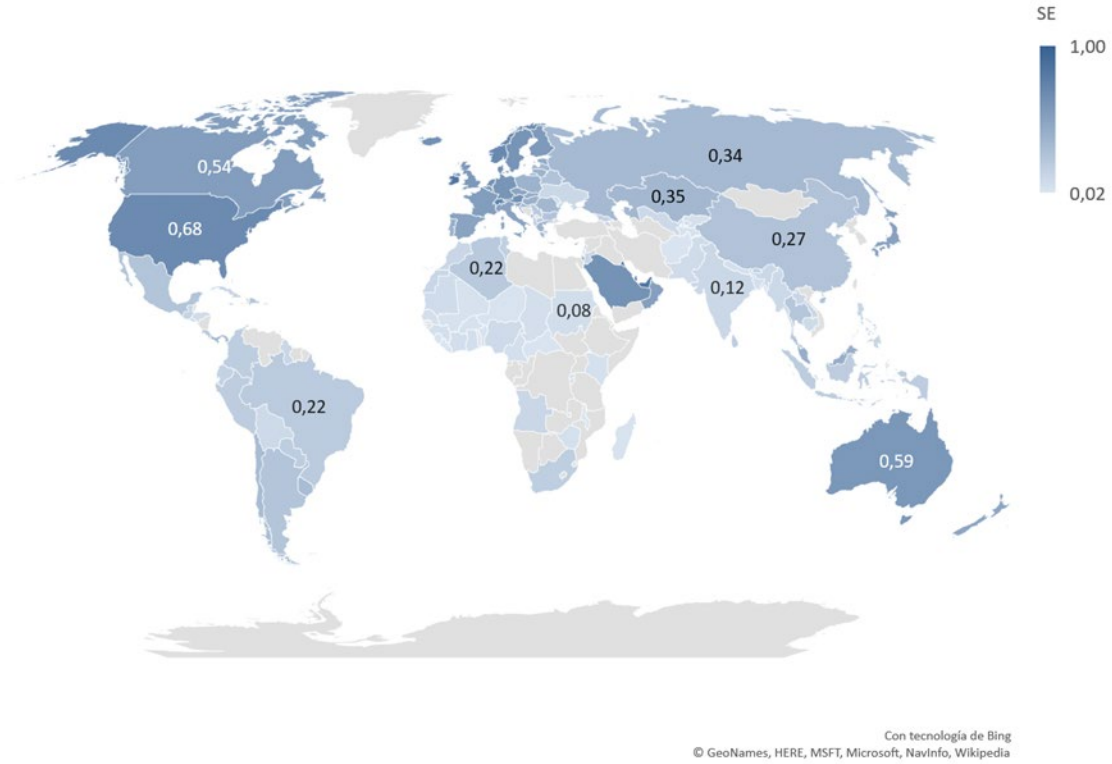

Figure 5 - Efficiency of scale ranking for the world's countries for the year 2018 Source: Own elaboration based on the estimation of a production function of world GDP by country explained by physical capital, human capital and employment.

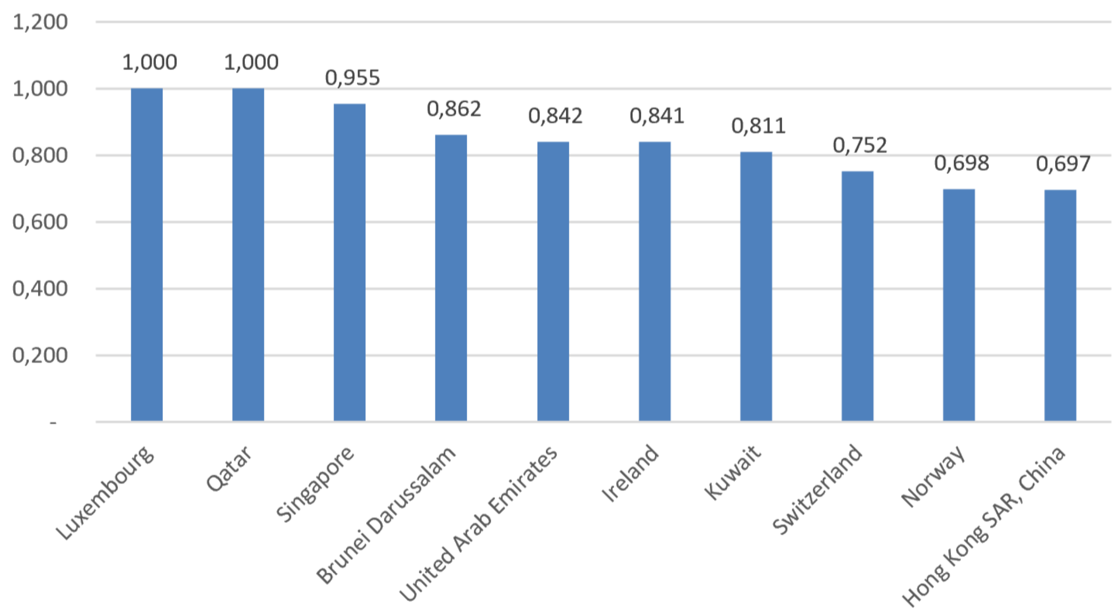

Figure 6 - Top ten countries in the world with the highest Efficiency of Scale in 2018 Source: Own elaboration based on the estimation of a production function of world GDP by country explained by physical capital, human capital and employment.

It can be seen that Qatar, Luxembourg and Singapore are the countries with the highest production scale efficiency (Figure 6), while Congo, Liberia and Gambia have the lowest production scale efficiency levels (Figure 7).

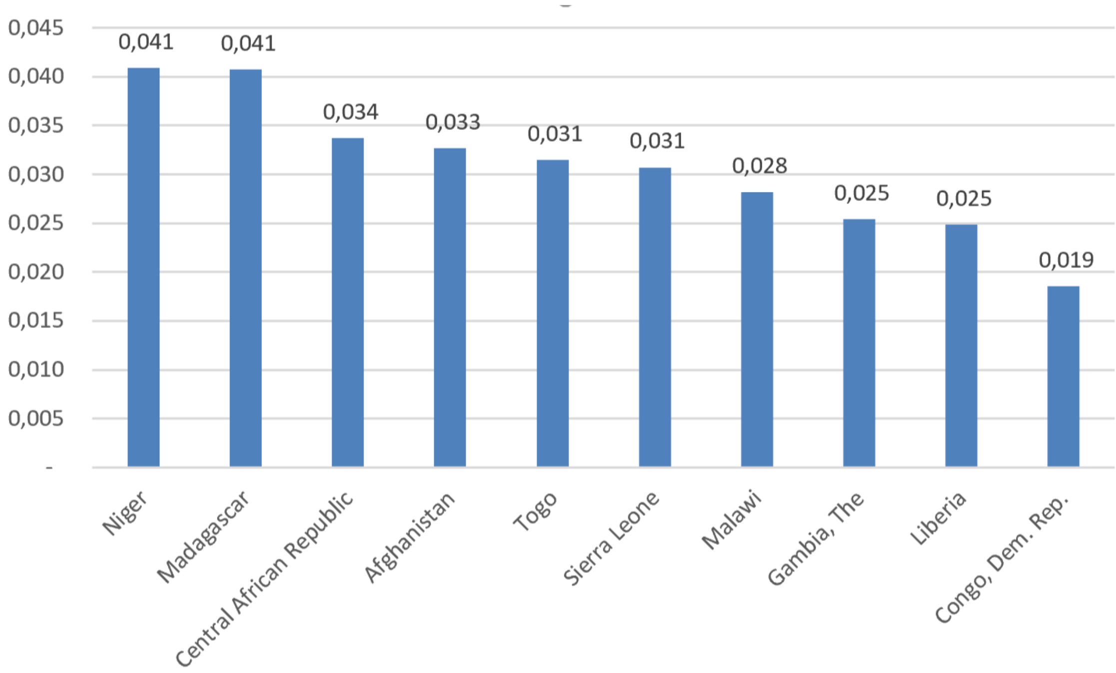

Figure 7 - Top ten countries in the world with the lowest Efficiency of Scale by 2018
Source: Own elaboration based on the estimation of a production function of world GDP by country explained by physical capital, human capital and employment.

Note that Scale Efficiency is defined as the quotient between Efficiency with Constant Returns to Scale and Efficiency with Variable Returns to Scale. As can be seen the results for Scale Efficiency are consistent with those for Efficiency at Constant Returns to Scale.

Logistics (LPI) has a positive sign and is statistically significant at the 1 % level, indicating that its impact on efficiency is positive and helps individual countries to approach their production frontier. Therefore, we find that countries with a high degree of logistical development perform well because of the benefits they gain in terms of scale efficiency.

As for the impact of LPI performance on Global Efficiency of Scale, the estimated LPI coefficient suggests that a 1 % increase in LPI performance increases the efficiency of scale of the world's countries by 0.42 %.

The results confirm that it is the right combination of non-isolated LPI components that causes the growing importance of networks in the evolution of the global economy.

These results also have important policy implications.

Policy makers can use preferential policies to encourage innovation and logistics activities and thus improve their productivity. In addition, governments should facilitate networking activities and develop the necessary infrastructure to encourage the establishment of logistics activities.

As noted by Rollery Waverman (2001), an adequate and reliable supply of infrastructure (e.g. infrastructure associated with communication and transport) facilitates mobility and efficient allocation of inputs as well as final products, reduces transaction costs and improves productivity.

6. CONCLUSIONS

Logistics has allowed the reduction of transport costs, facilitating the growth of the world economy through the use of logistics networks and platforms. Using a production function of the type proposed by Mankiw et al. (1992) the scale efficiency of 133 countries for the period 2007-2018 has been estimated through the DEA method and the application of the Simar and Wilson (2007) model.

This paper contributes to the literature by estimating the contribution of logistics to the scale efficiency of countries around the world. Therefore, to improving the state of knowledge on the impact of logistics in the world. This research is the first to document that logistics performance as measured by LPI (as the sole explanatory variable of efficiency) increases productivity through improved scale efficiency. It also includes as a novelty the breakdown of each of the components of LPI as explanatory factors of scale efficiency.

The results highlight the significant impact of logistics on global scale efficiency. Available data from the World Bank show that a 1 % increase in the logistics performance index increases the current global level of scale efficiency by 0.42 %.

There are substantial variations in the level of efficiency among the countries in the sample. Qatar, Luxembourg and Singapore achieve the highest technical efficiency. Congo, Liberia and The Gambia, on the other hand, have the lowest levels of scale efficiency in production.

In the empirical study, an estimation of the world production function has been carried out first. Here a panel data estimating a Cobb-Douglas type production function has been used.

In this first estimation, only the infrastructure quality index and the punctuality index are significant. The rest of the logistic components are not significant. I then carried out a more detailed non-parametric analysis using linear programming techniques with a DEA.

The results obtained with this second method verify the previous ones and also indicate that the logistic quality index goes from not being significant to being significant and having a negative sign. This means that logistics quality is currently a barrier to global production.

The results are meaningful and useful for policy makers. The different components of the synthetic LPI index show different results, allowing governments to improve the productivity of countries by acting on these components of the LPI.

The results obtained with the DEA methodology in the LPI components reveal glaring inefficiencies in customs processes and formalities, and in the quality and competencies of logistics services, which clearly identify the lack of global logistics. Inefficiencies in international transactions, and in the tracking and tracing of logistics chains could be corrected with blockchain technology, especially in multimodal and intermodal chains.

The results contrasted with DEA analysis indicate that logistics efficiency is positive and significant in its infrastructure and punctuality, significant but negative in logistics quality and not significant in customs, international shipment transactions, and tracking and tracing.

NOTES

1 In this study we use the LPI variable to approximate the level of logistical performance of each country. The World Bank has only published the International LPI for the periods mentioned.
2 See Coelli et al. (2005) for a more comprehensive review of the literature related to efficiency and productivity.
3 Connecting to Compete 2018 Trade Logistics in the Global Economy. The Logistics Performance Index and Its Indicators. World Bank 2018
4 In order to avoid problems of heterogeneity in the sample, only countries considered by the World Bank have been taken into account in the upper middle-income and high-income groups.
5 The capital stock of each country was calculated cumulatively from gross capital formation (in constant 2005 dollars). The methodology of Dhareshwar and Nehru(1994) has been followed.

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EUROPEAN MODULAR SYSTEMS PERFORMANCES COMPARISON IN FREIGHT TRANSPORT OPERATIONS

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ABSTRACT

European countries has been working in the last ten years in the implementation of high capacity vehicles in road networks. The EU allowed each member state to use combinations of cargo carriers with a modular concept, the European Modular Systems (EMS). This paper analyses the real behavior in road test of the Euro Modular vehicle of 70 tons of maximum load (called Duotrailer). A route in real conditions is used and comparisons between different vehicle typologies (Trailer, Gigatrailer and Duotrailer) in terms of fuel consumption and emissions are performed. Results in the route tested show that, as expected, the highest consumption correspond to Duotrailers. However, savings with regards to trailers are around 22 % (per ton) and 26 % (per ton and m^3), and savings with regards to Gigatrailers are around 9 % (per ton) and 23 % (per ton and m^3) considering that the charge factor is higher in Duotrailers. Although emissions are higher in Duotrailers, the load capacity is higher.

1. INTRODUCTION

Freight transport is a significant source of CO2 emissions. Hence, to find solutions to reduce the carbon footprint of road freight transport is necessary. The European Modular System (EMS) is a solution that allows combinations of existing loading units (modules) into longer and sometimes heavier vehicle combinations to be used on some parts of the road network. EMS improves road freight transport efficiency and reduces its environmental impact (Acea, s.f.).

The maximum vehicle´s dimensions and combinations, and masses are regulated in the European Council Directive 96/53/ EC revised by European Council Directive 2015/719. The EMS is defined in Article 4, Point 4. (b) of this directive as: "*Member States may allow vehicles or vehicle combinations used for goods transport which carry out certain national transport operations that do not significantly affect international competition in the transport sector to circulate in their territory with dimensions deviating from those laid down in points 1.1 , 1.2, 1.4 to 1.8 , 4.2 and 4.4 of Annex I*". Each country of the European Union have to transpose this directive to its national legislation.

Nevertheless, dimensions, masses and vehicle combinations are not uniform, as each country has taken up this directive with some modifications or different conditions (Jagelčák et al., 2019).

The experience of countries already using high capacity vehicles shows positive results, and CO2 reductions have been confirmed in practice. In the European Union, high-capacity vehicles in the form of combinations of EMS are allowed and used in Belgium, Denmark, Finland, most of the German federal states, the Netherlands, Portugal, Spain and Sweden (Acea, 2019).

The objective of this paper is to test this type of vehicles (70 t) in real conditions within a route in Spain performed by the company “Group Sesé”. Consumption and emissions are analysed in comparison with different vehicle typologies (Trailer, Gigatrailer and Duotrailer).

The rest of the paper is structured as follows. Section 2 presents the background of the study. Section 3 shows the method that has been applied. Section 4 analyses the main results, and finally, Section 5 concludes the main findings.

2. BACKGROUND

In recent years, research in the development and implementation of high capacity vehicles (HCV) has increased considerably in different countries. The “International Transport Forum” in its document “High Capacity Transport. Towards Efficient, Safe and Sustainable Road Freight ”(ITF, 2019) examines the experiences carried out in different countries in this regard, reviews the potential impact on road infrastructure and analyzes the consequences for other modes of transport, industry and society.

Countries such as Australia, Canada, the Netherlands, Finland, Sweden, Germany, the United States, Mexico, Argentina, New Zealand and South Africa have implemented additional regulations (e.g., additional features in vehicle performance, driver qualification, operation under special operations among others). This has allowed the deployment of these vehicles safely, with a positive impact in their public acceptance and by the Administration (Moore et al., 2014).

The precursor countries are Australia and Sweden. Since 2011, they have established different pilot tests in collaboration with the Public Administration. In turn, countries such as Australia, Canada, New Zealand and South Africa are also pioneers in the area, as they have developed Performance Based Standards.

Within the HCV are the so-called EMS. The EMS consists of the longest semi-trailer, with a maximum length of 13.6 m and the longest load support according to class C, with a maximum length of 7.82 m, allowed in the EU. This results in combinations of 25.25 m vehicles. The maximum length in the rest of Europe is 18.75 m. The EU allowed each member state to use combinations of cargo carriers with a modular concept. Sweden and Finland can combine a long and a short module, while in the rest of the EU only transport with two short or one long modules is allowed alternately. When using EMS, the volume of the three EU combinations can be transported by two combinations of EMS (TFK, 2007). See Figure 1 for more detail on this concept.

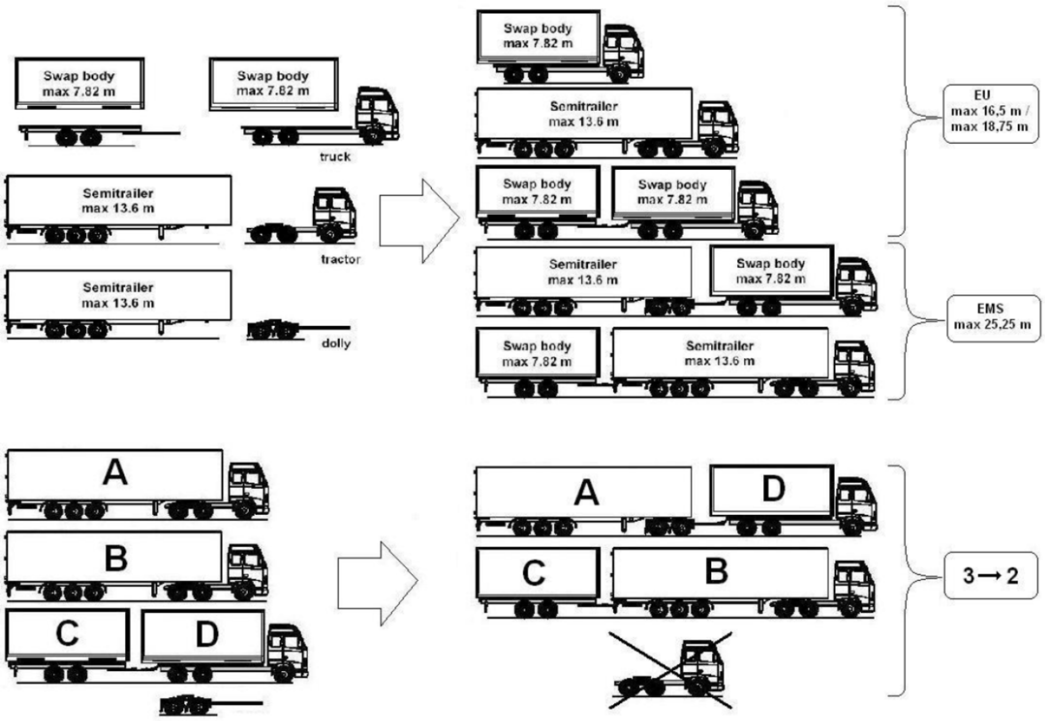


Fig. 1 – EMS configuration. Source (TFK, 2007)

In Finland, the experience in the use of high capacity vehicles nowadays includes 100 million km traveled, more than 300 km of transport annually, mixture of light cargo and food. In 2018, use of vehicles of dimensions 450x25.25 m and 60/ 64t. In 2023, it is expected to use 200x32-34m and 76t A-double vehicles and 120x 28-31m 64-76t vehicles + full trailer/ dolly + semi-trailer. As a result it is expected to obtain 25% less driving, and 15% less emissions (Lahti, 2020).

3. METHOD

The methodology proposed in this research consists of three steps: (1) the selection of the type of vehicles to be used, (2) a set of driving tests in real conditions considering a route and different load configurations, and (3) comparison in terms of consumption and CO_2 emissions.

3.1 Selection of type of vehicle

Different types (T) of vehicles were selected to compare results within a route (see Figure 2):

(1) T1: Trailer (conventional truck) of 16.50 m total length. Free movement on the Spanish road network.
(2) T2: HCV called Gigatrailer of 25.25 m total length. Free movement on the Spanish road network.
(3) T3: HCV called Duotrailer of 31.75 m total length. Subject to strict regulations and circulation under license by the Administration.

Tests were carried out with T3 vehicles (Duotrailer). Two types of Duotrailer were selected for the tests: 9 axle vehicles and 10 axle vehicles. The selection of vehicles tried to consider not only weight restrictions in Spain but also in Finland as a pioneer in the research and use of HCVs from many years. The maximum weight allowed in this country is 75 t. With this weight, a dolly of two axles is needed for the transport operation. On the other hand, tests in Spain are limited to 70 t and a one axle-dolly would be enough for the transport operation.

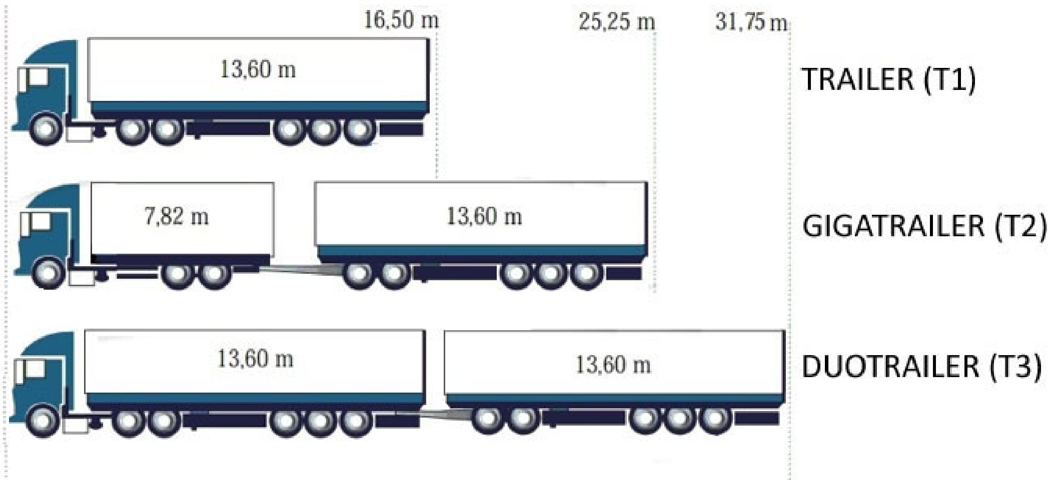
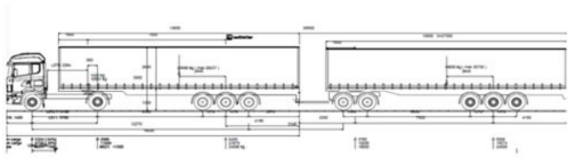
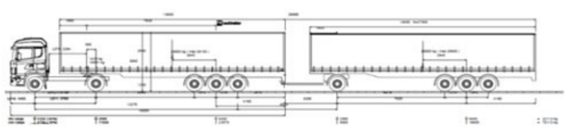


Fig. 1 – Comparison of vehicles within the route used for tests

The characteristics of the Duotrailer vehicles in terms of power, maximum authorised mass (MAM), technically permissible maximum masses (TPMM), and total length of the Duotrailer are shown in Figure 3 according to the tractor unit, semitrailer 1, dolly and semitrailer 2.



10 axle Duotrailer set



9 axle Duotrailer set

Typology	Power (kW) Tractor unit (T)	MAM (kg)	TPMM (kg)	MAM (kg) Semitrailer 1 (S1)	MAM (kg) Dolly (D)	MAM (kg) Semitrailer 2 (S2)	Total length (m)	Total number of axles
T3.1	383/427/464	18,000	70,000	35,000	Two axles 18,000	35,000	31.750	10
T3.2	383/427/464	18,000	70,000	35,000	One axle 10,000	35,000	31.750	9

Fig. 2 – Weights and dimensions of the used vehicles (Duotrailer)

Three vehicle configurations (VC) have been used in the tests (see Table 1).

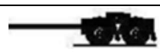
Vehicle Configuration	**T**	**S1**	**D**	**S2**
				
VC1	580 CV (2 axles)	3 axles	2 axles	3 axles
VC2	580 CV (2 axles)	3 axles	1 axle	3 axles
VC3	520 CV (2 axles)	3 axles	1 axle	3 axles

Table 1 – Identification of the vehicles used in the tests

3.2 Driving tests in real conditions

The transport company Group Sesé in Spain performed the tests in real operation. A route was chosen for the use of the Duotrailer vehicle: Azuqueca- Martorell (round trip) with a distance of 552 km (each trip). A load of 13.5 t was transported (30% use of the vehicle). A set of conditions for the vehicles has been stablished:

(1) **Characteristics of the set of vehicles:**

(1a) Tests with 9-axle and 10-axle vehicles.

- Resistance to advance, specific consumption.
- Manoeuvrability, interaction with infrastructure.

(1b) Tests with two available tractor units: 520 CV and 580 CV.

- Optimize energy efficiency.
- Emissions.

(2) **Characteristics of the type of route:**

(2a) Tests with different distances long and short routes.

- Average consumption.
- Energy efficiency.

(2b) Route profile (flat profiles and mountain profiles).

- Energy consumption.

(3) Characteristics of the type of merchandise.

(3a) Type of heavy good.

- Powers, consumption and emissions.

(3b) Type of bulky and light merchandise.

Tests were scheduled along 2018 and 2019. The schedule can be seen in Figure 3. A total number of 150 test were performed.

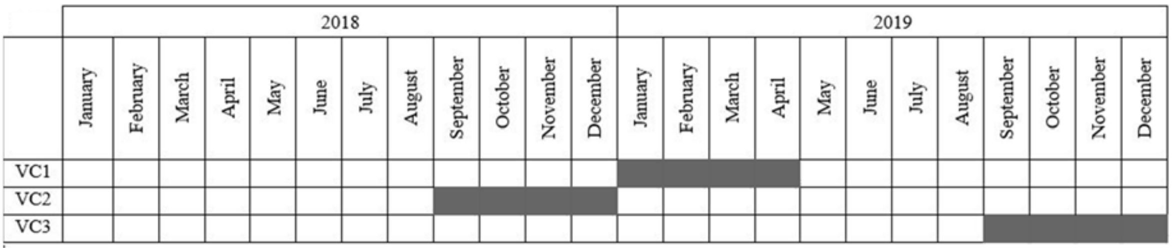


Fig. 3 – Tests schedule

3.3 Comparison of consumptions and CO_2 emissions

A matrix of cases is constructed. The calculation of consumptions has initially considered the following conditions:

- Condition 1: Influence of meteorological conditions:
  - Action of the wind.
  - Consumptions.
  - Ultrasonic wind speed measurement sensors.
- Condition 2: Influence of traffic conditions.
  - Heavy traffic or slow traffic
  - Average consumption.
  - Variation of speed conditions.
  - Considerable increase in braking and acceleration.
- Condition 3: Influence of driving type.
  - Average consumption of vehicles.
  - Short distance routes.
  - Transport of heavy merchandise.

To limit the number of tests to be carried out, the working intervals of each of the factors that were taken into account were established and the following working hypotheses were adopted:

(1) Hypotheses regarding the type of vehicle (HVE):

- Type of connection:
  - HVE1: Dolly of two axles (10-axle Duotrailer).
  - HVE2: Dolly of one axle (9-axle Duotrailer).

- Type of tractor (T):
    - HVET1: 520 CV (383 kW).
    - HVET2: 580 CV (427 kW).

(2) Hypotheses regarding the route (HR):

- Distance (HRD):
    - HRD1: Route of short distance traveled (<600 km).
    - HRD2: Route of long distance traveled (>600 km).
- Profile (HRP):
    - HRP1: Profile of the route with strong ramps accumulated (> 12%).
    - HRP2: Profile of the route with accumulated average ramps (> 5% and <12%).
    - HRP3: Profile of the route with slight accumulated ramps (<5%).

(3) Hypotheses regarding the merchandise (HM):

- Volume transport (HMV): ≤ 33% of maximum payload.
- Load volume (HML): medium load transport (> 33% of maximum payload) and full load transport (> 66% of maximum payload).

(4) Existence of externalities:

- Wind forces.
- Traffic congestion.
- Stressed driving.

The analysis of emissions was performed by using EcoTransIT (https://www.ecotransit.org/calculation.es.html) calculation tool. The tool provides information of emissions in terms of CO_2, CO_2 equivalent, NO_2, non-methane hydrocarbons, particles and distances. In this research, we focus on CO_2 emissions.

4. RESULTS

Table 2 shows the average results in terms of consumption for the route tested using Duotrailers (T3). It can be seen that, on average, consumption is higher for the transport from Martorell to Azuqueca than the road trip even if average payload transported is lower. This is due to the profile of the route.

	Azuqueca-Martorell	Martorell-Azuqueca
Average consumption (l/100km)	39.10	41.47
Average distance traveled (km)	552	552
Average payload transported (t)	14.25	12.75
Average charge factor	2.50	2.60

Table 2 – Average consumption results for T3 in the route tested

Table 3 shows a comparison between T1, T2 and T3 in the same route in terms of consumption savings. However, it has to be highlighted that different charge factors have been considered as the tests have been performed in real operation. The highest consumption correspond to T3 vehicles (Duotrailer). However, savings with regards to T1 vehicles are around 22 % (per ton) and 26 % (per ton and m^3) (mean), and savings with regards to T2 are around 9 % (per ton) and 23 % (per ton and m^3) (mean) considering that the charge factor is higher in T3 vehicles.

		Typologies of vehicles				
	T1(410 CV gas)	T1(450 CV)	T2 (580 CV)	T3 (520 CV)	T3 (580 CV)	T3 (580 CV)
Consumption (l/100km)	24.8	27.1	39.5	38	40.80	41.48
Saving per ton (%)	-	-	13.66	25.1	19.63	20.29
Saving per ton and m^3 (%)	-	-	2.9	29.90	24.87	23.52
Real charge factor	-	-	1.5 (theoretical)	2.53	2.5	2.5

Table 3 – Comparison of consumptions and savings between vehicles

Figure 4 shows a comparison in terms of mass transported and the unladen mass of the vehicles used. Although T3 vehicles (Duotrailer) are heavier, they transport nearly twice load.

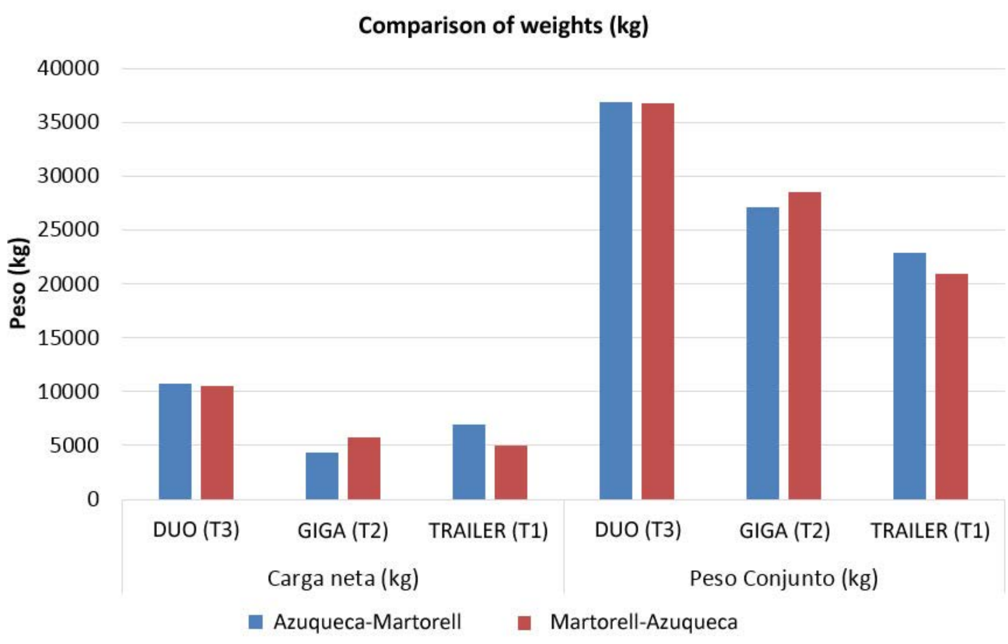


Fig. 4 – Comparison of weights of the vehicles used

Figure 5 shows the differences in total emissions between the three types of vehicles. T3 vehicles (Duotrailer) are the most polluting.

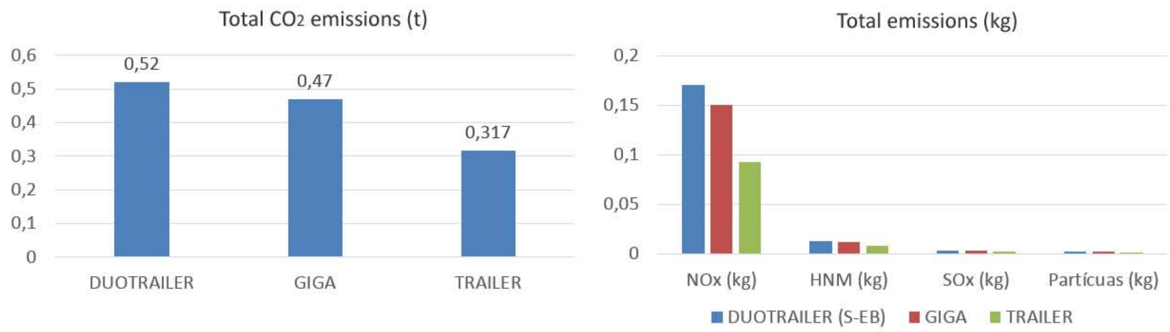


Fig. 5 – Difference of emissions in the vehicles used

Representando las emisiones de CO_2 en función de la masa desplazada y por carga útil.

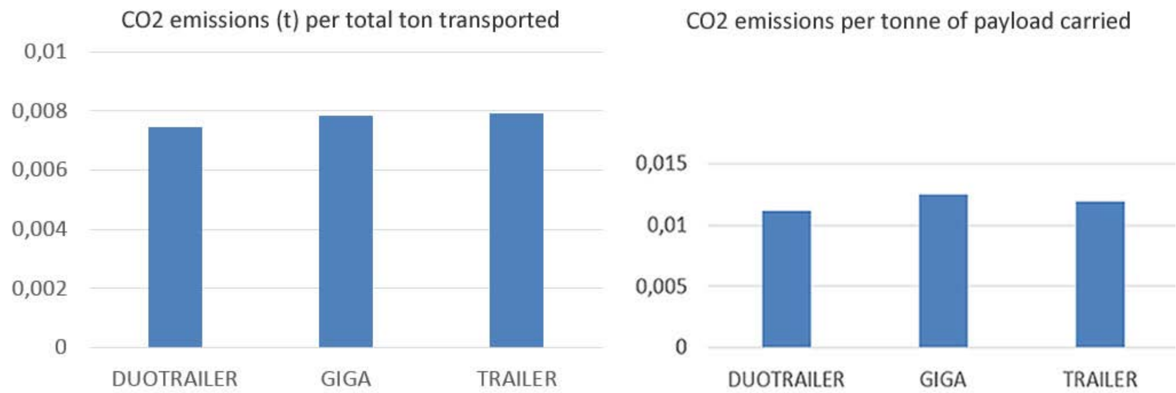


Fig. 6 – CO_2 emissions as a function of the mass displaced by each type of vehicle

5. CONCLUSIONS

In this research, through a set of experimental tests it has been possible to analyze the behavior of EMS vehicles in real road behavior, in this case the Duotrailer vehicles. The data capture and monitoring during the test allows obtaining data from the entire operation and a comparison with other vehicles, both in volume transport and maximum load.

Results are considered positive from the standpoint of the behavior of the vehicle, and the environmental, operational and economic improvement. Other conclusions include:

- The vehicle in terms of dynamics and mechanics behaves properly and its maneuverability is correct in all sections where it has been tested.
- The vehicle has shown safety throughout the test run and no incidents occurred during the tests.

- The vehicle is stable in running behavior and does not show road damage, given its distribution of axle loads.
- The test scenarios performed and their repetition, allows to verify the behavior of the vehicle both in terms of safety, maneuverability and its economic and environmental profitability.

Future research will focus on conducting more tests, in order to assess more possible scenarios, corroborate the results obtained and verify that the vehicle's behavior complies with all safety and effectiveness guarantees in road transport operations.

ACKNOWLEDGEMENTS

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MICRO DISTRIBUTION IN URBAN LOGISTICS. THE PILOT CASE OF THE OLD DISTRICT OF BARCELONA

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ABSTRACT

The total amount of kilometres travelled by freight vehicles is expected to triple between 2018 and 2050. Today, 64% of all the trips happen within urban environments. There is, hence, a need for organizing the mobility and the urban freight distribution in a more sustainable way.

E-commerce has taken more relevance in the last years and an important increase of this type of consumption is expected. E-commerce has compelled to modify supply chain strategies and the management of platform distributions. Urban areas, especially old quarters and pedestrian streets are not the best scenarios for deliveries. Streets are narrow and congested, with insufficient space for loading and unloading manoeuvres. The e-commerce is worsening this situation.

One of the possible solutions that have emerged in the last years is the micro consolidation centre, a transhipment point where logistic operators store their goods and transfer them through more environmentally-friendly and smaller vehicles such as cargo bikes, for last mile distribution.

This paper presents the study case of the micro distribution in “Ciutat Vella” quarter (Barcelona) and surroundings. This micro consolidation centre, part of H2020 project, GrowSmarter, is in the oldest and most touristic part of the city, with plenty of narrow streets, and the delivery is made by cargo bikes. During the months from January 2017 to March 2019, where the study case took place, the main key performance indicators of the initiative were tracked and analysed. The results of the analysis showed a reduction of the total number of vehicle kilometres, the amount of CO_2 emissions, energy and noise levels compared to using conventional vans for the last mile distribution.

Besides these direct results, the experience of this case study allows to establish some conclusions and policy recommendations for retailers and city planners in order to implement these types of measures.

1. INTRODUCTION

By 2050, it is estimated that 68% of the world's population will live in urban areas while the global freight demand is expected to triple according to ITF (International Transport Forum) studies (Nations United, 2018).

In the context of freight transport, last mile distribution represents one of the most serious problems in urban areas of large cities. For instance, in Europe, approximately 10-15% of vehicle kilometres (CIVITAS, 2015) are travelled by urban freight vehicles. Moreover, the last mile is considered as one of the most expensive, inefficient and polluting parts of the supply chain. Freight vehicles are responsible for more than 50% of NO_x emissions of the transport sector (Dablanc, 2011). Additionally, the fact that most of the door-to-door deliveries are done by small vans implies that the carbon footprint per kg is higher than that of transport by a bigger truck. This growing number of vehicle and transport needs in urban areas is having a severe impact on cities' quality of life.

In addition to that, today the e-commerce model is fully accepted in almost all societies and is present in all sectors of the economy. The numbers prove it: according to the National Institute of Statistics (INE) and the National Centre of Markets and Competition (CNMC), in Spain the internet sales have grown by 37% from 2014 to 2017. Whereas in the city of Barcelona, in 2017, freight transport represented approximately 21% of total traffic, which in absolute values was about 430.000 daily trips per year (Pimecomerç, 2018).

However, these same figures also indicate that there is still much growth ahead, given that there are other countries that show much higher levels of penetration of e-commerce. In fact, according to Europe last mile data, issued by the European Commission, in the period between 2005 and 2050 the transport of goods will increase by 80% (Commission, 2011).

Undoubtedly, the situation is testing the limits of the infrastructures of our larger cities, which will require the drastic restriction of CO_2 emissions due to the high levels of air pollution as proposed by EEA (European Environment Agency). Consolidation schemes (Janjevic and Ndiaye, 2014) are one of the most popular measures in city logistics. The most common of them being the Urban Consolidation Centres (UCCs).

The key purpose of UCCs is avoiding the need for freight vehicles to deliver part loads into urban areas (Browne, Woodburn and Allen, 2007).

Different cities, mainly in continental Europe, have conducted studies, trials and showed the growing interest in the UCCs (for instance, the UCC case initiatives of Parma in Italy, Huddinge in Sweden and Sheffield in UK) (ProSFeT, 2018).

However, despite their popularity, many researchers have also demonstrated the limits of the Urban Consolidation Centres, the difficulty to implement them in a competitive environment and their limited benefits (Ville, Gonzalez-Feliu and Dablanc, 2013).

Danielis, Rotaris and Marcucci (2010) have demonstrated that in few cases the UCCs survived financially without public subsidies or strong political commitment. Allen (2012) confirms that the success of the UCC is greatly dependant of its type and implementation conditions. The financial considerations are often too complicated and need to be resolved with schemes requiring on-going public subsidies for UCCs that serve part or all of an urban area. UCCs are successful only in specific conditions and most often with structural public subsidies. (Janjevic and Ndiaye, 2014)

Nevertheless, many innovative experiences have been performed in the cities across the globe (for instance, Manchester in UK, Stockholm in Sweden, Helsinki in Finland), offering a large panel of alternative consolidation schemes. In particular, many experiences have focused on downscaling the consolidation effort by grouping goods much closer to the point of reception, whereas UCCs do so outside the boundaries of the urban area.

Generally, these experiences are referred to as “micro consolidation initiatives” where the scale of the consolidation is smaller, and thus the size and weight of transported goods is also smaller.

Micro consolidation initiatives usually involve the urban light freight. In fact, bundling the goods near the reception point requires the setting-up of facilities in the heart of urban areas, making these initiatives unsuitable for heavy loads.

Some of the common characteristics of these micro consolidation initiatives are:

- The aim to reduce the total vehicle trips performed in an urban area (and particularly in most dense areas) by bundling the goods close to the final destination.
- The setting-up of logistical facilities in urban areas.
- Targeting the deliveries of small and light loads (i.e., parcels as opposed to pallets) that can be grouped under the common denomination of “urban light freight”.
- The use of clean vehicles or soft transportation modes (cargo bikes) for the last leg of the delivery.

Using micro consolidation centres located closely to the final destination is a frequent solution for the improvement of last mile delivery and collection. Moreover, there are alternative consolidation schemes. Verlinde, Macharis and Witlox (2012) have provided a first classification of the alternative schemes based on the nature of the measure (behavioural or physical), and a further classification of physical measures that consist of either traditional urban consolidation centres or alternative transhipment points. Whereas, the logistic spaces are classified according to spatial dimension i.e. the size of the urban area that is served, and that can vary from one building or street to a whole city. Some of these measures focus on small urban areas: loading and unloading areas, collection points and smart points.

The objective of this paper is to show the implementation of a pilot case, present the results and draw conclusions for other similar measures. Whereas the overall objective is to demonstrate that, compared to the conventional ways and vehicles used for the distribution of goods in the urban area of the city of Barcelona, the implementation of a new business model such as the micro urban consolidation centre (mUCC) would help reduce emissions as well as vehicle kilometres.

The paper offers a comparison between the deliveries with electric cargo bikes and deliveries with standard vans in urban areas in terms of CO_2 emissions, noise, and energy consumption. Moreover, the paper also presents a description of the business model used for the implementation of the pilot case in the “Ciutat Vella” of Barcelona.

For the purpose of this article, a thorough research has been carried out in order to establish a state of the art and the different types (see Figure 1) of micro consolidation measures currently implemented in the European cities. These types are:

1. Loading and unloading areas consist in setting-up zones where carriers can load and unload the goods destined to the neighbouring receivers. In addition to reducing parking problems and better accommodating trucks, the setting-up of this type of devices also reduces the vehicles-trips to be performed in the delivery area.
2. Collection point (Click and collect) consists in setting-up an urban service where carriers can deliver their goods to a communal delivery point. This service can be used by private or business customers. In addition to providing a new service and allowing off-hours deliveries, these points also aim to reduce the total vehicles-trips in the delivery area by bundling goods at the reception point.
3. The smart points are boxes that bundle the goods at reception and enable the deliveries in the absence of the receivers by setting-up automated lockers. This typology is valid for both business and private customer are currently used in different European cities for the delivery of letters and parcels in absence of the receivers. The lockers can be installed in the streets, residential zones, office

buildings, among others to create new many-to-many hubs between the company and the customers.

4. Micro consolidation centres (platforms) adopt a similar scheme as one of the classical urban consolidation centres - bundling the goods, combined with a fleet of non-polluting vehicles making rationalized rounds. However, as opposed to UCCS, micro consolidation centres are much closer to the delivery area and have a more limited spatial range that is conditioned by the range of vehicles used for the last mile (generally clean vehicles such as such as cargo bikes or light electric vehicles). Furthermore, the bundling of goods usually takes place in a suburban depot from where a consolidated transport is performed towards the micro consolidation centre.
5. Logistic facilities bundle goods and perform consolidated transport to the city centre where a transhipment point (i.e., a loading and unloading area) is used to transfer goods to lighter and more adapted vehicles.
6. Logistic facility in a combination with a mobile micro consolidation centre that is used to perform the consolidated transport of goods towards the urban area and that contains all the necessary equipment and vehicles for the last mile of the delivery.
7. Micro consolidation centres in combination with a Smart Point can be used by different distribution companies at the same time. The purpose of the local distribution station is to reduce the number of delivery vehicles in the city centre and to support carbon neutral logistics. The service is aimed at residents and commuters. Generally, the location of this hub is strategic, in order to make it easy for public transport users and pedestrians to grab a pre-ordered shopping bag from the hub.

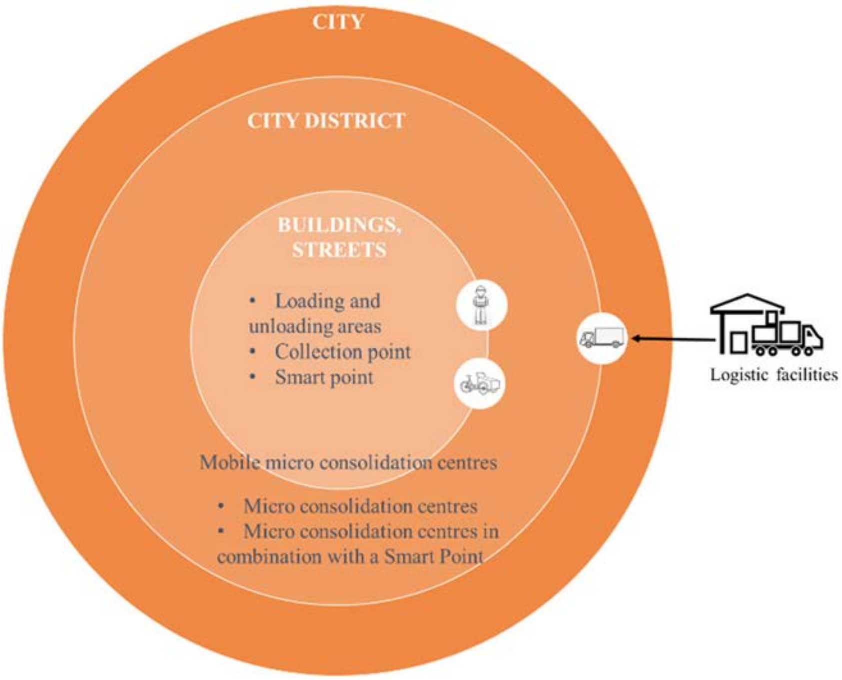

Figure 1: Urban logistic spaces within the city

This paper is based on a study case that analysed a micro urban consolidation centre (mUCC) where transport operators could store their products and transfer them to electric cargo bikes for the last mile urban distribution, covering a high-density area in the old town of Barcelona (narrow streets and stores). The project database was built with data from January 2017 to March 2019.

The remainder of the paper is organized as follows. The second section provides a brief review of the state of the art, giving context to the micro urban consolidation centres. The second section describes the study case in Barcelona. This is followed by the calculations of the key performance indicators, in the fourth section. The fourth section is an assessment of the environmental impacts. Then, the fifth section explains the business model in this study case. The following section offers a discussion of the results and policy recommendations.

2. THE DESCRIPTION OF THE STUDY CASE

Barcelona has opted for micro consolidation centre of goods to incentivize the use of friendlier transport. A consolidation centre was installed next to the "Estació de França" to serve the old town (
Figure **2**). It is an area of 4,49 km2 characterized by narrow streets, high density and an import commercial activity (the majority are small stores and restaurants) with high demand. Moreover, the area is characterized by a lack of parking space. Thus, freight delivery in this area can be critical if carried out by vans. The implementation of the solution was part of the Growsmarter project that ended in 2019.

However, the consolidation centre is still active and running.

The micro consolidation centre operates in the following way:

- The services of the last mile operator (independent operator) can be contracted by any logistics operator.
- The micro consolidation centre, owned by an independent operator, is the place of transhipment of all packages from vans to sustainable vehicles and is also used as a small storage place.
- The last mile distribution is carried out by electric cargo bikes.

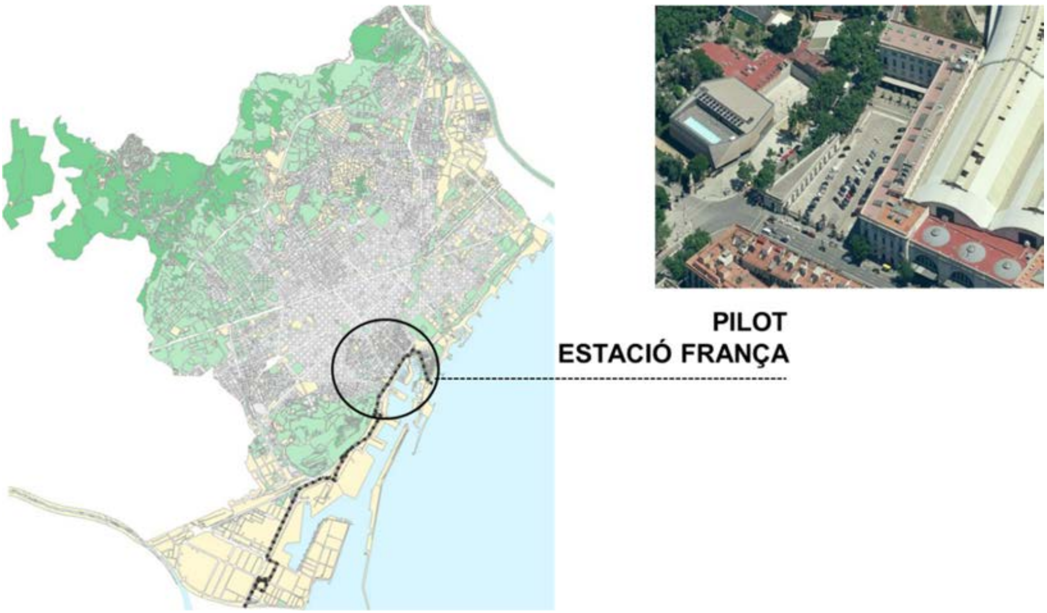

Figure 2: Area of delivery

Carriers bring their packages to the consolidation centre and the last-mile operator handles the delivery of goods to their final destination using electric cargo bikes, thus reducing congestion, diminishing emissions, and lowering delivery times in the highly populated areas as well as reducing costs for conventional carriers. During the implementation of the measure there was an increase in the use of electric cargo bikes, from 3 to 15 vehicles, and a modal shift from vans to electric cargo bikes.

3. CALCULATIONS OF THE KEY PERFORMANCE INDICATORS

The data was collected for a period of 26 months (from January 2017 to March 2019) as part of the Growsmarter project where the last mile deliveries were carried out through the usage of electric cargo bikes.

3.1 Vehicle kilometre reduction

The vehicle-km reduction was calculated as follows:

- It was assumed that, without this last mile delivery service, the deliveries were performed by regular vans. With the new service, last mile delivery was carried out by using cargo bikes, allowing the shortening of the routes, since cargo bikes can run through narrow streets (which do not allow access to regular vehicles).
- From the data collected from the trips, which were provided by the logistic operator involved in the study case, the difference in vehicle-kilometres between the two types of delivery was calculated.
- In Figure 3, it is possible to observe an example of a route in the studied area. As observed, the difference between the two routes (with vans and with cargo bikes) is 1,5 km.

Figure 3: Example route: the route of the van is blue, and the cargo bike route is orange

3.2 CO_2 reduction

An interview with the last mile operator was carried out as part of the study and the information provided by the interviewee was used for the calculations. The interview provided data and information about the number of cargo bikes, number of packages per cargo bikes and type of contract for each logistics company, among others.

In order to calculate the reduction of emissions obtained, a comparison was carried out between the emissions of the electric cargo bikes and the standard delivery vans. These steps were followed:

- The first step consisted of the calculation of the total number of kilometres travelled during the evaluation period (26 months) by cargo bikes taking into account all deliveries. The data on kilometres was provided by the logistic service provider that used GPS to track it. For example, during the Growsmarter project the cargo bikes travelled an amount of 72.183 km.
- The second step consisted in the conversion of the kilometres travelled by electric cargo bikes (calculated in step 1) to the equivalent kilometres that would have been carried out by standard courier services for the same deliveries. The conversion was implemented taking into account the route differences between the vehicles as shown in the example of Figure 3.
- During the third step, the calculation of the energy required by the cargo bikes was carried out. The energy required by the vehicles was represented by the capacity of the electric battery. To carry out the calculations of the energy that the standard services. would have consumed, the Catalan energy mix (Climàtic, 2020) was used.

This mix represents the average value of kg CO_2 emissions that 1kwh of produced energy generates. Two conditions were taken into account for the calculations:

1. The standard courier services (by truck/van) used for distribution produce local emissions.
2. The production of electricity (for cargo bikes) does not generate local emissions (only at the energy production site, if any).

- Finally, the amount of CO_2 emissions by the standard courier services was calculated considering the kilometres travelled as obtained in step 1 and the reference value in kg CO_2/km obtained from EEA (European Environment Agency, 2019) for standard delivery vans.

3.3 Energy saving

To calculate the savings in energy, a comparison between the energy needed for the cargo bikes and the energy needed for standard delivery vans, was carried out.

The energy of the cargo bikes is represented by their capacity. Thus, the total energy needed by the cargo bikes during the evaluation period was obtained by multiplying the capacity by the number of cargo bikes available and the number of working days.

To calculate the energy consumed by standard delivery vans, the total number of kilometres was multiplied by the amount of fuel per km.

Finally, the comparison between the values obtained was carried out. To carry out the calculations, get real values, better understand the practices carried out by logistic operators and cope with the reality of the sector, the interview with the last mile operator was of utmost importance.

3.4 Noise reduction

To calculate noise reduction in the pilot area, a comparison was carried out between the noises emitted by cargo bikes and noise emitted by standard delivery vans.

The number of cargo bikes available for the pilot was 15. Taking into account that approximately 1,5 cargo bikes were needed for each van (information obtained from the interview), the number of vans necessary for the same deliveries would have been 10.

The noise reduction was calculated assessing and comparing the noise a standard van generates in average for each operation (approx. 80 dB) with the noise generated by a cargo bike (approx. 45 dB). Since, decibels are a logarithmic scale, an increase of 10 decibels (dB) is perceived as a doubling of noise volume. The number of decibels from multiple sources cannot simply be added to get the total number of decibels.

If two trucks that produce 80 dB of noise each are passing the same location at the same time, they will produce a total of 83 dB. Table 1shows an approximate scheme for the calculation of the noise from overlapping of multiple sources. The table is accurate within 1 dB of the exact value.

Adding Decibel Amount differ by:	Add this amount to the higher value	Example
0 or 1 dB	3 dB	70 dB + 69 dB = 73 dB
2 or 3 dB	2 dB	74 dB + 71 dB = 76 dB
4 to 9 dB	1 dB	66 dB + 60 dB = 67 dB
10 dB	0 dB	65 dB + 55 dB = 65 dB

Table 1: Example of noise calculation (Rudy Hendriks, Bruce Rymer, David Buehler, 2013)

4. ASSESSMENT OF THE ENVIRONMENTAL IMPACTS

During the study period of 26 months when the data was collected (with the exception of June 2018, because there were contractual changes between the micro consolidation centre company and the different logistics companies), the number of deliveries has undergone large variations as can be observed in Figure 4. Despite the increase experienced during the first 6 months of the year 2017, the summer represented a difficult time for the company.

However, the difficulties encountered were due to the fact that one of the main logistic companies stopped using the micro consolidation centre. This fall was observed only for a few months, and as of October 2017, the number of deliveries carried out raised up again. From this point of inflection, they remained constant for a year. From October 2018 until March 2019, a new company joined and helped double the number of deliveries. During the study period, a total number of 207.000 deliveries was carried out.

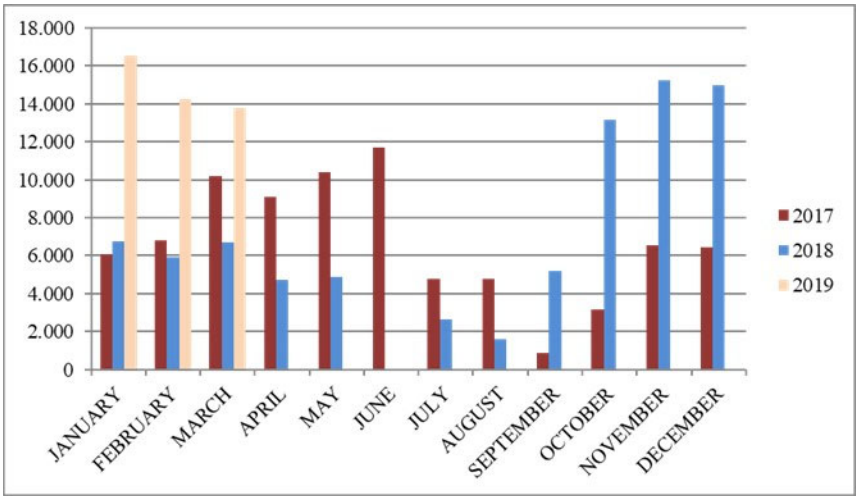

Figure 4: Number of monthly deliveries

Looking the data at a more disaggregated level, the distance between two delivery points is displayed in Figure 5. It can be noted, that with the increase of the number of cargo bikes available, the distance between delivery points decreases. The lower the distance between two delivery points, the more optimized and efficient are the routes, therefore a higher number of packages arrive on the micro consolidation centre for delivery because a higher number of logistic operators employ the service.

The overall average distance between two delivery points during the study period was 427 m.

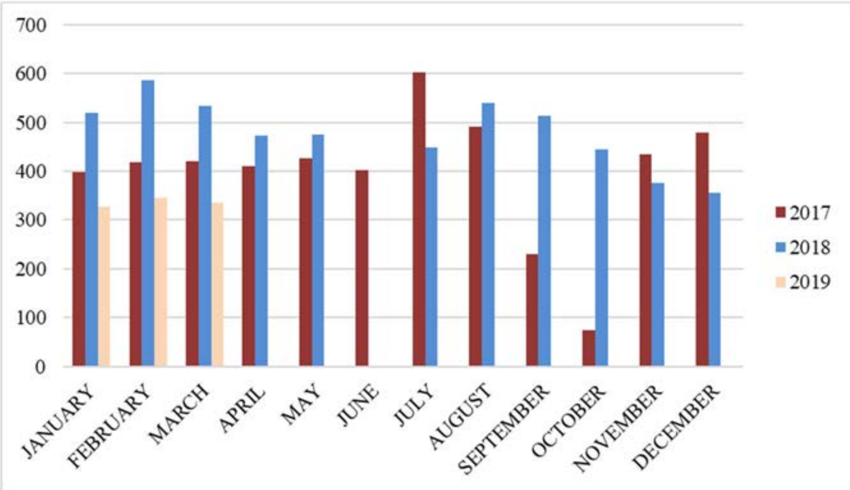

Figure 5: Distance between two delivery points (m)

More in detail, the number of expeditions carried out per hour is plotted in Figure 6. The expected number of hours corresponds to the time needed for the trip, excluding the time required for loading the cargo bicycle, for example, at the beginning of the route or the time used for lunch stops. On average, during the study period, 7,12 deliveries per hour were carried out.

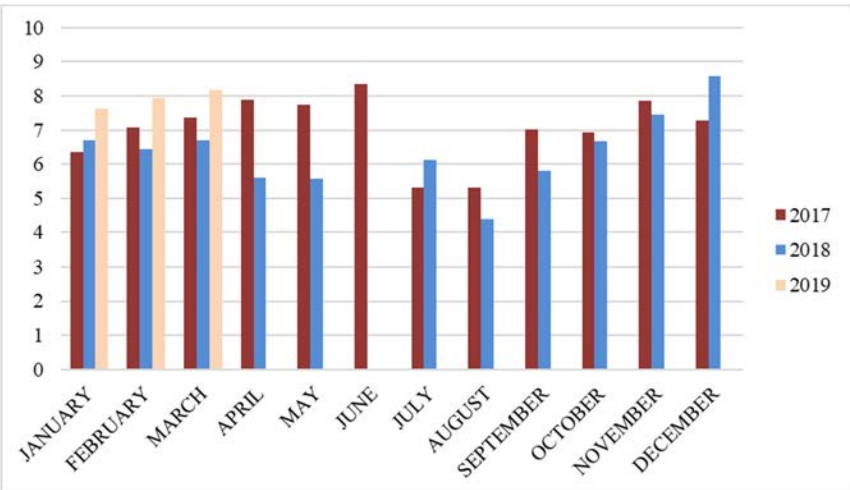

Figure 6: Expedition per hour

Moreover, the number of kilometres travelled by each cargo bike per day is shown in Figure 7, with an average of 19.3km per day. The figure indicates the variations that have occurred over the study period. The variations are lower during the end of the pilot (2019), because the micro consolidation centre has been used by more logistic companies than the ones operating in the study zone.

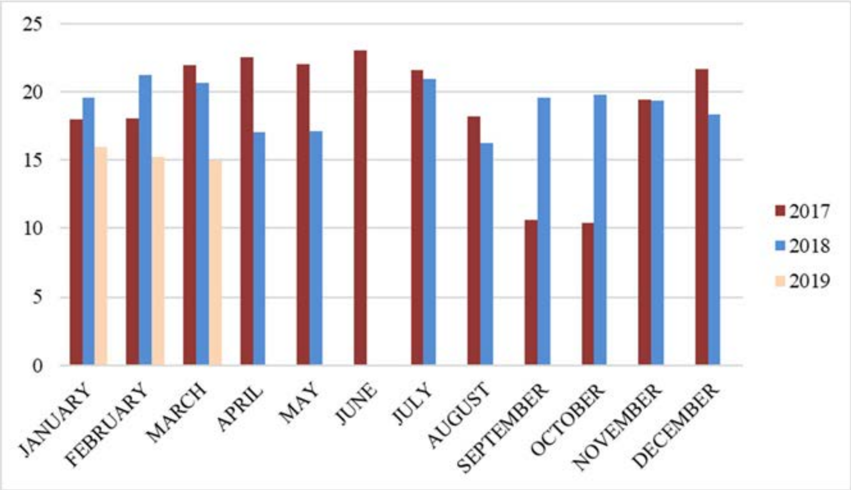

Figure 7: Number of daily kilometres covered per cargo bike

The number of kilometres covered by the cargo bikes during this time period is shown in Figure 8. It can be noted that it follows a similar shape to the curve of the number of deliveries (see Figure 4). Moreover, as can be seen from the figure, October 2018 was the month in which the highest number of kilometres was covered, more than 5.000 km.

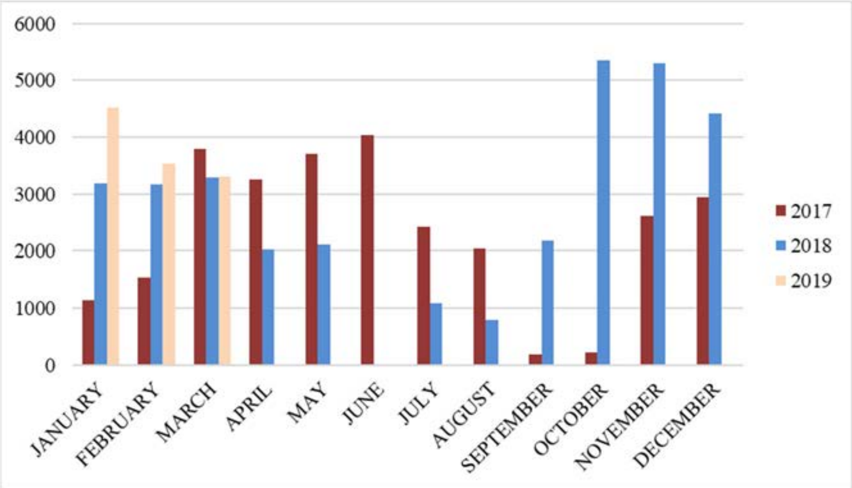

Figure 8: Total distance covered by all vehicles monthly (km)

Table 2 presents the main indicators calculated to check if the modal change in last mile distributions in the old part of Barcelona has helped reducing pollution, energy and noise.

	Average emissions per heavy vehicle kilometre (kg CO_2/km)	Average energy use per heavy vehicle kilometre in the site (kWh/km)	Number of heavy vehicle kilometres shifting to renewable fuels (km)	Number of bicycle/tricycle kilometres needed to perform the same deliveries (km)
Key indicators baseline	0,26	0,79 kwh/km	101.778 km	0
Key indicators 26 months	-	-	0	72.183 km
	Total estimated reduction of emissions (kg CO_2) based on indicators	Total estimated reduction of energy use (% kwh) based on indicators	Total estimated reduction of emissions (% CO_2) compared to baseline	Total estimated reduction of noise (dB) based on indicators
Key indicators baseline	27.084 kg CO_2	80.970 kwh	-	115 dB
Key indicators 26 months	1.085 kg CO_2	97,55% kWh	95,99% CO_2	90 dB

Table 2: KPIs evaluated

The reduction in terms of emissions generated in kg of CO_2 using electric cargo bikes instead of heavy vehicles is 95,9%. Similarly, the energy reduction between these two types of vehicles is about 97,5% and the noise reduction is about 22%.

Finally, the data gathered during the pilot study indicates that the implementation of the micro consolidation centre helped reduce the number of vans circulating in the area as well as pollution, congestion and noise.

5. BUSINESS MODEL

The current study takes into account the business model based on the micro urban consolidation centres. Through the business model, the municipality aimed at making these services economically autonomous with no need for monetary subsidies.

The business model was created following the canvas methodology. The following table summarizes it:

<table>
<tr><th>Key Partners</th><th>Key Activities</th><th>Value Propositions</th><th>Customer relationships</th><th>Customer Segments</th></tr>
<tr><td rowspan="3">1) Carriers / Transportation companies
2) City council / local governments</td><td>1) Reception and consolidation of goods into the consolidation centre
2) Operating the micro distribution centre
3) Delivery to their final destination using cargo bikes
4) The Workshop</td><td rowspan="3">1) Customers / citizen: increased time frame to perform deliveries and extended delivery coverage
2) Traditional carriers: they avoid entering the limited access and pedestrianized areas of the city centre and costs saving. The sensors in the cargo bikes can help optimizing delivery routes, and to make it more competitive for the last mile operator
3) Community: reduced environmental and noise impact
4) City Council: to monitor the noise and pollution levels in that area</td><td>1) Customer support
2) Personal assistance</td><td rowspan="3">1) Users / customers
2) Carriers / Transportation
3) City Councils / Municipalities</td></tr>
<tr><td>Key Resources</td><td>Channels</td></tr>
<tr><td>1) Physical assets (UCC construction and maintenance, electric cargo bikes)
2) Human resources (Delivery staff, operation staff at the consolidation centre)
3) Technology
4) Public Financing</td><td>1) With users/consumers: website and mobile phone apps
2) With City Councils: WLAN communications
3) With carriers: sales force and web sales</td></tr>
<tr><td colspan="2">Cost Structure</td><td colspan="3">Revenue Streams</td></tr>
<tr><td colspan="2">1) Fixed costs (Running costs, Salaries, Cargo bikes)
2) Variable costs (Costs of operating the micro distribution centre)</td><td colspan="3">1) Fee charged from carriers
2) Delivery fee charged from customer</td></tr>
</table>

Table 3: Business model canvas

With regards to Table 3, three main considerations are taken into account: (1) the main revenues are dedicated to delivery parcel (which is very scarce). Additional revenues are provided through maintenance/repairs to other cycle companies or electric cycle owners and by pick-up points (storage services); (2) the rent of offices of the logistics company in this case, is responsibility of the City Council; (3) the more efficiently parcels are delivered, the more profitable can the company be.

The micro consolidation centre is managed by a company which negotiates different conditions with each logistics company. These conditions might include different benefits per package delivered, advertising of the logistics company on the cargo bikes, uniform for distributors etc. The procedure followed for the delivery consists in each logistic company sending their packages to the micro consolidation centre (early in the morning) which are then delivered by the cargo bike operators to their end customer. Nevertheless, the details of the agreement between the last mile company and the logistics companies are confidential and cannot be presented.

During the current study, all logistic companies used a micro consolidation centre which was managed by a company that offered last mile solutions. However, there is a risk that partners (logistics companies) may build their own micro consolidation centres of a high enough parcel delivery density to be profitable. If such thing happened, we would increase the number of micro consolidation centres and thus the number of cargo bikes moving through the city as well as the number of vehicles that distribute parcels in the different micro consolidation centres.

Thus, the best solution would be to use shared micro consolidation centres, in order to reduce the risks and optimize the routes and last mile deliveries. Moreover, a neutral stakeholder/company should operate the micro consolidation centre, otherwise, it would be unlikely to be accepted by all the logistic operators, who should be ensured that they will not lose clients as there is tough competition between them. The city – or another public authority – should take care that the neutral operator stays neutral.

6. CONCLUSIONS

This paper describes the pilot case of a micro consolidation centre located in the oldest part of Barcelona. On-bike sensors were installed to assist with routing and to monitor the service and environmental conditions for research purposes along the routes. Over 207.000 journeys were made by the e-cargo bikes over a 26-month period, reducing CO_2 emissions by approximately 96% compared to delivery by trucks, and also cutting noise and pollution.

The results indicated that the reduction of vehicle kilometres, emissions, energy and noise could be achieved by using micro consolidation centres with cargo bikes for urban last mile distribution.

Last mile delivery is an emerging market segment, and creative support from city administrations is needed to accelerate a transition to sustainable delivery systems. Such support could be given in terms of e.g., designating a zone for deliveries with a dense population and high turnover of parcels; mandating actors to deliver within the zone and monitoring non-compliance; and – in this case – identifying premises and agreeing a tenancy arrangement to enable implementation. Identifying a suitable location for the service, agreeing the terms of operation, and ensuring a suitable installation of the sensor units on the bikes were the main challenges and achievements. It is important to reach a trade-off between robustness, safety and functionality.

The urban freight transport possibilities are generally determined by policies of public authorities, such as the local government, the national government, and for some issues even the European Commission (e.g., setting EURO-standards for truck engines).

However, lessons learned from past experiences in European projects show that success in implementing urban freight logistics measures such as the micro consolidation centres, requires the involvement of multiple stakeholders. Private, public and community stakeholders are all impacted by last mile issues and/or could potentially play a role in developing their solutions.

ACKNOWLEDGEMENTS

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OPERATIONAL EFFICIENCY OF LAST MILE DELIVERY THROUGH DATA ANALYTICS

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RESUMEN

Hoy en día, las ciudades están experimentando un proceso de urbanización, y el transporte urbano de mercancías tiene que hacer frente al actual auge del comercio electrónico, que produce un fuerte aumento de la actividad de transporte de mercancías y complica la logística de las ciudades. A partir de los resultados de un caso de estudio real, este artículo pretende identificar las principales (in)eficiencias de las entregas postales de última milla en condiciones reales de tráfico, tanto en términos de consumo energético como de características operativas. Con esta investigación, se quiere ofrecer una visión más amplia a los planificadores de transporte y a los responsables políticos en cuanto a la gestión, planificación y funcionamiento de la distribución urbana de última milla.

Durante un mes, trece conductores de una misma empresa logística condujeron vehículos ligeros eléctricos y diésel para sus entregas habituales. Mientras tanto, se registraron instantáneamente la posición GPS, la velocidad y otros parámetros de los vehículos: se analizaron 242 rutas de reparto, cada una de las cuales duraba unas 4 horas. Se identificaron 4.479 microviajes de entrega de paquetes individuales, correspondientes a 7.262 km de ruta recorrida en el centro de la ciudad y en la zona periurbana de Madrid.

Los resultados de este análisis subrayan claras ineficiencias en el rendimiento actual de las entregas de última milla, tanto a nivel energético como a nivel operativo. En este contexto, una gran proporción de las entregas de última milla consideradas en el estudio debería pasarse a modos de transporte no motorizados, especialmente en el centro de la ciudad, ya que el 40% de ellas se caracterizan por una velocidad media inferior a 10 km/h. Además, la proximidad de los puntos de entrega entre sí, la falta de espacio de aparcamiento y los frecuentes atascos producen una considerable ineficiencia en términos de consumo energético. A través de este estudio, se pone de manifiesto que la mayoría de las ineficiencias operativas en las entregas de última milla son similares independientemente de la zona de entrega, pero las soluciones deberían variar en función de ellas. Los responsables de las administraciones de las ciudades y los operadores logísticos deberían trabajar de forma proactiva para desarrollar nuevos esquemas logísticos que minimicen los impactos negativos del transporte urbano de mercancías, cambiando las tendencias actuales de altas emisiones que producen.

1. INTRODUCCIÓN

Según el informe social de las Naciones Unidas, a partir de 2020 más del 50% de la población mundial vive en zonas urbanas (Naciones Unidas, 2020), lo que produce, entre otro, un aumento inevitable del movimiento de mercancías dentro de las ciudades. Debido a la antigüedad de las flotas de vehículos y a la frecuencia de sus paradas, el reparto urbano de mercancías es responsable de elevadas emisiones locales y afecta directamente a la salud de los ciudadanos: en las grandes áreas urbanas europeas, los vehículos de carga son responsables de un tercio de las emisiones de NOx relacionadas con el transporte (Macharis y Melo, 2011; Marcucci et al., 2017).

Por otro lado, el reciente crecimiento del comercio electrónico ha dado lugar a un aumento significativo del número de entregas directas al consumidor y a los retos asociados de "última milla", sobre todo en las zonas urbanas (Savelsberg y Woensel, 2016). De hecho, la entrega de última milla suele ser uno de los capítulos más caros, menos eficientes y más contaminantes de la cadena logística (Gevaers, et al., 2011): los problemas de los costes de la entrega de última milla suponen posiblemente entre el 13% y el 75% del coste total de la logística.

En los últimos años, se han investigado y promovido diferentes estrategias e iniciativas para hacer frente a los retos de la entrega de última milla. Para aumentar su eficiencia y mitigar los impactos negativos medioambientales y socioeconómicos, los estudios anteriores se centraron en identificar soluciones estratégicas, administrativas o de planificación urbana específicas para la logística urbana. Entre otras, herramientas relativas a la mejora de las rutas de los vehículos, flotas logísticas “verdes y limpias”, las innovaciones tecnológicas de los vehículos y la cooperación de los competidores (Savelsbergh y Woensel 2016).

A pesar del creciente interés por el tema, hay una escasez de estudios basados en datos reales sobre la entrega de última milla, lo que permitiría comprender en profundidad el problema. De hecho, muchos estudios se basan en simulaciones haciendo que la mayor parte de la investigación actual sea cualitativa y no cuantitativa. Como consecuencia, las soluciones propuestas suelen ser excesivamente amplias y generales, sin diferenciar por contexto geográfico y entorno urbano. Teniendo en cuenta estas limitaciones, esta investigación pretende contribuir a la comprensión de las actividades de transporte urbano de mercancías y a reducir su impacto negativo en la sociedad.

Basándonos en un caso de estudio real, investigamos los principales patrones y características operativas de las entregas postales de última milla en diferentes contextos geográficos dentro de la Comunidad de Madrid, en España.

A través de una campaña de toma de datos reales realizada en colaboración con Correos, obtenemos datos que muestran la eficiencia (o ineficiencia) operativa de los envíos postales de última milla en diferentes entornos, siendo urbanos y periurbanos. El objetivo de la investigación es demostrar cómo las características operativas pueden variar en una misma empresa logística según el contexto geográfico. Además, se pretende poner de manifiesto la inadecuación de la aplicación de determinadas soluciones en algunos entornos urbanos.

2. TENDENCIAS Y ESTADO ACTUAL DE LA DISTRIBUCIÓN URBANA DE ÚLTIMA MILLA

En 2020, el último informe social mundial de las Naciones Unidas afirma que, por primera vez en la historia, hay más gente viviendo en las ciudades que en las zonas rurales (Naciones Unidas, 2020). De hecho, cada vez más, existe una tendencia de desplazamiento de la población del campo a la ciudad. En la actualidad, el 55% de la población mundial vive en zonas urbanas, una proporción que se espera que aumente hasta el 68% en 2050: las proyecciones muestran que la urbanización, combinada con el crecimiento global de la población mundial, podría añadir otros 2.500 millones de personas a las zonas urbanas en 2050 (Naciones Unidas, 2020). En el transcurso de un siglo se habrá producido un cambio de paradigma: el entorno vital menor se ha convertido en el dominante (Monzón y Boggio-Marzet, 2020). Por ello, el sistema de transporte debe seguir el ritmo de esta tendencia a la urbanización; debe adaptarse y tratar de avanzar hacia la aplicación de estrategias de movilidad sostenible.

En este contexto, un transporte de mercancías eficiente y bien planificado puede mejorar el funcionamiento de una ciudad y aumentar su competitividad. De hecho, es necesario considerar la movilidad de las mercancías en las zonas urbanas no solo como una cuestión de tráfico o medioambiente, sino también como un problema concreto de gestión de un sistema socioeconómico complejo, ya que afecta a las funciones de uso de todo el "sistema" de la ciudad. Es necesario encontrar soluciones que permitan alcanzar un equilibrio entre un sistema logístico urbano eficaz y un nivel sostenible de externalidades producidas, con especial atención a la congestión del tráfico, las emisiones contaminantes y la seguridad.

Según el Programa de las Naciones Unidas para el Desarrollo, las ciudades representan entre el 60% y el 80% del consumo de energía y al menos el 70% de las emisiones de carbono, a pesar de que sólo ocupan el 3% de la superficie terrestre (PNUD 2019). Otra vez, la evolución de la movilidad urbana resulta ser una clave fundamental para cambiar la realidad actual de un entorno poco propicio para una adecuada calidad ambiental.

Estudios anteriores estiman que el transporte urbano de mercancías representa hasta el 30% de las emisiones totales del tráfico, dependiendo del contexto local (Marcucci et al., 2017).

Dentro de la movilidad urbana, la entrega de última milla es el último tramo de la cadena logística directa al consumidor, y suele ser uno de los capítulos logísticos más caros, menos eficientes y más contaminantes (Gevaers, et al., 2011). La entrega de última milla se define como el movimiento de mercancías desde un centro de transporte hasta el destino final. Así, además de las externalidades reconocidas en la mayor parte de la literatura (como el tráfico, la ocupación del suelo urbano, las emisiones de GEI y el ruido), los problemas de LMD también están relacionados con la recogida de mercancías y correos, y con aquellos paquetes que son objeto de reclamaciones o entregados a un cliente final equivocado. Todo ello, puede suponer entre el 13% y el 75% del coste logístico total de una empresa.

Además del fenómeno de la urbanización, el sistema de transporte urbano de mercancías tiene que hacer frente al actual auge del comercio electrónico, que ha producido un aumento drástico del número de paquetes entregados cada día y ha incrementado las expectativas de los clientes, que ahora incluyen no solo la entrega rápida sino también la gratuita. Solo en España, el comercio electrónico superó los 48.800 millones de euros en 2019, lo que supone un aumento de casi el 25% desde el año anterior, con un incremento interanual constante (Comisión Nacional de los Mercados y la Competencia, 2020). Según Ragás Prat (2018), el "Boom" del comercio electrónico conlleva dos consecuencias principales: primero, el número de entregas y, la movilidad de los vehículos de mercancías que circulan por la ciudad que se multiplica.

En segundo lugar, cualquier dirección se convierte en un potencial punto de entrega. En otras palabras, la distribución urbana de mercancías se lleva a cabo en zonas residenciales no diseñadas para acoger este tipo de operaciones a escala masiva. En este contexto, que la distribución urbana de mercancías se está transformando rápidamente y requiere respuestas urgentes por parte de los operadores y las administraciones.

Varios autores han identificado tendencias y avances tecnológicos que conducen a un nuevo paradigma de la logística urbana. Según Sevelsbergh y Woansel (2016), las tendencias de crecimiento de la población y la urbanización, junto con el aumento del comercio electrónico, el deseo de rapidez y la economía colaborativa, aumentan la complejidad de la logística de la ciudad y agravan sus impactos negativos en la congestión, la seguridad y el medio ambiente. Por otro lado, las nuevas y emergentes tecnologías, como la conectividad digital, el big data y la tecnología del automóvil, podrían impulsar la innovación en la logística de las ciudades y disminuir potencialmente estos efectos.

Para aumentar la eficiencia energética, mitigar sus impactos negativos sobre el medioambiente y hacer frente a los retos de la entrega de última milla, se promueven varias estrategias e iniciativas, como las mejoras en las rutas de los vehículos a través de la instalación de sistemas de Green navigation, la elictrificación de la flota, las innovaciones tecnológicas de los vehículos y la cooperación de los competidores (Schliwa et al., 2015;

Savelsbergh y Woensel 2016; de Mello Bandeira, et al., 2018; Alho et al., 2018; Giordano et al., 2018; Lafkihi et al., 2019; Simoni et al., 2019). Sin embargo, estas iniciativas encuentran en la práctica varias dificultades de aplicación, como la falta de información en tiempo real para ofrecer un servicio dinámico de rutas de vehículos; los costes de inversión que son muy elevados para los transportistas; y los competidores del sector del transporte de mercancías que no están dispuestos a compartir información valiosa para cooperar, ya que la misma información forma parte de su negocio. Se necesitan estrategias o soluciones factibles y rentables.

Ranieri et al. (2018) agruparon diferentes soluciones de última milla para el transporte de mercancías según cuatro aspectos principales: innovación en los vehículos, estaciones o puntos de proximidad, soluciones colaborativas y cooperativas e innovación en políticas e infraestructuras públicas. En la misma línea, Lafkihi et al. (2019) y Mangiaracina et al. (2019) llevaron a cabo una exhaustiva y extensa revisión bibliográfica sobre los retos y oportunidades del transporte de última milla e identificaron varias soluciones efectivas, entre las que se encuentran por ejemplo las entregas nocturnas, que pueden desplazar el tráfico a las horas valle, reduciendo así la congestión diurna y, por tanto, las emisiones de GEI relacionadas. Según Olsson et al. (2019), para optimizar las operaciones de última milla, las empresas pueden optar por diferentes niveles de actuación: (1) nivel estratégico, como la ubicación de los centros de distribución, (2) nivel táctico, como el tamaño de la flota y las entregas nocturnas, y (3) nivel operativo, como el enrutamiento de los vehículos.

La literatura señaló la importancia de darse cuenta de que las circunstancias geográficas, económicas, sociales y culturales afectan a la logística de la ciudad y a la percepción de la gente sobre los temas críticos relacionados con la logística urbana. Dependiendo del área de aplicación y de la intensidad, las mismas iniciativas pueden dar lugar a resultados diferentes en cuanto a la reducción de los impactos sociales y medioambientales del transporte de mercancías. Además, la mayoría de las publicaciones científicas sobre el tema abordan la política de transporte con un enfoque teórico sin presentar datos reales; otras simulan las soluciones en un área específica, sin tener en cuenta los diferentes entornos a aplicar. Faltan datos reales sobre las características operativas de las empresas logísticas, y la falta de datos reales complica la investigación de soluciones sostenibles para la logística urbana.

Resulta esencial caracterizar adecuadamente los viajes urbanos de mercancías tanto en las zonas urbanas como en las periurbanas, en las que hay una mayor demanda de movimientos de mercancías, teniendo en cuenta que todavía falta una comprensión completa del tema. Hasta donde sabemos, hay una verdadera escasez de estudios que presenten un análisis de las ineficiencias de las entregas de última milla basado en datos reales de pruebas de campo. A partir de aquí, el objetivo de esta investigación.

Tras introducir el contexto de la investigación, la motivación del trabajo y el estado del arte, la sección 3 presenta la metodología utilizada para llevar a cabo la investigación, incluyendo la definición del caso de estudio, la campaña de toma de datos y el procesamiento de los mismos. El análisis de los resultados y la discusión se presentan en la Sección 4. Por último, en la sección 5 se describen las principales conclusiones y recomendaciones futuras.

3. METODOLOGÍA

Para este trabajo se ha desarrollado una metodología sistemática. En primer lugar, se ha definido el estado del arte mediante la realización de una profunda y exhaustiva revisión bibliográfica de investigaciones y artículos anteriores (Sección 2). Esto ayuda a centrarse en las lagunas de investigación más urgentes en el transporte urbano de mercancías, proporcionando problemas y desafíos, así como comparando los impactos de las estrategias actuales ya implementadas en la entrega de última milla. Este trabajo, quiere analizar las pautas operativas de la distribución urbana de última milla, con el objetivo de identificar sus principales ineficiencias, tanto operativas como energéticas, y poder actuar sobre las mismas. Para ello, contamos con una campaña de toma de datos reales en colaboración con la empresa logística de Correos.

CORREOS es el servicio público postal de España (100% estatal) con 51.000 empleados, que distribuye más de 3.600 millones de envíos al año. Con el apoyo de la empresa, fue posible realizar la campaña de toma de datos simultáneamente en la zona de reparto urbana y peri-urbana de Madrid, gracias a la colaboración de 13 conductores profesionales de dos centros de distribución urbana (CDU) de CORREOS en la misma área metropolitana de Madrid. Además, la ventaja de colaborar con una empresa pública estatal es facilitar la homogeneidad de la muestra. De hecho, la flota de vehículos está compuesta para ambos casos por vehículos ligeros diesel y eléctricos del mismo fabricante y modelo. Además, el hecho de considerar una zona de reparto urbana y otra peri-urbana dentro de la misma área metropolitana de Madrid, hace que las circunstancias económicas de ambas zonas sean mayoritariamente homogéneas.

La campaña de toma de datos tuvo lugar en septiembre y octubre de 2018 en zonas de reparto tanto urbanas como peri-urbanas de Madrid. 13 conductores de la misma empresa condujeron a lo largo de su normal ruta de trabajo vehículos diésel o eléctricos de carga ligera mientras entregaban paquetes en el área Metropolitana de Madrid. En todos los vehículos diésel que participaron en la prueba de campo había una llave OBD preinstalada, que registraba segundo a segundo la posición GPS del vehículo, así como la velocidad, el tiempo de viaje y otras variables. Para los vehículos eléctricos, las mismas variables fueron monitorizadas y registradas segundo a segundo a través de un teléfono móvil en el que estaba preinstalada la App Mytracks.

Además de las variables registradas, a través de la programación con el software R -un entorno de software libre para la computación estadística y los gráficos- y la ayuda de ArcGis, se calcularon otras variables instantáneas relativas al comportamiento de conducción, al consumo de energía y a las condiciones de la carretera. Tras la toma de datos y el cálculo de las variables, se crea finalmente el conjunto de datos y se valida a través de su procesamiento. Así, como conjunto de datos se almacenan dos tipologías de datos: datos relacionados con el viaje y datos relacionados con el patrón de conducción.

El último paso de la metodología es el análisis de los datos. El análisis de datos tiene como objetivo caracterizar la entrega de última milla en términos de distancia, velocidad, tiempo de parada, etc., en diferentes contextos geográficos, ya sean urbanos o peri-urbanos. Para caracterizar el rendimiento operativo de la entrega de última milla y presentar en qué medida varían las operaciones de distribución para una misma empresa en dos zonas de entrega estudiadas, urbana o peri-urbana, adoptamos el método estadístico. Los resultados obtenidos, deberían proyectarse a las empresas de distribución de mercancías, para mejorar su impacto ambiental y económico.

3.1 El caso de estudio

El caso de estudio se desarrolla en el área metropolitana de Madrid, capital de España. Madrid es la principal ciudad de España, capital del país y de la misma Comunidad de Madrid. El área metropolitana asociada a la ciudad tiene una población de 6,6 millones de habitantes, lo que la convierte en una de las más pobladas de la Unión Europea; la mitad de los habitantes se concentran en la misma ciudad de Madrid (Monzón et al., 2017).
El Área Metropolitana de Madrid tiene una extensión de 8.030 km2, con una proporción de superficie urbanizada del 11%. Tres autopistas orbitales rodean la ciudad (la M-30, M-40 y M-50) a las que se accede desde siete autopistas radiales. Por lo general, el terreno que rodea la ciudad es relativamente llano, salvo la cordillera, que es relativamente remota y fronteriza, situada en el noroeste de la provincia.

Los datos en los que se basa el estudio, derivan de una campaña de toma de datos reales realizada en 2018 en colaboración con Correos, que es el servicio postal nacional español (de titularidad 100% estatal). Cuenta con 51.000 empleados y distribuye más de 3.600 millones de envíos al año. Dentro de la Comunidad de Madrid, Correos cuenta con 27 CDU que realizan la distribución en vehículo ligero: 15 están ubicados dentro de la ciudad de Madrid y 12 fuera de la ciudad. Dos de ellos, uno situado en el centro de la ciudad y el otro en la zona periurbana de Madrid, participaron en la prueba de campo, lo que hace que nuestro experimento sea bastante representativo de la realidad.

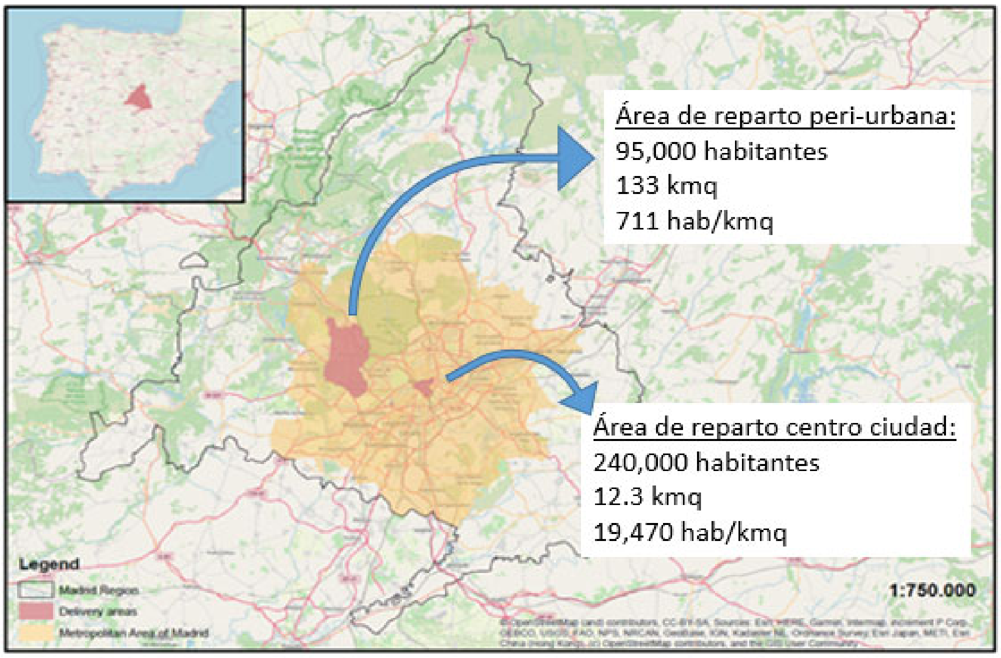

Figura 1- La Región de Madrid y las áreas de reparto del experimento

La figura 1 muestra las dos áreas de reparto involucradas en el experimento, que son un punto clave para entender las características operativas de la distribución urbana de última milla. Uno de los dos depósitos de Correos se encuentra en el municipio de Las Rozas, situado en la franja noroeste del Área Metropolitana de Madrid, y cubre un área de entrega periurbana de más de 130 km2. El otro depósito está situado en el centro de la ciudad de Madrid, y da servicio a un área de entrega diez veces menor, de unos 12 km2, pero 27 veces más densa que la de Las Rozas.

Como se ha mencionado anteriormente, el objetivo de esta investigación es determinar las principales ineficiencias operativas y energéticas de las actividades de distribución urbana de última milla. Los datos en los que se basa nuestro análisis proceden de un experimento realizado en condiciones reales de tráfico para estudiar la cuestión a partir de datos y circunstancias muy reales.

La campaña de toma de datos tuvo lugar durante cuatro semanas. Durante un mes, 13 conductores profesionales participaron en la prueba de campo, siendo 11 hombres y 2 mujeres, con edades comprendidas entre los 33 y los 62 años. Ellos condujeron vehículos de reparto eléctricos y diésel a lo largo de sus rutas de trabajo habituales, mientras que la posición GPS, la velocidad y otros parámetros se recogían instantáneamente cada segundo.

En total, se registraron 242 turnos de trabajo de reparto válidos (cada uno de ellos correspondiente a una ruta de reparto) de unas cuatro horas cada uno; así, se analizaron 1.050 horas de conducción, que cubrieron 7.262 km de recorrido.

Las rutas no estaban predefinidas, sino que el conductor las definía cada día de forma diferente para optimizar todas las entregas durante su jornada laboral. Por lo tanto, los conductores se enfrentaron a diferentes situaciones de tráfico, lo que afectó a las variables de la investigación, como la velocidad y los tiempos de espera debidos a la congestión del tráfico. No obstante, este aspecto refleja su trabajo real.

Por último, después de cada ruta de entrega, recogimos la opinión de cada conductor a través de un breve cuestionario en el que, entre otros puntos, podían informar de cualquier incidencia encontrada, como la congestión del tráfico o la falta de aparcamiento. Esta información fue muy útil para entender los problemas reales relacionados con la distribución de paquetería según las diferentes zonas de entrega.

3.2 Definición del Dataset

Para llevar a cabo el siguiente análisis y alcanzar los objetivos de la investigación, fue necesario definir el conjunto de datos en dos dimensiones diferentes: las rutas de entrega diarias – ruta de reparto - y los microviajes de entrega de cada paquete – microviaje. Cada ruta de reparto contiene un cierto número de entregas de paquetes (microviajes) cuyas características varían en función de las distintas condiciones de tráfico y entorno. Así, hemos creado dos bases de datos diferentes: la primera adopta la forma de rutas de reparto y describe los principales aspectos del reparto postal de última milla en términos de características generales de funcionamiento; la segunda permite caracterizar los patrones de conducción propios de los microviajes de reparto de paquetes individuales y comprender la ineficiencia energética durante el reparto.

Para ello, utilizamos todos los datos registrados para definir manualmente los microviajes de entrega dentro de cada ruta de reparto, basándonos en los registros instantáneos.

Seleccionamos aquellos segundos en los que la velocidad era nula, y si el tiempo consecutivo con velocidad nula era superior a 2 minutos (± 30 segundos dependiendo del posicionamiento GPS) lo considerábamos como una parada de entrega entre dos microviajes consecutivos. No obstante, este no era un criterio absoluto, y teníamos que comprobarlo manualmente con los datos del GPS. Así, creamos dos conjuntos de datos diseñados como base para el análisis mediante la programación en R, un conocido entorno de software libre para la computación estadística y los gráficos. La primera base de datos (Ruta de entrega) cuenta con 242 rutas de entrega, cada una de las cuales incluye unas cuatro horas de conducción. La segunda base de datos (microviajes) consta de 4.479 microviajes de entrega de paquetes individuales. Así, se han analizado 1.050 horas de conducción, correspondientes a 7.262 km de recorrido: 1.965 km en el centro de Madrid y 5.297 km en la zona periurbana de Madrid.

Como se ha mencionado anteriormente, nuestro objetivo es identificar las principales ineficiencias de la entrega de última milla tanto en términos operativos como de consumo energético.

En el caso de las ineficiencias operativas, nos basamos en el análisis estadístico basado en las dos bases de datos creadas, y en las opiniones de los conductores. Para el caso del análisis de la ineficiencia energética del vehículo, hemos considerado la base de datos compuesta por microviajes de entrega de paquetes individuales, considerando varios parámetros de conducción que han demostrado tener una influencia significativa en el consumo de energía del vehículo (Ericsson, 2001; Lois et al., 2019; García-Castro et al., 2018).

4. ASPECTOS PRINCIPALES DE LA DISTRIBUCIÓN DE ÚLTIMA MILLA

Una vez completado el procesamiento de los datos, desarrollamos un método de análisis de los mismos, es decir, la correcta manipulación de los elementos, para generar y abordar resultados significativos en relación con los objetivos de investigación fijados. Adoptamos métodos estadísticos para caracterizar el rendimiento operativo de la entrega de última milla, y para presentar el grado de variación de las operaciones de distribución para una misma empresa en dos zonas de entrega estudiadas (urbana y periurbana), así como sus ineficiencias. Así, en primer lugar, definimos las principales características operativas de las entregas de última milla para mejorar el conocimiento de la actividad de reparto en las dos zonas consideradas. A continuación, identificamos sus principales ineficiencias: tanto en términos de energía como de características operativas, tanto en la zona de reparto urbana como en la periurbana.

4.1 Ineficiencias energéticas en la distribución de última milla

Para tener una idea concreta de los principales aspectos de las actividades de reparto, se presenta la siguiente tabla. Distinguiendo entre zona de reparto periurbana o urbana, la Tabla 1 muestra los valores medios, así como el mínimo y el máximo, de las principales características operativas según la zona de reparto

	Área Peri-Urbana (Las Rozas)			Área urbana Centro ciudad (Madrid)		
Parámetros	Min	Max	Media	Min	Max	Media
Longitud ruta de reparto [km]	17.38	93.67	50.93	5.64	55.44	14.34
Tiempo de ruta de reparto [hh:mm]	02:27	06:22	04:24	02:02	05:58	03:57
Longitud microviaje [km]	0.02	19.22	2.25	0.01	6.82	0.77
Velocidad microviaje [km/h]	0	94.9	24.8	0	44.02	12.8
% Tiempo de microviaje con velocidad < 3km/h	0%	70%	9%	0%	87%	21%

Tabla 1- Características operativa de las rutas de reparto

A pesar de que el tiempo total para cumplir la ruta de reparto de ambos CDU implicados en la prueba de campo es similar (una media de 4 horas), en la zona de entrega urbana, la distancia media recorrida durante una ruta de entrega es de 14,3 km, que es 3,5 veces menor que en la periurbana. En el caso urbano, durante el 21% del tiempo de viaje la velocidad es inferior a 3 km/h. Además, el 50% de los microviajes en la zona es inferior a 477 metros de longitud y se realiza con una velocidad media inferior a 13 km/h.

El caso periurbano es bastante diferente en términos de características operativas. La distancia media recorrida por cada conductor durante la ruta de reparto es de 50,9 km, y la distancia media para entregar un solo paquete es de 2,25 km (SD: 3,24), lo que implica una zona bastante dispersa. Allí, el 50% de los microviajes tiene una longitud superior a 1,1 km. La velocidad media es de 25 km/h y el porcentaje de tiempo a velocidades operativas inferiores a 3 km/h es del 9%, menos de la mitad del porcentaje propio del centro ciudad.

Además, la velocidad instantánea del vehículo es un factor decisivo a la hora de definir la eficiencia energética de la entrega de última milla. La imagen siguiente (Figura 2) muestra la velocidad instantánea de un vehículo durante su ruta de reparto, tanto en zona urbana como periurbana.

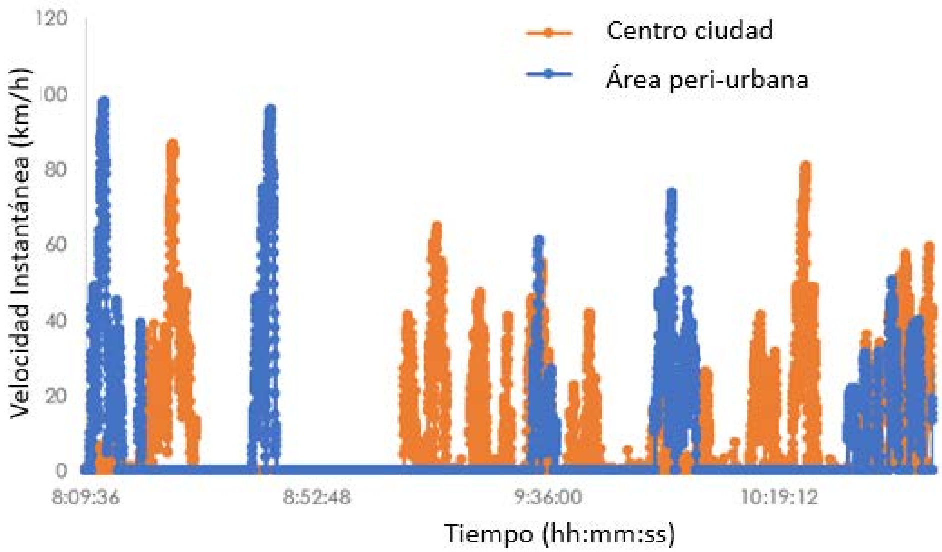

Figura 2- Velocidad instantánea del vehículo durante una ruta de reparto en centro ciudad y en área peri-urbana

En el centro ciudad, los conductores conducen casi tres veces más despacio que en área periurbana, y el 20% del tiempo en el centro ciudad el vehículo está parado debido a la congestión de la carretera, o al semáforo o al hecho de entregar el paquete en sí. De hecho, la baja velocidad de circulación puede deberse a varios factores. Según nuestros datos, en el centro de la ciudad, entre el 16% y el 27% del tiempo de viaje se pasa con velocidades operativas inferiores a 3 km/h. En concreto, el 35% de los microviajes en el centro de la ciudad tiene una velocidad media de 7 km/h, y las velocidades superiores a 19 km/h sólo se alcanzan en el 5% del tiempo de viaje. Por lo tanto, estas entregas podrían realizarse con otros medios de transporte distintos de los vehículos ligeros, ya que la distancia media de las entregas individuales es inferior a 500 m, una longitud que puede cubrirse fácilmente a pie o en bicicleta, por ejemplo. Además, la covarianza de la velocidad (es decir, la variabilidad de la velocidad durante la conducción) durante estas entregas es la más alta registrada, hasta 0,8 en la mayoría de los casos, lo que pone de manifiesto un estilo de conducción caracterizado por altas aceleraciones y desaceleraciones que, en parte debido a la red de carreteras y los flujos de tráfico, aumentan el consumo de combustible y las emisiones resultantes (Lois et al., 2019). Allí, aunque se mantenga la velocidad reducida, el alto nivel de covarianza hace que el consumo energético aumente notablemente, y en consecuencia el consumo de combustible y las emisiones.

Para aclarar el concepto, la siguiente imagen (Figura 3) muestra el posicionamiento instantáneo y la velocidad de un vehículo en zona urbana durante una ruta de reparto. Los colores se corresponden con la velocidad operativa del vehículo: rojo para la velocidad inferior a 10 km/h, amarillo para la velocidad entre 10 km/h y 30 km/h y verde para la velocidad superior a 30 km/h.

Figura 3-Posicionamiento y velocidad instantánea de un vehículo durante una ruta de reparto en el centro ciudad (Boggio-Marzet y Monzón, 2021)

En el 40% de los casos, en el centro de la ciudad, la velocidad media de un micro viaje es inferior a 10 km/h. Este aspecto debería hacernos reflexionar sobre la necesidad real de transferir las operaciones de entrega de última milla de los vehículos a medios no motorizados, especialmente en las zonas del centro de la ciudad. Además, como se muestra en la figura 3, hay algunas calles que se recorren varias veces durante la misma ruta de reparto, debido a las calles de un solo sentido típicas del centro ciudad, así como a la falta de plazas de aparcamiento. Este aspecto puede justificar en parte la bajísima velocidad de funcionamiento propia de la muestra. De hecho, el conductor se ve obligado a pasar por la misma calle varias veces durante diferentes micro viajes de la misma ruta de reparto, debido a la conformación de la red vial de la zona.

En cuanto al tema de la eficiencia energética de los vehículos, ya se ha demostrado en la literatura que las aceleraciones y desaceleraciones fuertes provocan un aumento considerable del consumo energético del vehículo (Ericsson, 2001; ECOWILL, 2013; García-Castro et al., 2018; Wang & Boggio-Marzet, 2018). Así, queremos analizar la proximidad de las paradas que el conductor realiza durante su viaje. Aparte de aquellas paradas provocadas por el tráfico, los semáforos y los pasos de peatones, el conductor, durante las entregas de última milla, debe adaptar su conducción a una especie de intermitencia de situaciones caracterizada por frecuentes arranques y paradas y, en consecuencia, por producir altas emisiones de GEI y contaminantes. Además, las entregas son prácticamente las mismas de un día a otro. De hecho, la ruta de entrega de un conductor concreto es bastante homogénea cada día, ya que cada conductor es responsable de una “microzona” determinada dentro del área de entrega del CDU.

Las variaciones menores se deben a un único cliente final situado en una carretera cercana, en un edificio concreto o en un edificio cercano, pero en la misma "microzona" de la que es responsable cada conductor.

En este contexto, sería útil realizar un análisis profundo de la geolocalización de los puntos de entrega y determinar la ubicación óptima para instalar un conjunto de “Taquillas inteligentes”. Asimismo, el 18% de las entregas en la zona periurbana se realizaron en menos de un minuto y medio, a unas decenas de metros de distancia. Estas entregas se refieren a las realizadas a lo largo de amplias vías flanqueadas por grandes casas, una al lado de la otra, con poco tráfico, donde el mensajero puede detener el vehículo justo delante de la puerta, y entregar el paquete al conserje, para luego repetir el proceso a lo largo de toda la avenida. Este proceso produce entregas con un impacto medioambiental muy elevado. Dado que los vehículos contaminan mucho durante su arranque, en aceleración y en frenado, sería aconsejable en este contexto vial implantar otro sistema de entrega.

4.2 Ineficiencias operativas en la distribución de última milla

Para este análisis, además de considerar los datos instantáneos de los vehículos implicados, hemos tenido en cuenta las entrevistas que hemos realizado a los conductores después de cada ruta de reparto. Así pues, los principales aspectos relativos a la ineficacia operativa de distribución de mercancía en las entregas de última milla se han ahondado tanto a partir del análisis estadístico como, en su mayor parte, de las entrevistas a los conductores.

La primera ineficiencia identificada en ambas áreas de reparto es el largo tiempo de espera necesario para realizar determinadas entregas. Aunque el tiempo medio de entrega es de 5 minutos, hay algunas entregas que requieren un tiempo de espera de más de una hora. En el centro de la ciudad, la entrega se realiza en una media de 04:17 minutos, con una desviación estándar de 06:14, lo que significa que alrededor del 70% de las entregas se realizan en menos de 10 minutos. En la zona periurbana, la entrega se realiza en una media de 07:25 minutos con una desviación estándar igual a 09:41, lo que significa que alrededor del 70% de las entregas se realizan en menos de 15 minutos. Sin embargo, el tiempo máximo de entrega registrado durante la campaña de toma de datos es respectivamente de 52 minutos en el centro de la ciudad y de 96 en el entorno periurbano, independientemente del conductor. Esto se debe a que, el cliente final puede ser un polígono industrial o una gran empresa con amplias instalaciones, por lo que el mensajero debe ser identificado y pasar varios controles de seguridad antes de realizar la entrega, y luego entregar en varios edificios del polígono. Desgraciadamente, no hay un único conductor responsable de todo este tipo de entregas, y por tanto no hay una ruta fija que cubra estos puntos de entrega; así, se pierde eficiencia operativa, aumentando el porcentaje de largos tiempos de espera para todos los conductores que participan en la logística de última milla.

Otro aspecto interesante es el de las entregas que fracasan, por ejemplo porque el cliente no está en casa cuando llega el mensajero o porque la dirección del punto de entrega es errónea. Si el mensajero no encuentra al cliente en casa, debe volver una segunda vez, al final de su ruta de entrega. Si el cliente sigue ausente, el mensajero transfiere el paquete al conductor responsable de la siguiente ruta de entrega, que tendrá que cambiar su ruta a propósito. Evidentemente, esto implica una pérdida de tiempo y reduce la eficacia operativa de LMD, pero también genera un gasto de consumo de energía para el vehículo, además de que se recorren más kilómetros, lo que implica que se crea más tráfico, se emiten más contaminantes, etc. El porcentaje de entregas fallidas en el primer intento ronda el 25% en ambas zonas de reparto, y se reduce al 11% en el caso de las entregas periurbanas y al 8% en el centro de la ciudad mediante las entregas posteriores. Este fenómeno tiene un extraordinario efecto negativo en el medio ambiente de nuestras ciudades, ya sea en términos de congestión, contaminación, ruido, etc. Por ello, sería interesante crear un sistema de geolocalización instantánea, aunque, en este caso, nos enfrentaríamos sin duda a problemas de privacidad entre otros.

Por último, según los informes de los conductores al rellenar la breve encuesta después de cada ruta de reparto, hay dos preocupaciones principales en sus comentarios: la falta de espacio para aparcar y los problemas relacionados con la congestión. La falta de espacio para aparcar es una de las principales razones que provocan una mayor distancia de viaje y una baja velocidad de circulación (en busca de una parcela de aparcamiento libre), lo que aumenta el uso de energía y produce mayores emisiones y contaminantes atmosféricos. En este caso, se requiere información sobre el estacionamiento en tiempo real y debería considerarse la posibilidad de utilizar otros modos, como la moto o bici eléctrica, para sustituir al vehículo motorizado en el futuro.

Cabe destacar que la falta de espacio para aparcar representa el 29% de los problemas detectados durante el reparto en el centro de la ciudad, pero, según la opinión de los conductores, no es relevante en el caso periurbano.

El otro problema clave revelado por los conductores es la congestión de las carreteras. Alrededor del 40% de las rutas de reparto realizadas informan de situaciones de atasco, independientemente de la zona de reparto considerada. Este aspecto debería ser tenido en cuenta por los responsables políticos, ya que la naturaleza profunda de los LMD se caracteriza por su corta duración, por lo que los atascos pueden tener una influencia mucho mayor en la eficiencia operativa de las entregas de última milla comparado con las entregas de larga distancia. De acuerdo con los resultados, la distribución urbana de última milla debería realizarse durante las horas valles, de menor afluencia en carretera, adoptando la información de tráfico en tiempo real para seleccionar las rutas menos congestionadas.

5. CONCLUSIONES Y RECOMENDACIONES

En los últimos años, las ciudades están experimentando un considerable proceso de urbanización, y el sistema de transporte urbano de mercancías tiene que hacer frente al actual auge del comercio electrónico, que produce un fuerte aumento de la actividad y complica aún más la logística de la ciudad. A través de esta investigación, caracterizamos las pautas clave de las entregas de última milla urbanas y periurbanas. Con el fin de cambiar las tendencias actuales de las emisiones producidas por la entrega de última milla sobre las ciudades y los ciudadanos, nos propusimos estudiar en términos cuantitativos, cuáles son las ineficiencias más evidentes en términos operativos y energéticos, en diferentes áreas de entrega de la misma región de Madrid.

Tras realizar una campaña de toma de datos reales, se analizaron 242 rutas de reparto, correspondientes a 4.479 microviajes de entrega de paquetes individuales realizados durante 1.050 horas de conducción, cubriendo un total de 7.262 km de ruta: 1.965 km en el centro ciudad y 5.297 km en la zona periurbana de Madrid. Las principales conclusiones se presentan a continuación.

De nuestros resultados se desprende que existen claras ineficiencias operativas en el desempeño actual de las entregas, tanto en términos de consumo energético como de eficiencia operativa: una gran proporción de las entregas que actualmente se realizan en vehículos ligeros deberían pasar a modos de transporte no motorizados, especialmente en el centro de la ciudad. De hecho, el 40% de las entregas en el centro de la ciudad se caracterizan por una velocidad media inferior a 10 km/h, y al ser inferiores a 400 m de longitud, estas entregas podrían cubrirse fácilmente a pie o en bicicleta cargo.

Desde el punto de vista del consumo energético, sería útil realizar un análisis profundo de la geolocalización de los puntos de entrega y determinar la ubicación óptima para instalar un conjunto de taquillas inteligentes para paquetes, ya que la mayoría de las veces los puntos de entrega a los que llegan los conductores son casi los mismos, día tras día.

Además, la proximidad de los puntos de entrega entre sí supone un gasto adicional de combustible debido a las frecuentes paradas de inicio y final de viaje que se suman a las producidas por el contexto vial, es decir, por los atascos, los semáforos o los pasos de peatones.

Desde el punto de vista operativo, nuestros resultados muestran una clara falta de homogeneidad en cuanto al tiempo necesario para la entrega. Aunque por término medio se tarda 5 minutos en hacer una entrega, se puede llegar a tardar una hora. Podría ser útil definir una ruta fija que cubra las entregas a las grandes empresas, evitando que todos los conductores tengan que experimentar los mismos tiempos de espera.

La falta de espacio para aparcar, así como las entregas fallidas y los frecuentes atascos encontrados, implican una pérdida de tiempo para el mensajero y reducen la eficacia operativa de la LMD; también generan un gasto extra de consumo energético para el vehículo, así como hace sí que se recorran más kilómetros, y, en consecuencia, se emiten más contaminantes. La distribución urbana de última milla debería realizarse durante las horas de menor afluencia y adoptando la información del tráfico en tiempo real para seleccionar las rutas menos congestionadas. A través de esta investigación, señalamos que la mayoría de las ineficiencias operativas de las entregas de última milla son similares independientemente de la zona de entrega, pero las soluciones deberían variar según el contexto geográfico.

Debido a la gran cantidad de datos analizados, esta investigación ofrece una visión más amplia a los planificadores de transporte y a los responsables políticos en cuanto a la gestión, el funcionamiento y el uso de la distribución de última milla en áreas urbanas. La misma, puede ayudar a diseñar estrategias de reducción de emisiones para que las empresas de transporte urbano de mercancías mejoren su impacto medioambiental entre otros.

Los responsables de las ciudades deberían trabajar de forma proactiva con las partes interesadas para desarrollar nuevos esquemas logísticos que minimicen los impactos negativos del transporte urbano de mercancías, cambiando las tendencias actuales de las emisiones que producen.

Las investigaciones futuras deberían ampliar el área de estudio y centrarse en medir y cuantificar el impacto de las diferentes soluciones de última milla según las circunstancias sociodemográficas.

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LOGÍSTICA URBANA FERROVIARIA Y E-COMMERCE: ANÁLISIS DE COSTES EXTERNOS DEL MODELO M4G (METRO FOR GOODS)

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ABSTRACT

Las ciudades están en el centro de la vida humana y están viviendo un intenso proceso de transformación en distintos ámbitos (económicos, sociales, medioambientales) donde la distribución urbana de mercancías aparece como uno de los grandes retos para el sector del transporte y la logística, afectando directamente a este proceso de transformación de la ciudad.

La aparición de la covid-19 ha tenido especial relevancia e impacto en la movilidad de la ciudad y en el comercio electrónico. El B2C, o negocio de empresa a consumidor, ha crecido notablemente en los últimos años y se ha acelerado a raíz de la pandemia, aumentando el acceso de la población a Internet y produciendo cambios en los hábitos de comportamiento de los consumidores. En las áreas metropolitanas, el "efecto Amazon" (amplia selección de minoristas online, envío rápido, devoluciones gratuitas y precios bajos) ha llevado a un mayor uso de vehículos ligeros en el reparto del comercio electrónico en las ciudades. Este hecho está afectando el funcionamiento racional del sistema de transporte urbano de mercancías, incluyendo un alto grado de fragmentación, baja optimización de carga y, entre otras externalidades, mayor congestión del tráfico.

Este articulo expone las principales soluciones sostenibles dentro del ámbito de la logística de la ciudad y pone el foco en los sistemas de transporte ferroviarios urbano como una posible solución a considerar. De forma práctica, investiga el potencial uso de la red de metro, en una gran ciudad como Madrid, para proporcionar servicios de entrega de paquetes de e-commerce aprovechando su actual capacidad de transporte disponible y utilizando las estaciones para la entrega de los paquetes. Se definen las características de un nuevo modelo de distribución mixto (M4G: Metro for Goods).

Los resultados muestran las externalidades sociales y los costes medioambientales derivados del nuevo modelo M4G son significativamente menores que los costes actuales de reparto a través de furgonetas.

1. INTRODUCCIÓN

La población urbana está en continuo crecimiento, el 55 % de las personas del mundo ya vive en ciudades y el porcentaje de urbanización crecerá hasta el 68 % en el año 2050 (Naciones Unidas, 2018), lo que trae consigo un aumento de la demanda de bienes y servicios concentrados principalmente en áreas urbanas, que a su vez presentan cada vez más restricciones de acceso. Este hecho, inevitablemente, está llevando a las ciudades de todo el mundo a enfrentarse a mayores desafíos en términos de transporte eficiente de personas y mercancías, al tiempo que tratan de minimizar sus impactos negativos en la calidad de vida de sus ciudadanos.

Este aumento de bienes y servicios tiene su máximo exponente en el comercio electrónico, donde el incremento de las compras online se espera que, en 2024, sea 5 veces superior al que se realizaba en 2014. El efecto pandemia ha obligado a muchos consumidores a buscar opciones de compra en los canales online, modificando sus hábitos de compra no solo durante el periodo de la covid-19, sino en el periodo pospandemia. En España, los sectores como los supermercados o la compra de electrodomésticos, en 2020, casi doblaron su facturación online respecto al tercer trimestre de 2019 (CNMC, 2020).

Más personas viviendo en las ciudades y más personas realizando transacciones online se traduce en mayor número de demanda de entregas en la ciudad, sobre todo tras la aparición del q-commerce (Delivery Hero, 2020) o comercio rápido, que aparece como un nuevo modelo dentro del comercio electrónico donde prima la velocidad, la conveniencia y la atención al cliente. La entrega de última milla representa el 53 % del coste total de envío y el 41 % de los costes totales de la cadena de suministro (World Economic Forum, 2020).

Este mayor número de entregas ha hecho que todos los agentes implicados en el reparto urbano teman un colapso en la última milla y se planteen medidas que permitan aumentar su capacidad de entrega y, a su vez, reducir el impacto medioambiental que tiene su actividad en las grandes ciudades. Si no se producen intervenciones de los grupos de interés, se espera un aumento del 32 % en las emisiones de car-bono del tráfico de reparto urbano para 2030 (World Economic Forum, 2020).

Las medidas propuestas tienen dos vertientes diferenciadas. Por parte de las autoridades públicas, tratan de minimizar los impactos derivados de la logística urbana para mejorar la calidad de vida de sus ciudadanos y restringir el uso de los vehículos en las ciudades (Civitas, 2015). Por parte de los actores que intervienen en la distribución urbana (Macharis y Kin, 2017), se plantean iniciativas que aumenten su productividad de entrega y minimicen sus costes, teniendo cada vez más presentes los impactos medioambientales.

1.1 Medidas regulatorias y soluciones para la mejora de la logística urbana

Diferentes autores han organizado las numerosas medidas para la mejora de la logística de la ciudad en distintas categorías. Sobre la base de los resultados de los proyectos europeos, Russo y Comi (2011) proponen cuatro categorías de medidas, que están relacionadas con: (i) la infraestructura material, (ii) los sistemas de transporte inteligentes o telemáticos, (iii) los equipos de carga y unidades de transporte, y (iv) la gestión de la red de tráfico. Los autores proponen esta categorización de medidas como una herramienta para ser utilizada por las autoridades de la ciudad, al diseñar elementos de regulación para las actividades de logística y transporte de mercancías en las ciudades.

Browne et al. (2012) parten de la relación existente entre cinco características del transporte urbano de mercancías y sus externalidades. Estas características son: (i) niveles de ruido causados por cada transporte de mercancías, (ii) emisiones de contaminantes atmosféricos, (iii) consumo de combustible fósil, (iv) kilómetros totales recorridos por el vehículo, y (v) riesgo de accidente por kilómetro recorrido por el vehículo. Para cada una de estas características, los autores combinan iniciativas específicas que pueden reducir los impactos. Estas pueden agruparse en tres categorías: (a) compartir espacio y tiempo, (b) fomentar la cooperación (también entre el sector público y el privado), y (c) cambiar el comportamiento de los usuarios.

Por otro lado, Stathopoulos et al. (2012) definen seis clases de medidas para reducir los problemas de transporte: (i) medidas basadas en el mercado, (ii) medidas regulatorias, (iii) planificación del uso del suelo, (iv) medidas de infraestructura, (v) nuevas tecnologías y (vi) medidas de gestión. En esta misma línea, el proyecto Civitas (2015) enumera una serie de iniciativas para ciudades de entre 50 000 y 250 000 habitantes, tanto desde un punto de vista estratégico como desde la propuesta de medidas de pequeño impacto que podrían implementarse con mayor facilidad. Las citadas medidas pueden resumirse en las siguientes: (i) compromiso de los grupos de interés, (ii) medidas regulatorias, (iii) medidas basadas en el mercado, (iv) planificación del uso del suelo y medidas de infraestructura, (v) nuevas tecnologías y (vi) concienciación ecologística.

Esta breve descripción general de las distintas categorizaciones demuestra la gran variedad de medidas con relación a la logística urbana que se han introducido, probado y (o) implementado en las ciudades. Sin embargo, la literatura se ha centrado principalmente en la perspectiva de las autoridades locales y los responsables políticos, a pesar del papel clave del sector privado en muchas de estas medidas. En respuesta a esto, Macharis y Kin (2017) se centran en las medidas de logística urbana que incluyen explícitamente a los grupos de interés que son responsables y actúan en la logística en las ciudades. Las clasifican según las llamadas «cuatro aes» (inglés): (i) concienciar (awareness), (ii) evitar (avoidance), (iii) actuar y cambiar (act), y (iv) anticipación de nuevas tecnologías (anticipation). Dentro de las soluciones en logística urbana que “desplazan” al coche de la ciudad, los grupos de interés públicos tratan de restringir el acceso de vehículos con medidas reguladoras (restricciones de acceso a zonas sensibles, regulación de estacionamiento, etc.), medidas basadas en el mercado (peajes, impuestos, tarifas de estacionamiento, etc.) o medidas relacionadas con las infraestructuras (zonas de carga/descarga, área de entregas cercanas).

Por parte de los grupos de interés que son responsables y actúan en la logística de la ciudad, las medidas innovadoras tratan de buscar la eficiencia en las operaciones de reparto la entrega de la última milla. Con relación a los medios de reparto, se estudian iniciativas para sustituir los vehículos comerciales por vehículos no tripulados (drones o vehículos terrestres) que permitan, a su vez, hacer entregas minimizando el uso de las calles de la ciudad. Estas soluciones presentan, en la actualidad, numerosas barreras que es necesario solventar para que el reparto urbano con drones o con vehículos terrestres no tripulados pueda ser una realidad en muchas urbes. En la figura 1 se recopilan las diferentes iniciativas o medidas relacionadas con la logística urbana y afectan a la distribución urbana de mercancías.

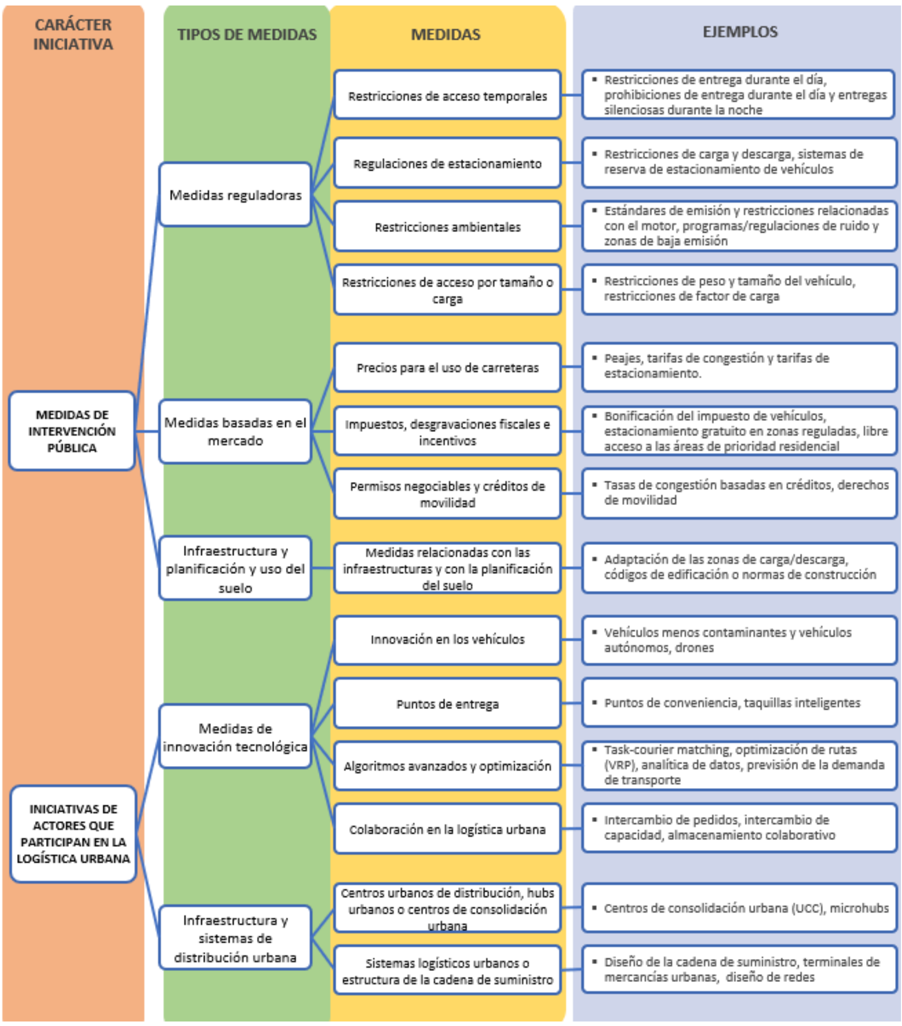


Figura 1: Medidas e iniciativas relacionadas con la logística urbana. Fuente: elaboración propia a partir de Stathopoulos et al. (2012); Civitas (2015); Macharis y Kin (2017).

1.2 Sistemas logísticos urbanos a través de metro o tranvía (M-ULS)

El transporte de mercancías por carretera es el modo que generalmente domina en las operaciones de entrega urbana. En un intento por mejorar la eficiencia de la distribución de mercancías en las ciudades y lograr y mejorar la sostenibilidad ambiental, las autoridades locales buscan políticas específicamente dirigidas a la logística urbana. Por lo general, estas políticas consisten en modelos de restricción de acceso que evitan que ciertas categorías de vehículos ingresen a áreas sensibles. Estos son, típicamente, los centros de las ciudades, donde se enfrentan varios desafíos simultáneos: la falta de espacio, la protección de la salud de los ciudadanos y la protección del patrimonio (Alessandrini et al., 2012). Existen, de forma adicional, diferentes ineficiencias y costes asociados a la distribución urbana de mercancías: edad media de los vehículos, dificultades de acceso y estacionamiento, restricciones de velocidad, congestión, etc. que favorecen el uso de modelos alternativos (Sładkowski et al., 2014)

Con relación al transporte ferroviario, se han producido una serie de estudios y pruebas en los últimos años con el propósito de utilizar este medio de transporte de mercancías en diversas ciudades. Las razones para utilizar el ferrocarril para llevar a cabo la distribución urbana se definen como consecuencia de intentar minimizar el transporte por carretera en la logística de la ciudad. El transporte por carretera es uno de los medios más utilizados, pero también resulta más contaminante y menos sostenible, reforzando así la necesidad de entregar bienes de forma innovadora.

Muchas ciudades europeas disponen de una extensa infraestructura ferroviaria para cumplir con las funciones principales de transporte público, ya sea a través de un sistema de metro, trenes o una red de tranvías, existiendo cada vez más posibilidades de utilizar estos sistemas para el transporte de mercancías en el centro de las ciudades. A diferencia de la industria del transporte de mercancías por ferrocarril pesado, que necesitaría una considerable inversión, el transporte de mercancías a través del metro o tranvía utilizaría la infraestructura existente. No es necesario cambiar las infraestructuras del material rodante ni de las estaciones, aunque deben realizarse modificaciones y adaptaciones (Dampier y Marinov, 2015).

Los estudios sobre sistemas logísticos subterráneos (ULS o UFT) llevan desarrollándose durante casi 50 años, pero no es abundante la literatura científica que aborda la distribución urbana a través de sistemas ferroviarios. Robinson y Mortimer (2004) señalaron el potencial de estos sistemas y su posible contribución a reducir la congestión del tráfico urbano al proporcionar una alternativa a la distribución por carretera. Para su posible implantación, es necesario que los costes operativos sean equiparables a los del transporte por carretera, se minimicen los conflictos entre el viajero y los trenes de carga, y se produzcan mejoras en las infraestructuras y la organización. Dampier y Marinov (2015) propusieron una nueva concepción de ULS, integrando el transporte subterráneo de mercancías en el sistema de metro de pasajeros (denominado M-ULS o sistema logístico subterráneo por metro), que ofrece una solución viable con un presupuesto limitado. Su ventaja no solo radica en los beneficios tradicionales de ULS para aliviar la congestión del tráfico, mejorar el entorno urbano y la eficiencia del transporte de mercancías, sino que también contribuye a un gran ahorro del espacio subterráneo, reduciendo los costes y el periodo de construcción.

En los últimos años, los sistemas de intercambio de pasajeros y carga, que son diferentes de los tradicionales vehículos de carga dedicados, han recibido una atención cada vez mayor. De este modo, se introducen conceptos como pooling logístico (reutilización de recursos), flete en tránsito, entrega multimodal, uso del transporte público urbano para entregas, cargo hitching (transporte mixto de pasajeros y mercancías), integración de sistemas de transporte de pasajeros y de carga, etc. La combinación de los flujos de pasajeros y mercancías brinda la oportunidad de promover aún más las ganancias de eficiencia. Las estrategias de intercambio actuales para los servicios de carga se basan en modos de transporte público como el metro o autobuses (Cochrane et al., 2017).

Otros estudios recientes han analizado la viabilidad y la eficiencia de utilizar el transporte público, como el metro y los tranvías, para la entrega urgente. Kikuta et al. (2012) estudiaron la integración del sistema de metro en Sapporo, Japón, con el sistema tradicional de transporte por camión para facilitar la distribución de mercancías entre los barrios del centro de la ciudad. Diziain et al. (2014) compararon los sistemas urbanos de transporte intermodal de mercancías entre Francia y Japón. Estos sistemas son prometedores pero difíciles de implantar en la última milla ya que los servicios ferroviarios requieren de gran volumen, suponen altos costes y conllevan dificultades organizativas. Dampier y Marinov (2015) estudiaron la viabilidad del sistema de metro, en Tyne y Wear (Reino Unido), para entregar mercancías directamente en el centro de la ciudad. Arvidsson et al. (2016) revisaron el éxito y el fracaso de los sistemas de tranvía para el transporte urbano de mercancías y propusieron una solución de transporte multimodal de bajas emisiones utilizando este medio de transporte. El proyecto Cargo hitching (van Duin et al., 2019) comenzó con el objetivo de utilizar la capacidad excedente del transporte público para el transporte de paquetes, y su viabilidad depende de poder incluir y valorar conceptos sociales como aportación a los clientes y a la sociedad. Por su parte, Jiang et al. (2020) concluyen que el metro es adecuado para la distribución en ciudades con una gran rotación de mercancías, mientras que los autobuses y los tranvías resultan más adecuados para la distribución en áreas con baja rotación de mercancías. En la sociedad actual, donde la eficiencia energética es cada vez más importante, el transporte urbano de mercancías basado en el metro es más competitivo que los autobuses y tranvías. La distribución de mercancías a través del metro puede aprovechar su alta capacidad de transporte, la alta velocidad de operación, su puntualidad y fiabilidad en los horarios y la baja contaminación ambiental producida.

Partiendo de una falta de estudios que cuantifiquen el efecto socioeconómico-medioambiental de estos sistemas dentro del sector logístico, el planteamiento del problema en este estudio es el siguiente: dentro del ámbito de las grandes ciudades, ¿puede considerarse un sistema de transporte público como el metro una alternativa eficiente y sostenible para la logística urbana en la era del comercio electrónico? A continuación, se muestran una serie de objetivos que pretenden ayudar a dar respuesta a la pregunta de la investigación:

- ¿Qué nivel de demanda de paquetería justificaría el uso de la red de metro como operador logístico urbano?
- ¿Cómo se pueden utilizar las infraestructuras y los trenes para implementar este modelo?
- ¿Cuáles son los beneficios sociales y medioambientales derivados del uso de metro para distribuir paquetes en el centro de la ciudad?

El resto de este documento está estructurado de la siguiente manera: La Sección 2 describe la metodología empleada para evaluar los costos externos del modelo propuesto. Las secciones 3 y 4 presentan el caso de estudio y la aplicación de la metodología para la ciudad de Madrid. La sección 5 analiza los resultados y, por último, la sección 6 presenta las conclusiones y posibles áreas de investigación.

2. METODOLOGÍA

2.1. Propuesta metodológica

La Figura 1 muestra el marco metodológico utilizado, donde se describen los pasos, procedimientos y fuentes de datos empleadas para resolver las preguntas planteadas. Es importante señalar que las fuentes de información empleadas se corresponden con datos de organismos oficiales.

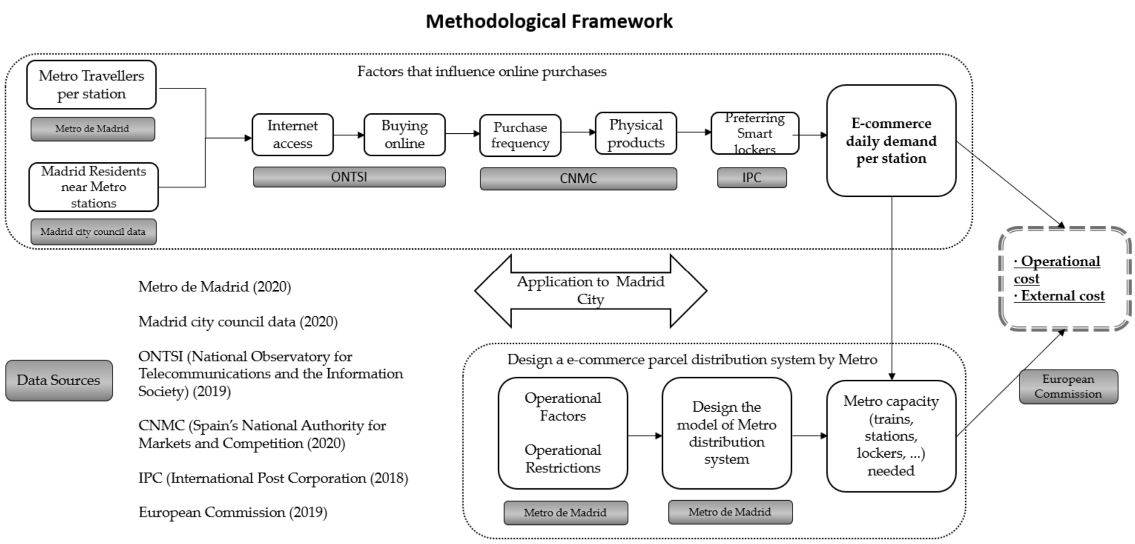


Figura 1: Marco metodológico. Fuente: elaboración propia

2.2. Definición del modelo de reparto en la última milla: modelo M4G

Antes de describir el modelo M4G, se representa en la Figura 2 un diagrama de procesos del modelo actual de reparto e-commerce B2C con entrega a domicilio, donde se explican las principales actividades realizadas:

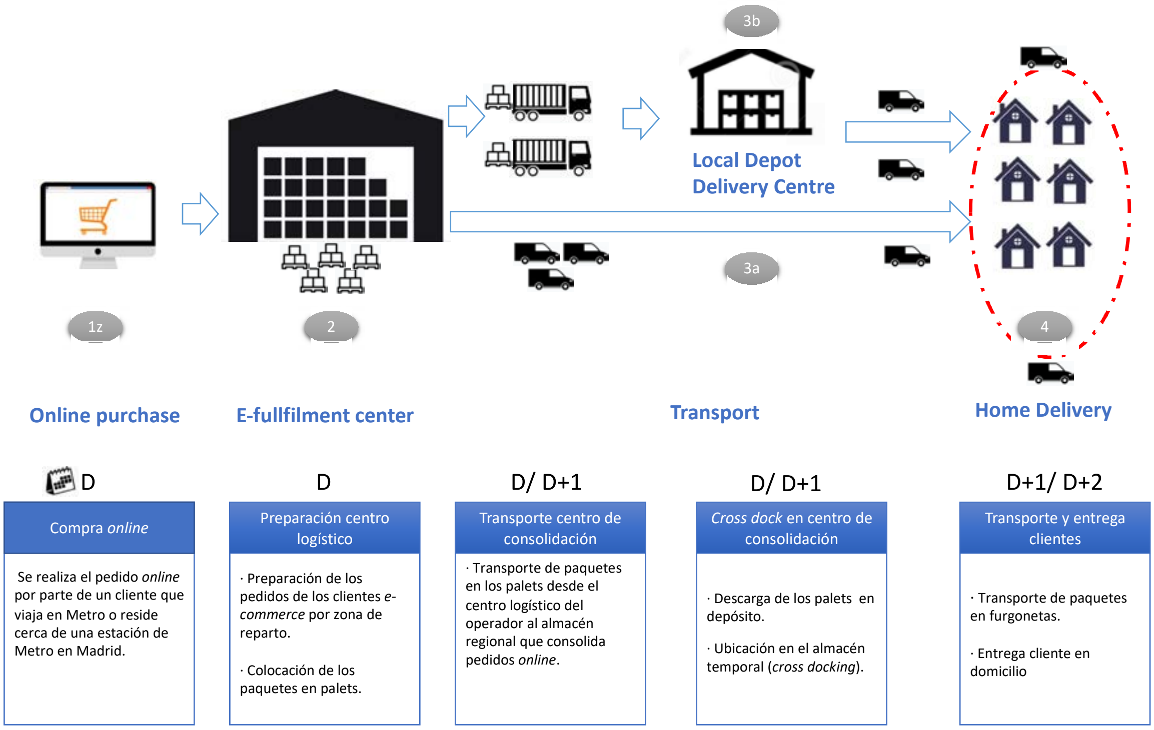


Figura 2. Modelo actual de reparto de e-commerce. Fuente: elaboración propia

1. Se realiza el pedido *online* por un residente y selecciona entrega en su domicilio.
2. Se procesa el pedido en el *e-fulfillment center* (centro logístico o centro de consolidación del minorista o del operador logístico, situado en las afueras de la ciudad). En el *e-fulfillment center* se prepara el paquete y está listo para el transporte.
3. Transporte desde el centro logístico hasta el domicilio del cliente. Dos opciones:
   i. Un camión pesado desde el centro logístico hasta un almacén local o centro de consolidación más cercano al centro de la ciudad (*local depot*). Posteriormente se clasifica el pedido y se envía al domicilio del cliente mediante furgonetas (LCV, *light comercial vehicle*).
   ii. El LCV tiene su origen en el centro logístico (*e-fulfillment*) y envía directamente al domicilio del cliente. Esta es la opción que se considera en la comparativa de este estudio.
4. Se entrega el pedido de *e-commerce* en el domicilio del cliente.

El modelo M4G, el diagrama de los procesos del modelo M4G de reparto de *e-commerce* se muestra a continuación en la Figura 3 y se describen a continuación.

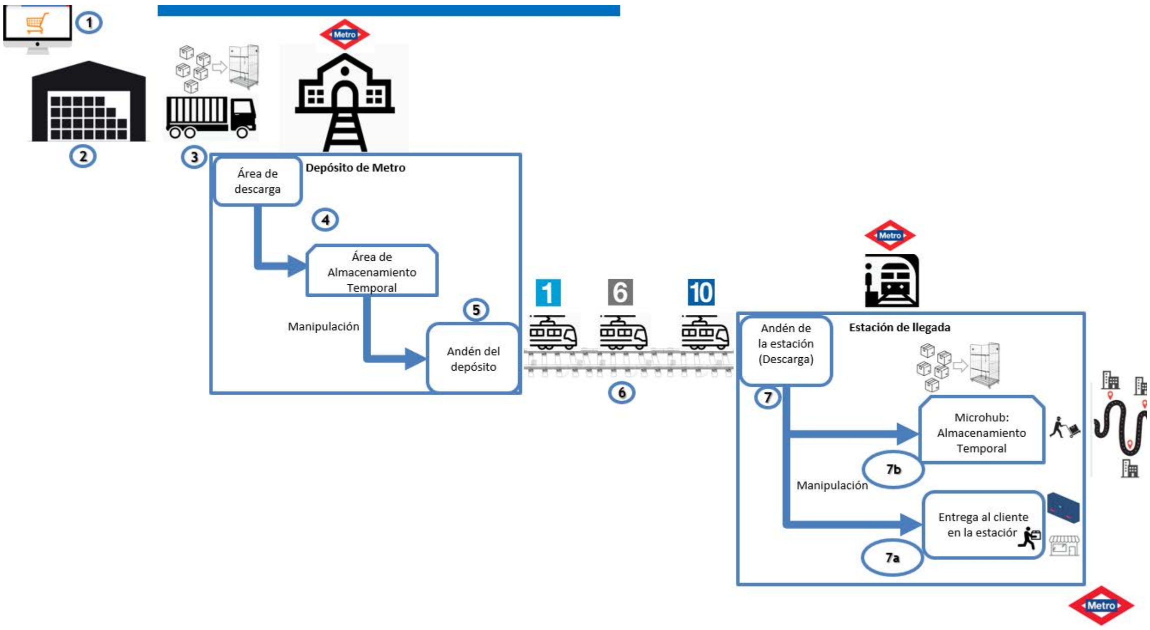


Figura 3. Modelo M4G. Fuente: elaboración propia

Para llevar a cabo la distribución urbana propuesta, a través de la red metropolitana, se detallan las 7 grandes actividades a realizar, y que serían las siguientes:

1. Se realiza el pedido *online* por un viajero de metro o por un residente de algún barrio cercano a una estación de metro. El cliente selecciona un método de entrega concreto (taquilla, centro de recogida, entrega a domicilio, etc.).
2. Se procesa y se prepara el pedido en el centro logístico/centro de consolidación del minorista o del operador logístico. Los paquetes correspondientes a pedidos *online* se preparan y colocan en los contenedores rodantes (*rollers containers*, ver Figura 4) por estación. Los contenedores rodantes son sistemas para el transporte de forma ágil de paquetes y otros productos. Son ligeros y permiten cargas de 500-800 kg. Pueden tener diferentes tamaños para adaptarse a las características interiores de cada tren. La utilización de contenedores rodantes, en la preparación de pedidos, minimiza la ruptura de la carga en todo el proceso (descomposición total o parcial del contenedor al proceder al almacenaje o transporte al receptor de la carga).

Figura 4. Ejemplo de roll container. Fuente: Todo Contenedor (https://cutt.ly/6bVKy0n)

Llegados a este punto el pedido estaría listo para el transporte.

3. Transporte hasta el depósito de metro: con un camión pesado (HGV) se transportan, mediante contenedores rodantes, los paquetes agrupados por destinos, desde el centro logístico hasta el depósito o cochera de metro seleccionado.
4. Descarga y almacenamiento temporal en las instalaciones de metro: los contenedores que contienen paquetes con pedidos de *e-commerce* se ubican, de forma temporal (*cross dock*), en el depósito a la espera de ser cargados en los trenes para su distribución posterior.
5. Carga de los paquetes en los trenes: antes del inicio del trayecto del tren, que va a circular por toda la línea, se cargan los coches/vagones necesarios con los contenedores que llevan la mercancía.
6. Transporte desde el depósito de metro hasta cada estación: el tren se carga con los contenedores rodantes en el depósito de metro y se utiliza el tren para transportar los pedidos hasta las estaciones.

Dentro de este punto, hay un aspecto fundamental a tener en cuenta en el reparto de mercancías a través de trenes en redes metropolitanas. Se trata del empleo de trenes compartidos o trenes exclusivos para transportar los contenedores rodantes. A saber:

- Trenes compartidos: en este caso, el mismo tren es compartido por viajeros y paquetes, pero no están mezclados ya que cada coche que compone el tren transporta o viajeros o paquetes. Se puede utilizar un coche de la composición de ese tren para el transporte de paquetes, y el resto transporta viajeros (ver Figura 5). Con esta alternativa se utilizan los mismos horarios de paso de los trenes en esa línea. Para que no afecte a las ratios viajeros/m^2, es recomendable utilizar esta opción durante los periodos valle.

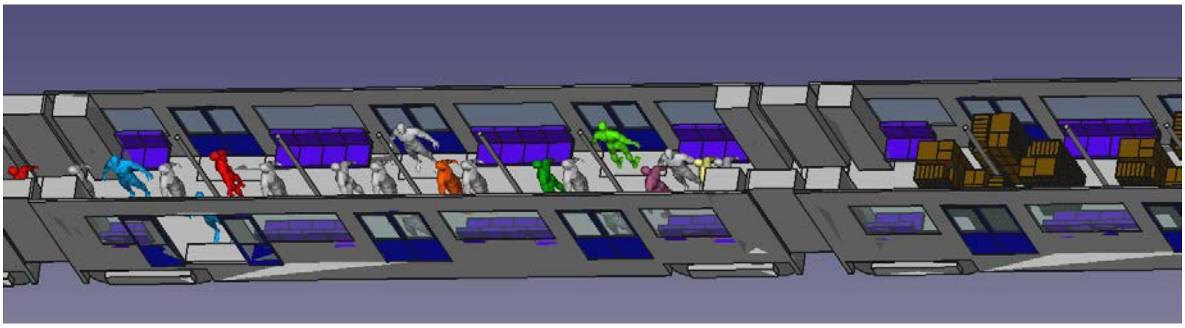


Figura 5. Ejemplo de trenes compartiendo viajeros y paquetes. Fuente: elaboración propia

- Trenes exclusivos: para esta opción, el tren que recorre las diferentes estaciones de la red de metro solo transporta paquetes. En este caso, no se modifica la estructura ni el diseño interior del tren, cada coche se carga con los contenedores rodantes que, a su vez, están llenos de paquetes. La composición del tren (número de coches que lo componen) puede variar y los horarios no coinciden con la tabla de trenes definida para los viajeros, con el fin de no interferir con ellos.

En cada estación se descargan los paquetes correspondientes. Dentro del modelo M4G y teniendo en cuenta las características descritas en el cuadro anterior, se pueden considerar dos grandes categorías en la entrega final de la mercancía al cliente que realiza el pedido de e-commerce: 7a) Entregas dentro de la estación (centros de recogida o taquillas inteligentes) y 7b) Entregas fuera de la estación (domicilio/oficinas).

2.3. Cuantificación de la demanda de paquetes de *e-commerce*

Los compradores online disponen de numerosas alternativas para elegir qué productos comprar, dónde pueden comprarlos y cuándo pueden comprarlos.
De igual forma, cuando hablamos de la entrega de paquetes en el comercio electrónico, los clientes esperan poder elegir diferentes alternativas. Una empresa que ofrezca (o el cliente perciba) un alto valor del servicio para una entrega de comercio electrónico, generalmente producirá la satisfacción del cliente dentro del proceso de compra y, además, tendrá un efecto directo en su lealtad y permanencia, lo que finalmente generará mayor consumo y, por extensión, aumentará los beneficios de las empresas (Copenhagen Economics, 2013).

Por lo tanto, la forma en que se materializa la entrega física también condiciona la demanda del comercio electrónico.

La demanda diaria de pedidos de comercio electrónico del modelo M4G tiene dos componentes, la demanda de viajeros y la demanda de residentes:

2.3.1 Demanda diaria de viajeros (DDV)

Una de las principales sinergias entre el transporte urbano ferroviario de personas y el transporte urbano de mercancías en las grandes ciudades se produce cuando un viajero de metro puede, a su vez, ser un cliente de comercio electrónico y recoger los pedidos cuando entra o sale de una estación.

El cálculo de esta demanda diaria potencial de pedidos de e-commerce de los viajeros de metro se construye aplicando el método de proporciones en cadena propuesto por Kotler y Keller (2012), que consiste en multiplicar un número base por una serie de porcentajes hasta llegar a la demanda objetivo.
La formulación sería la siguiente:

$$DDV=A\times P1\times P2\times P3\times P4\times P5\times P6\times P7 \qquad (1)$$

donde:

- A = viajes diarios en metro por estación
- P1 = % promedio de viajeros distintos en metro por estación
- P2 = % promedio de personas que viajan en metro > x años por estación
- P3 = % promedio de personas > x años que usan Internet
- P4 = % promedio de personas > x años que usan Internet y compran online
- P5 = % promedio de personas > x años que usan Internet y compran online de forma diaria
- P6 = % promedio de personas > x años que usan Internet y compran online de forma diaria bienes y productos físicos que pueden entrar en un paquete de tamaño estándar
- P7 = % promedio de personas > x años que usan Internet y compran online de forma diaria bienes y productos físicos que pueden entrar en un paquete de tamaño estándar y muestran preferencia por un método de entrega concreto (taquillas o recogida en centro o domicilio)

2.3.2 Demanda de residentes (DDR)

La privilegiada ubicación de todas las estaciones de metro en las grandes urbes (en distancia y en accesibilidad) les otorga una ventaja competitiva a la hora de determinar los posibles puntos de entrega de pedidos de comercio electrónico para los residentes de estas ciudades.

De forma análoga al método anterior, se calcula la demanda potencial diaria de pedidos de e-commerce para las personas que residen dentro del área de influencia de una estación de metro (se considera área de influencia de una estación el área que ocupa el barrio donde vive el residente).

Para este caso, la formulación sería:

$$DDR = Y \times P3 \times P4 \times P5 \times P6 \times P7 \qquad (2)$$

donde:

Y = personas residentes que viven en un área de influencia de una estación de metro > x años y no viajan en metro de forma regular.

La demanda diaria total de pedidos de e-commerce por estación DDT(i) será la suma de ambos conceptos:

$$Demanda\ diaria\ de\ pedidos\ e - commerce\ de\ la\ estación\ DDT(i) = DDV(i) + DDV(i) \qquad (3)$$

(i) = estaciones de metro

2.4. Análisis de costes externos

Según la Comisión Europea (European Commission, 2019), «Los costes externos, también conocidos como externalidades, surgen cuando las actividades sociales o económicas de una persona (o un grupo) tienen un impacto en otra persona (o grupo) y cuando ese impacto no se contabiliza por completo o no se compensa por la primera persona (o grupo)».

Estos costes, generalmente, no son asumidos por el usuario de transporte y no se tienen en cuenta a la hora de decidir qué medio de transporte utilizar. La Tabla 1 muestra las dos grandes categorías de costes externos y el tipo externalidad que la componen, donde:

Costes externos	Tipo de coste externo	Variables que influyen en el tipo de coste	Definición
I: Social (CS)	Costes de congestión C(c)	$Cc = f(D, T, M, P)$	Pérdida de tiempo que sufre un individuo y que aparece cuando un vehículo adicional reduce la velocidad de otros vehículos dentro de un flujo de tráfico, aumentando el tiempo de viaje.
	Costes de accidentes C(a)	$Ca = f(D, M, P)$	Tiene en cuenta, no solo los costes materiales (costes administrativos, daños materiales en otros vehículos e infraestructuras, etc.), sino también los costes inmateriales
II: Medioambiental (CM)	Costes de ruido C(r)	$Cr = f(D, M, T, P, H)$	El ruido se puede definir como sonidos no deseados de diferente duración, intensidad u otra calidad que causan daño físico o psicológico a los seres humanos. Los sistemas de transporte son fuentes de ruido.
	Costes por polución de aire C(pa)	$Cpa = f(D, M, P, F, S, E)$	Los motores de transporte emiten ciertos contaminantes (por ejemplo, SO_2, NO_x, PM_{10}, CO) a la atmósfera. Tienen en cuenta tanto los efectos sobre la salud como otro tipo de daños
	Coste de cambio climático C(cc)	$Ccc = f(D, M, P, F, S, E)$	Los costes del cambio climático se definen como los costes asociados a todos los efectos del calentamiento global, como el aumento del nivel del mar, la pérdida de biodiversidad, los problemas de gestión del agua,etc.

donde: D (km): distancia recorrida para entregar los paquetes de comercio electrónico por un determinado modo de transporte. M: modo de transporte (LCV, HGV, Metro). T situación del tráfico (sobrecapacidad, congestionado, cerca de la capacidad, por debajo de la capacidad, denso, fluido, etc.) P: área de actuación en el transporte de paquetes (área urbana, área interurbana, etc.) H: momento del día. F: tipo de combustible. S: tamaño del vehículo. E: tipo de emisión.

Tabla 1- Costes externos y variables que influyen en el tipo de coste

La cuantificación monetaria de las externalidades del modelo de distribución de paquetes de comercio electrónico a través del sistema M4G considera los siguientes costes agregados totales (CT):

$$CT = CS + CM \tag{4}$$

donde:

$$CS = C(c) + C(a)$$
$$CM = C(r) + C(pa) + C(cc)$$

2.5. Capacidad de la red de metro y factores operativos

El cálculo de la oferta de servicios logísticos de comercio electrónico por estaciones de metro (para residentes y viajeros) estará condicionado tanto por aspectos vinculados a la demanda de entregas en cada una de esas estaciones, como por factores logísticos operativos. Como se muestra en la Tabla 2, los siguientes factores operativos condicionarán el coste de envío por paquete a través del modelo M4G.

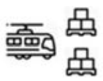
Factor operativo	Definición	Característica
Tipo de tren 	En función de las líneas con mayor demanda de paquetes, el tipo de tren (serie) que circula por ellas es diferente. Cada uno de estos trenes puede presentar un diseño interior en cada coche que lo compone y por lo tanto tiene una capacidad de transporte de paquetes distinta.	Capacidad interior +++ (por coche) Capacidad interior + (por coche)
Tamaño del contenedor 	Debido a su facilidad de manejo y su capacidad, se utiliza el *roll container* como medio para transportar paquetes en los trenes. En función de la capacidad interior del tren, se selecciona el tamaño de *roll* más adecuado.	*Roll container* grande *Roll container* mediano
Operativa de trenes	Trenes compartidos: los trenes no modifican su frecuencia actual para el transporte de viajeros y se utiliza parte de un tren para dar servicios logísticos. Trenes específicos: se utiliza un tren para transportar paquetes. Este tren no está disponible para los viajeros y tiene un horario diferente.	Tren compartido Tren específico
Tiempo de descarga de contenedores en estación 	Tiempo para la descarga de *rollers containers* en cada estación.	Trenes compartidos = al de tiempo de parada de transporte de viajeros Trenes específicos = en función del número de *rollers containers*
Tamaño paquetes 	Se consideran diferentes tamaños de paquetes. Esto permite 1 pedido = 1 paquete, así es posible incluir varios productos en un mismo paquete o considerar varias combinaciones en función de los m^3 necesarios.	Paquete pequeño Paquete mediano Paquete grande Paquete especial
Tamaño de las taquillas, de los centros de recogida y  del *microhub*	En función de la demanda de paquetes diaria de cada estación, el tamaño de las taquillas inteligentes puede ser diferente. Para el caso de los centros de recogida y del almacén urbano situado en la estación (*microhub*), se determinará la superficie necesaria en función de la demanda diaria de paquetes en esa estación.	Estaciones con alta demanda de taquillas ++++ Estaciones con menor demanda Taquillas ++ La superficie de los centros de recogida y los *microhubs* de estaciones están condicionados por la demanda de paquetes de esa estación A mayor demanda mayor superficie de almacenaje

Tabla 2- Factores operativos del modelo M4G

3. CASO DE ESTUDIO

El siguiente apartado describe la aplicación del sistema de reparto mixto de última milla propuesto para mercancías de comercio electrónico en la ciudad de Madrid. A continuación, se define el modelo M4G para la distribución de los paquetes originados por el e-commerce, considerando el caso de la ciudad de Madrid. Esta nueva distribución urbana se realiza a través del sistema de transporte público ferroviario Metro de Madrid (Metro). El objetivo es poder comparar las externalidades de este nuevo modelo con el modelo actual de reparto urbano de paquetes en la ciudad de Madrid.

3.1 Background

La distribución urbana es fundamental para la actividad y el desarrollo de cualquier ciudad, y Madrid no es una excepción. Por su relieve y la evolución histórica de su estructura urbana, la distribución dentro de la ciudad de Madrid es una de las más complicadas entre las grandes ciudades europeas. La ciudad, motor esencial de la economía española que representa el 12% del PIB nacional, está dividida en 21 distritos con una población total de 3,3 millones (INE, 2020) y tiene una superficie total de 60.436,7 hectáreas, con una densidad de población media de 54 habitantes por hectárea.
En la actualidad, existen dos tipos principales de problemas asociados a la distribución urbana en la ciudad de Madrid (Área de Gobierno de medioambiente y Movilidad, 2019):

- Infraestructura urbana:
  · No hay planificación urbana de puntos de distribución.
  · Problemas con el uso de áreas de estacionamiento y carga / descarga.
  · Crecimiento significativo de viviendas particulares como puntos de entrega de comercio electrónico.
- Gestión:
  · No existe un modelo de gestión de la logística de distribución que identifique y organice adecuadamente los numerosos agentes y operaciones para cada canal de distribución urbana.
  · Crecimiento del comercio electrónico y nuevos modelos de entrega.
  · Mal uso de las actividades de carga / descarga.

En Madrid el problema se agrava ya que, siguiendo las directrices europeas, se están tomando medidas para expulsar (o desplazar) al coche que más contamina del centro de la ciudad (por ejemplo, Madrid Central o Madrid 360) y lograr una mejor calidad del aire. Esta prohibición de acceso de los vehículos a determinadas zonas plantea los siguientes inconvenientes:

- Si no se sustituyen los vehículos actuales de reparto por otros menos contaminantes, un porcentaje considerable de la flota de estos vehículos (84 321 LCV distintos accedieron a Madrid Central de enero a junio de 2019) no podrán hacer la distribución en el centro de la ciudad en el futuro a corto plazo.

- Si se produce una sustitución de los vehículos actuales de reparto por otros menos contaminantes (por ejemplo, eléctricos), no se habrá logrado el objetivo de «expulsar» al vehículo de la ciudad y seguirán existiendo problemas de congestión.

En Madrid, el transporte por carretera supuso el 34,1% del total de emisiones de gases de efecto invernadero, según el Inventario de Emisiones de Gases Contaminantes a la Atmósfera 2016. La flota de coches de Madrid destaca por su elevado porcentaje de vehículos diésel y la edad media ronda los 9,3 años. (Área de Gobierno de medioambiente y Movilidad, 2019). El porcentaje de vehículos comerciales e industriales con más de 10 años rondaba el 73,2% a finales de 2018 (Anfac, 2018). Según datos del Ayuntamiento, durante los meses de enero y junio de 2019, entre 13.000-16.000 vehículos LCV accedieron (en días laborables) a la zona de bajas emisiones establecida en 2018 como Centro de Madrid (una superficie de 472 hectáreas).

Por otro lado, Metro de Madrid es el mayor operador de metro de España y un referente internacional por su red, calidad de servicio e innovación y capacidad tecnológica. Con más de 100 años de experiencia, es el medio de transporte público más utilizado en la Comunidad de Madrid. La red, compuesta por doce líneas y un ramal especial, presenta una extensión total de 294 kilómetros y conecta 12 municipios. Durante la temporada de invierno, más de 2,3 millones de viajeros (periodo pre-covid) utilizan el metro cada día laborable. El desplazamiento diario por motivos de trabajo o estudio representa el 70% del volumen total (https://www.metromadrid.es/es).

3.2. Descripción del modelo M4G en la ciudad de Madrid

La Figura 6 describe el modelo para el reparto de paquetes de e-commerce B2C para los residentes y viajeros de Metro de Madrid, a través del suburbano. Este modelo, M4G, presenta las operaciones involucradas desde que se realiza el pedido online por un cliente hasta que llega a las estaciones de Metro.

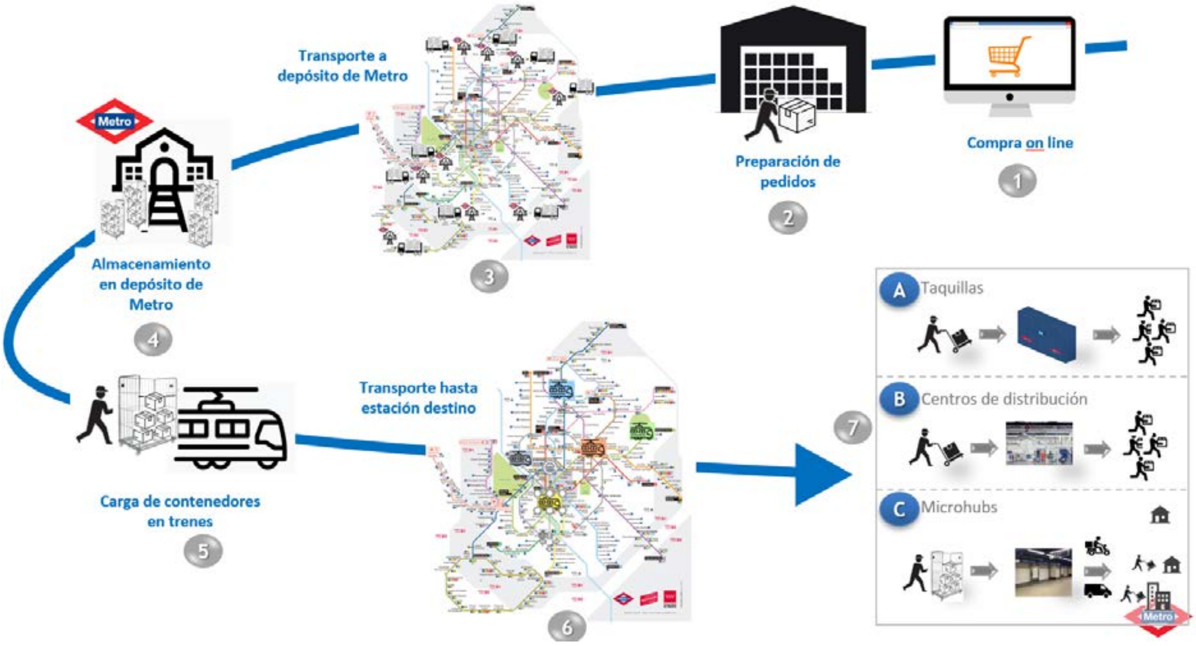


Figura 6. Flujograma de actividad del modelo M4G para la ciudad de Madrid. Fuente: elaboración propia

Las actividades descritas en la Figura 6 son:

1. Se realiza el pedido *online* por un viajero de Metro de Madrid o por un residente de la ciudad de Madrid. En ese momento el cliente selecciona un método de entrega.
2. Se procesa y se preparan los pedidos *online* en el centro logístico (del minorista o del operador, según el caso). En una ciudad como Madrid, estos centros de almacenaje y preparación de pedidos se ubican en las afueras de la ciudad (corredor del Henares, Alcobendas, Getafe, Pinto, etc.). En ellos, se preparan los paquetes y se señalan los contenedores rodantes que los transportan (ver Figura 6), quedando listos para el transporte y diferenciándose por estación.

Figura 7. Contenedor rodante cargado con paquetes. Fuente: elaboración propia

3. Transporte de paquetes B2C hasta un depósito de Metro: los paquetes se trasladan desde el centro logístico situado a las afueras de Madrid hasta el depósito de Metro seleccionado. El transporte se realiza con un camión pesado cargado de contenedores rodantes llenos de paquetes B2C y la mercancía se descarga en un espacio habilitado en el depósito.
4. Almacenamiento temporal en el depósito de Metro de Madrid: los contenedores rodantes se almacenan en una carpa o almacén de Metro durante un breve periodo de tiempo (horas o días, según el caso).
5. Traslado y carga de contenedores rodantes en trenes: antes de iniciar el reparto de los pedidos de *e-commerce*, se trasladan los contenedores desde el almacén temporal hasta las vías donde se sitúan los trenes que inician su recorrido desde el depósito.

   Se colocan los contenedores rodantes en los coches que componen un tren. Dependiendo de la alternativa seleccionada, los trenes tienen una composición de coches con viajeros más coche con paquetes o el tren se compone solo de coches con paquetes.

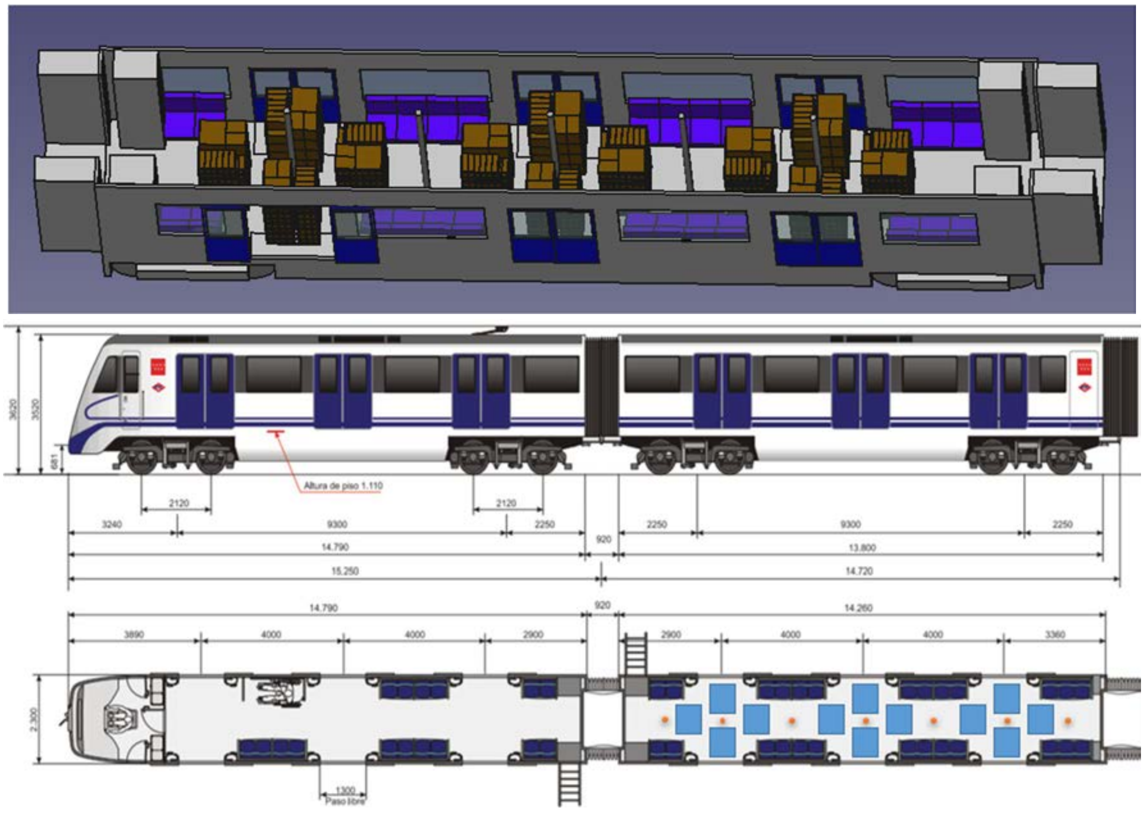


Figura 8. Coche serie 3000 de Metro de Madrid cargado con contenedores rodantes. Fuente: elaboración propia a partir de Metro de Madrid
(https://www.metromadrid.es/es)

6. Transporte desde el depósito de Metro hasta la estación de destino: se transportan los pedidos de *e-commerce* en trenes desde el depósito de Metro (inicio de la ruta) hasta cada una de las estaciones destino donde se descargan los contenedores rodantes con paquetes.
7. Entrega al cliente final en un centro de recogida: la entrega se realiza dentro de la estación en un centro de recogida de paquetes que funciona similar a una tienda de conveniencia o punto de recogida. El operador logístico lleva directamente los paquetes desde el tren hasta el centro de recogida que está dentro de la estación de Metro. Hay una persona que entrega el paquete al cliente.

4. APLICACIÓN DE LA METODOLOGÍA AL CASO DE ESTUDIO

4.1. Diferentes alternativas de aplicación del modelo M4G

Se distinguen dos alternativas del modelo M4G teniendo en cuenta la forma de transportar paquetes dentro de los trenes: trenes compartidos (paquetes + viajeros) o trenes específicos para el transporte de paquetes e-commerce. Se muestran en la Tabla 3:

Alternativa	Características de la entrega	Modo de transporte desde el centro logístico al cliente	Demanda de paquetes
Alternativa 1 (A1)	Entrega de paquetes de *e-commerce* en centros de recogida en la estación	HDV + trenes compartidos	DT1
Alternativa 2 (A2)	Entrega de paquetes de *e-commerce* en centros de recogida en la estación	HDV + trenes específicos	DT1

Tabla 3- Alternativas y características del modelo M4G

Cada una de las alternativas del modelo M4G se compara con el modelo actual de reparto de paquetes de *e-commerce* a través de LCV, que es el denominado escenario de referencia.

Alternativa	Características de la entrega	Modo de transporte desde el centro logístico al cliente	Demanda de paquetes
Escenario de referencia para la alternativa 1 (A0)	Entrega de paquetes de *e-commerce* con LCV en el domicilio del cliente	HDV + LCV	DT1

Tabla 4- Escenario de referencia para las alternativas del modelo

4.2. Cálculo de la demanda de paquetes por Línea

Siguiendo lo explicado en el apartado 2.3. se cuantifica la demanda de paquetes diaria para las alternativas del modelo M4G.

La demanda es igual para ambos casos, ya que las alternativas se diferencian en función del uso de trenes en el transporte (específicos o compartidos). Además, en la Tabla 5 se detallan el número de contenedores rodantes necesarios para el transporte de esos paquetes. Para el cálculo de la demanda, se tienen en cuenta aquellas estaciones que están dentro de la ciudad de Madrid, excluyendo las estaciones de Metro de Madrid que están en ciudades colindantes. De igual forma, se excluyen las líneas 8 y 11 por tener muy poco alcance.

Alternativa A1&A2			
Línea	Paquetes	Contenedores utilizados	Estaciones con centro de recogida
Línea 1	2147	57	Plaza de Castilla, Cuatro Caminos, Sol, Pacífico, Villa de Vallecas
Línea 2	1645	72	-
Línea 3	2086	89	Villaverde Bajo-Cruce, Legazpi, Embajadores, P. España, Moncloa
Línea 4	1319	58	-
Línea 5	1271	34	-
Línea 6	2421	64	Carpetana, Plaza Elíptica, Conde de Casal, Nuevos Ministerios, P. Pío
Línea 7	1416	38	-
Línea 9	1438	39	-
Línea 10	1485	40	-
Total best 3	6654	210	-

Tabla 5- Number of parcels, roll containers and parcel lockers (daily per Line)

La columna Paquetes de la Tabla 5 se corresponde con la suma de las 5 estaciones (donde se situarían los centros de recogida) con mayor demanda de pedidos por cada línea. De estas, se seleccionan las tres líneas de mayor demanda (Total best 3). La estimación de paquetes diarios entregados es de 6654 en 15 estaciones diferentes. Los trenes inician el recorrido en los depósitos de las líneas 1, 3 y 6 y entregan paquetes en los centros de recogida, donde se almacenan hasta que el cliente final retira su paquete. Estos centros de recogida pueden ser también centros que presten servicios alternativos al viajero, como atención al cliente u oficina de objetos perdidos.

Se considera que no hay límite de envío de paquetes por estación (el máximo de entrega diario lo presenta la estación de Sol con 673 paquetes) y la demanda potencial está formada por la suma de pedidos de *e-commerce* que realizan viajeros de Metro y de los residentes de barrios en los que está la estación donde se encuentra el centro de recogida

4.3. Datos de la modelización

Para realizar el cálculo de los principales indicadores del modelo y sus alternativas, se utilizan datos de partida basados en la literatura estudiada y teniendo en cuenta la opinión de los expertos de las principales empresas del sector de paquetería e-commerce en Madrid. Diversos estudios realizados para ciudades distintas (Edwards et al., 2009; Lemke et al., 2016; de Maere, 2018) nos muestran que la productividad de la entrega varía considerablemente según el área donde se realiza. Existen algunas características comunes en toda gran ciudad: a mayor densidad de población, mayor productividad de entrega en la distribución urbana, y existen zonas de alta congestión o críticas, que concentran importantes niveles de actividad económica. Este tipo de zonas, que incluyen sectores como los centros históricos, los distritos comerciales, los de entretenimiento, entre otros, albergan un elevado número de establecimientos comerciales y, por tanto, atraen continuamente una alta intensidad de flujos logísticos (Merchán et al., 2015).

En el presente caso de estudio, se considera el funcionamiento actual de la logística de última milla en Madrid que responde al esquema tradicional, con grandes centros de clasificación y reparto situados en el extrarradio. Se trata de centros logísticos con grandes capacidades y volúmenes. Desde estos centros, y siempre mediante furgonetas ligeras, se accede a los diferentes núcleos urbanos en largos periodos de reparto.

<u>Validación de datos del escenario actual:</u> con objeto de corroborar la fiabilidad de estos datos y particularizarlos a la ciudad de Madrid, durante los meses de enero y febrero de 2020 se llevó a cabo una consulta individual con cuatro expertos de los de los principales operadores logísticos de comercio electrónico que operan en Madrid. A partir de esta información, se estableció en 60-100 paquetes transportados por un mensajero estándar. En cuanto al peso transportado, el grupo de expertos consultados consideró un peso medio de entre 1,5 y 3 kg por bulto. El modelo considera un valor de 2 kg, siguiendo los datos de una encuesta de International Post Corporation (2020).

Con base en la literatura y las opiniones de los expertos, se consideran los siguientes valores con relación al reparto de paquetes de e-commerce en la ciudad de Madrid:

- T (jornada laboral) = 8 horas
- Km (kilómetros recorridos) = 90 km
- Pr (paquetes en ruta) = 80
- FTHR (tasa de acierto a la primera) = 25 %
- Pd (paquetes entregados) = 60
- Peso del paquete = 2 kg
- Distancia del centro de cumplimiento electrónico al depósito = 25 km
- Peso del contenedor rodante = 15 kg

- Logística inversa depósito Metro-Centro de consolidación = 5 % paquetes
- Optimización de la carga de camiones desde el centro de cumplimiento electrónico hasta la estación de Metro: >80 % (≥ 22 contenedores grandes o ≥ 35 contenedores rodantes medianos).

4.4. Calculo de costes externos y principales indicadores

Tomando como base el Manual de costes externos de la Comisión Europea (European Commission, 2019), la Tabla 6 muestra la valoración de los costes diarios medioambientales y sociales (€) que supone cada una de las diferentes alternativas de entrega de paquetes de e-commerce. En su segunda columna, se indica el modo de transporte de paquetes que genera la externalidad (furgoneta LDV, camión HDV o Metro).

Coste externo		Modo	*DT1*		
			Courier (A0)	*Shared trains* (A1)	*Dedicated trains* (A2)
Medioambiental	Ruido Cr	LDV	169,67		
		HDV Rigid 20-26 t EIV		65,89	65,89
		Metro			
	Costes por polución de aire Cpa	LDV Euro 4 Diesel	418,19		
		HDV Rigid 20-26 t EIV		88,69	88,69
		Metro			23,87
	Coste de cambio climático Ccc	LDV Euro 4 Diesel	257,50		
		HDV Rigid 20-26 t EIV		55,75	55,75
		Metro			21,06
	Total medioambiental (€/día)		845,36	210,33	255,27
Social	Costes de accidentes Ca	LDV Euro 4 Diesel	75,85		
		HDV Rigid 20-26 t EIV		5,07	5,07
		Metro			6,28
	Costes de congestión Cc	LDV Near capacity	2604,93		
		HDV Near capacity		174,5	174,50
	Total social (€/día)		2680,79	179,57	185,85

Tabla 6- Costes externos para las diferentes alternativas (A0, A1 y A2)

A continuación, la Tabla 7 compara los principales indicadores para cada una de las alternativas analizadas del modelo M4G (A1 y A2) y del escenario de referencia de reparto a través de furgonetas (A0).

	DT1 (Centros de recogida)		
	Courier (A0)	*Shared trains* (A1)	*Dedicated trains* (A2)
Paquetes de *e-commerce* entregados por día		6654	
Estaciones de Metro utilizadas	-	15	15
Emisiones de CO_2 LDV/HDV (toneladas/año)	418,25	87,52	87,52
Kilómetros en carretera LDV/HDV (km/día)	9981	500	500
Consumo diésel (litros/año)	144 140	28 635	28 635
Costes medioambientales por paquete	0,127	0,032	0,038
Costes sociales por paquete	0,403	0,027	0,028
Total coste externo por paquete	0,530	0,059	0,066

Tabla 7- Principales indicadores de las alternativas analizadas

5. ANALISIS DE RESULTADOS

Los costes totales estimados para las alternativas propuestas indican que el uso del sistema ferroviario metropolitano para entregar paquetes de comercio electrónico puede ser una alternativa prometedora desde un punto de vista social y ambiental.

Esta sección analiza los resultados desde varias perspectivas:

1) Coste externo por paquete:

Para poder comparar la eficiencia social y ambiental de cada alternativa, es necesario asociar el coste externo total por cada paquete entregado y para cada una de las alternativas, como se muestra en la Figura 9.

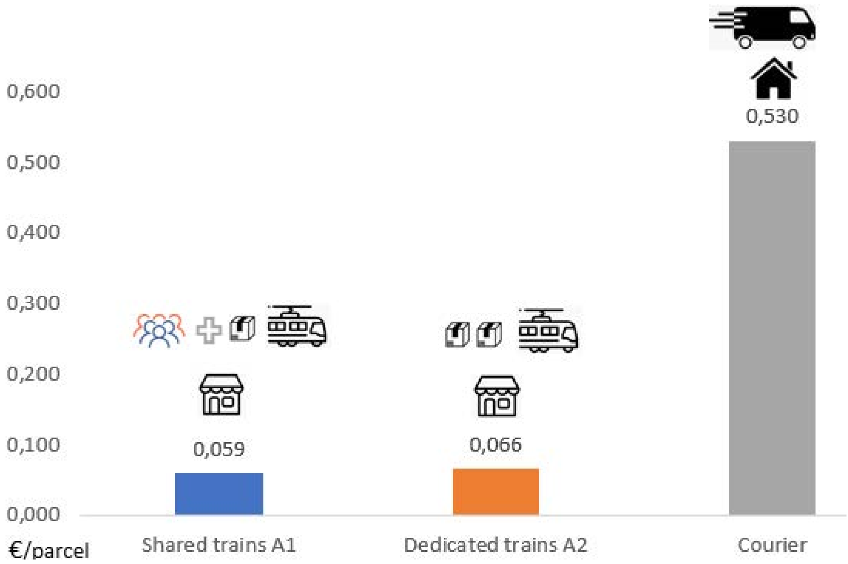


Figura 9. Coste externo (€) por paquete para las alternativas analizadas (A1, A2, A0).

Como se puede observar en la Figura 9, las dos alternativas del modelo M4G presentan unos costes externos notablemente inferiores a la situación de reparto actual mediante furgonetas. En concreto, los costes medioambientales y sociales suponen entre un 88,87 % y un 87,63 % menos que los mismos costes externos del modelo actual de reparto.

Dentro de las alternativas del M4G, los valores son similares y las externalidades provocadas por los trenes específicos son poco relevantes. Como puede verse en el desglose de cálculos de los costes externos de las alternativas con la misma demanda de paquetes, los costes externos de los camiones pesados que viajan a los depósitos de Metro suponen un impacto significativamente mayor que las externalidades de los trenes dedicados que transportan paquetes. Para las alternativas que involucran trenes, la diferencia en los costes externos radica en optimizar el número de camiones pesados que transportan contenedores empleados en el transporte a depósitos de Metro

2) Coste por tipo de externalidad:

Dentro de todos los costes externos, los costes de congestión son los que producen mayor impacto en cualquiera de los escenarios analizados. Dentro del modelo M4G, la congestión media de las dos alternativas (42,0 %) es producida por los camiones que transportan paquetes desde el centro logístico a los depósitos de Metro, y en el caso del escenario actual, la congestión (73,9 %) es producida por el número de furgonetas que reparten desde el centro logístico al domicilio de cada cliente.

Con relación al medioambiente, la polución del aire es el principal causante de los costes debido a la participación dominante que ostenta el transporte como medio por carretera (24,2 % en el caso de M4G y 11,9 % en courier). La externalidad con menor relevancia es el coste que se produce por accidentes con, aproximadamente, un 2 % de los costes externos.

La Figura 10 muestra la media de los costes externos de las alternativas del modelo M4G (A1-A2) y el coste externo del modelo actual de reparto (courier).

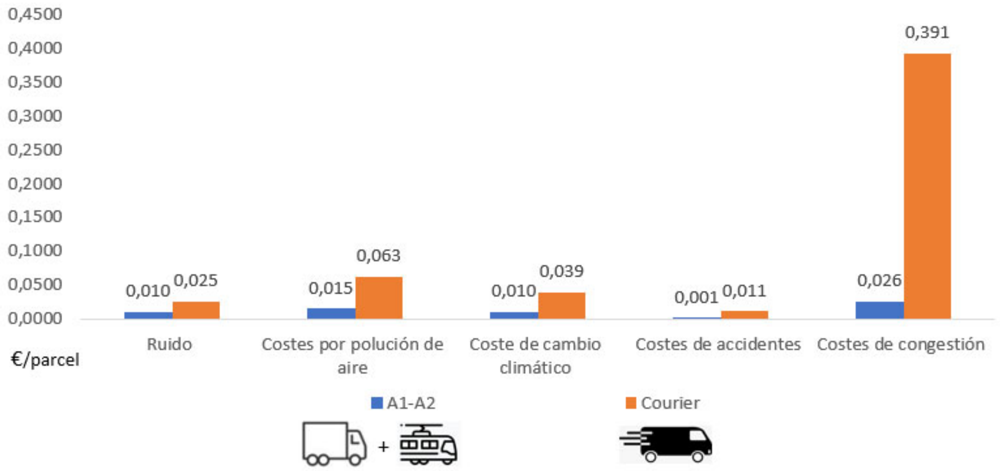


Figura 10: Coste externo promedio por paquete para las diferentes externalidades.

3) Analisis de sensibilidad:

Se considera en este estudio la variación de la demanda de paquetes como consecuencia del incremento o disminución del potencial número de compradores online, es decir, para el caso de estudio: (i) el número de viajeros de Metro, y (o) (ii) el número de residentes en los barrios donde hay una estación de Metro para recoger el pedido online.

Potencial número de compradores online: el porcentaje total de paquetes solicitados por viajeros es del 39,6 % y por residentes del 60,4 %. A priori, estos porcentajes se pueden considerar valores estables con pequeños crecimientos o decrecimientos a lo largo de los años, pero la aparición de la covid-19, si bien no ha tenido incidencia significativa en el número de residentes de los barrios de Madrid, sí que ha supuesto una modificación sustancial en el número de viajeros que utilizan el transporte público metropolitano. En la Figura 11 se muestra la evolución de los residentes en la ciudad de Madrid y la evolución de los viajes en Metro en el periodo 2000-2020.

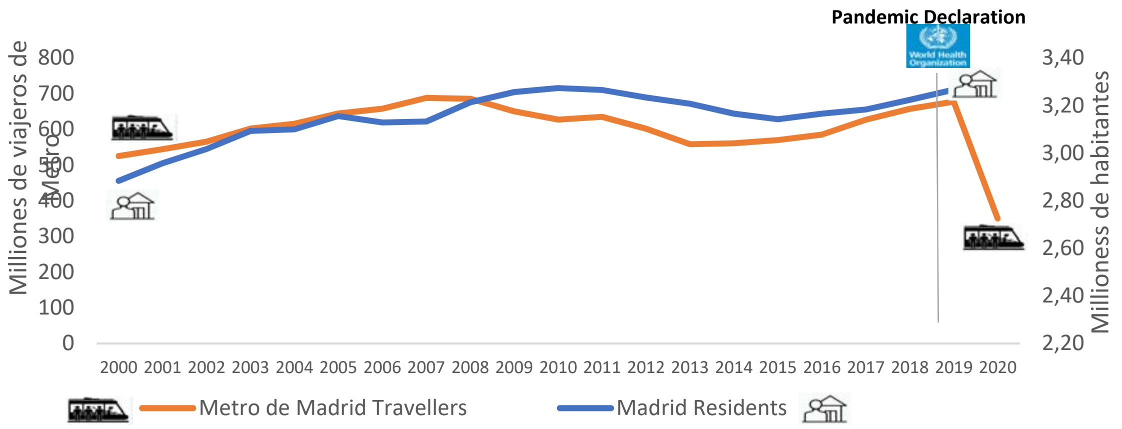


Figura 11: Evolución del número de residentes y del número de viajeros de Metro de Madrid (2000-2020).

Las dos curvas presentan evoluciones similares hasta el año 2020. En ese año, mientras los residentes de la ciudad de Madrid siguen creciendo, la demanda de Metro de Madrid cae drásticamente. En 2019, Metro de Madrid realizaba una media de 2,3 millones de viajes al día, de lunes a viernes. Durante la pandemia, excluyendo los periodos de máxima restricción (marzo-junio de 2020), la demanda de viajeros se mantuvo estable en el 50 % del periodo precovid-19. Desde la Comunidad de Madrid (https://cms.uitp.org/wp/wp-content/uploads/2020/12/201221-NP-TRANSPORTES-Balance-y-campa%C3%B1a-transporte-p%C3%BAblico.pdf), se prevé que se pueda recuperar las cifras previas a la crisis en 2023. Parece factible una recuperación progresiva de la demanda de viajeros, lo que parece más complicado es alcanzar los niveles de demanda de viajeros precovid-19, debido a los cambios sociales y de movilidad que ha experimentado la sociedad.

En el caso de una variación de la demanda de viajeros de Metro (manteniendo la misma estructura de la matriz origen-destino y el resto de variables constantes), la variación de la demanda diaria de paquetes de e-commerce influye solo en los pedidos que realizan los viajeros de Metro.

Ante estos cambios en la demanda de paquetes, las alternativas analizadas presentan costes externos muy estables (Figura 12 y Figura 13). El volumen máximo de paquetes (9981) no requiere trenes adicionales para el caso de la alternativa de trenes específicos y, como se explicó anteriormente, las externalidades provienen principalmente de los camiones que realizan el transporte desde el centro logístico al depósito de Metro. Si no cambian estos parámetros, la variación es casi nula en ambos casos. En términos sociales y medioambientales (costes externos), la opción de reparto a través de M4G es mucho más eficiente que el reparto actual ante cualquier variación de la demanda de paquetes.

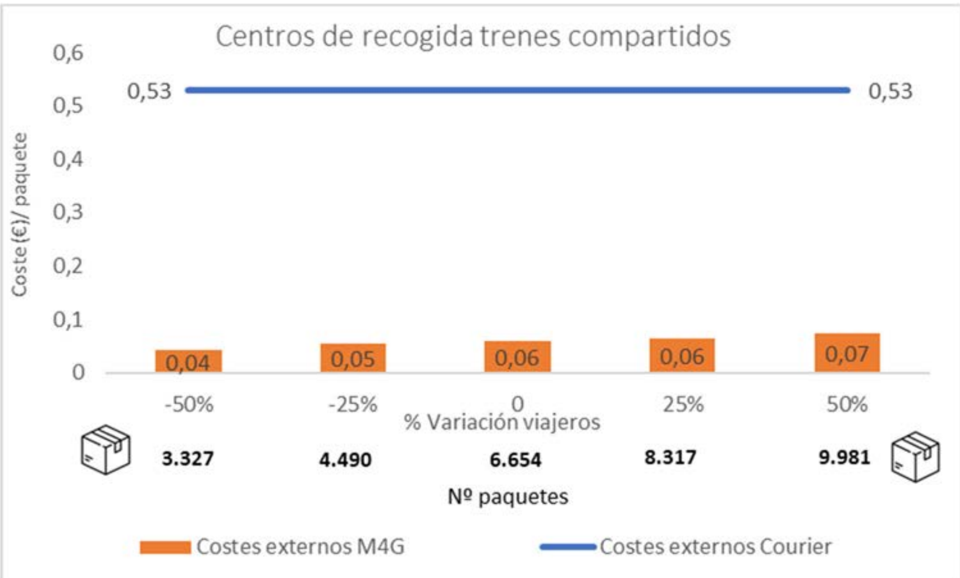


Figura 12. Costes externos (€/paquete) ante variaciones en el número de paquetes para centros de recogida y trenes compartidos

Figura 13. Costes operativos (€/paquete) ante variaciones en el número de paquetes para centros de recogida y trenes compartidos

Una limitación operativa de esta alternativa se produce cuando el número de paquetes que se concentran en un centro es muy elevado. Por ejemplo, en el caso de un incremento de viajeros en un 50 %, el número de paquetes diarios que se entregarían en la estación de Sol es de 1010, lo que supondría disponer de unas infraestructuras suficientes para almacenar y entregar este volumen de paquetes diarios.

6. CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

Este estudio plantea la cuantificación de los costes externos de un nuevo modelo de entrega de paquetería de comercio electrónico a través de la red de transporte público ferroviario urbano de una gran ciudad.

Los resultados, aplicados a una ciudad como Madrid, buscan dar respuesta a las preguntas planteadas en la introducción. En primer lugar, la demanda de compras por comercio electrónico por parte de viajeros y residentes que viven cerca de las estaciones alcanza un volumen suficiente para justificar el uso de trenes para su entrega. Cabe destacar que las perspectivas de crecimiento del comercio electrónico contemplan mayores volúmenes en el futuro. En segundo lugar, en relación al uso de las infraestructuras y medios necesarios para implementar el modelo, debemos considerar: (i) la capacidad de transporte de paquetería en cada tren, (ii) la posibilidad de emplear trenes dedicados o compartidos, (iii) el horario y carga / descarga de mercancías de los trenes, (iv) la interacción con los viajeros, y (v) el uso de centros de recogida para completar las entregas.

Por último, los costes sociales y ambientales asociados con el modelo de entrega propuesto son considerablemente más bajos que los del sistema actual basado en LCV.

En la actualidad, el coste externo promedio por paquete entregado se sitúa entre 8,0 y 8,98 veces mayor que las alternativas del modelo propuesto. En el caso de los trenes compartidos, las externalidades son generadas por camiones pesados que viajan desde el centro de cumplimiento electrónico hasta la estación de Metro, mientras que en el caso de los trenes dedicados, los costes externos son muy similares a los de los trenes compartidos. Por lo tanto, se deben considerar otras variables para seleccionar entre ambas opciones.

Inevitablemente, surgen varias limitaciones en el estudio, que representan direcciones valiosas para futuras investigaciones. Por un lado, sería valioso cuantificar con precisión todos los costes (económicos, sociales y ambientales), para poder realizar un análisis de costo-beneficio social (SCBA) y así contemplar las necesidades de cada grupo de interés.

Por otro lado, este estudio podría ampliarse considerando otras formas de entrega (taquillas inteligentes, entregas a domicilio, etc.) y evaluando los impactos sociales y ambientales de las principales alternativas existentes actualmente en el comercio electrónico.

Por último, sería interesante conocer la posición de los usuarios de Metro en cuanto a compartir infraestructuras (trenes, ascensores, etc.) en sus desplazamientos fuera de las horas punta.

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ANALYSIS OF THE TECHNICAL AND OPERATIONAL CAPACITY OF A COMBINED SEMI-TRAILER RAIL TRANSPORT SERVICE BETWEEN THE PORT OF ALGECIRAS AND ZARAGOZA.

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ABSTRACT

The aim of this study is to evaluate the feasibility to run an Autopista Ferroviaria with Iberian width from a technical and operational point of view in order to analyse the business model in the short term.

A.F. (Autopista Ferroviaria) is defined by the Spanish Public Works Department as a combined transport in which semitrailers are transported by train in a shuttle service using specific wagons and terminals conditioning for this service according with the chosen operational typology. According to this definition, Spain, for the moment, still has not a service that could be called A.F. in Iberian width.

This study is based on the current Iberian railway line between the Port of Algeciras and Plaza (Logistic Platform of Zaragoza) and its focus is to determine whether from a technical and operational point of view, this rail line provides enough features to be used as A.F. To reach this goal, a European Ten-T corridor, the Atlantic one, and two important connections which are included in the Core Networks: Algeciras and Zaragoza are considered.

1. COMBINED FREIGHT RAIL TRANSPORT IN SPAIN

How is it possible that a country with an incredible technologic railway level, a good GDP level and a large railway net in three different gauge has one of the worst Europe figures in terms of freight rail? And the last but not the least question: Why Spain still has not an Iberian track rail motorway with the target of increasing rail freight transportation? Is it a technical issue due to the current infrastructure? Operational or Economic trouble? Or perhaps, could it be due to the past and present of the public policies in matters of rail freight transportation?

Nowadays, in Spain, the freight transport by rail compared to the total freight in all the transportation modes, inside the country, is around 1,4%.

The percentage of the freight transportation between the two terrestrial modes (road versus rail) indicates that the 95% of the terrestrial frights are moved on the roads. Only 5% are transported by train. The percentage of Spain in comparison with the European average and with several countries with similar characteristics is pretty small. The graphic bellow describes the curve of the historical evolution of the freight via road versus rail in Spain.

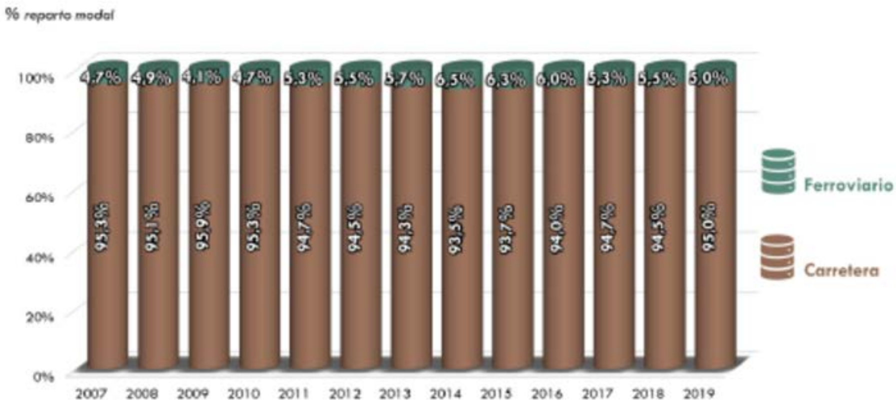

Fig. 1 – Percentage of modal split Spanish terrestrial transport. Source: Informe OTLE 2020

The question is easy: What makes these numbers possible? The answer is not so easy to respond. In the past, the freight operations were running by a state company in a monopoly market that oriented the Spanish railway sector just on passengers, not freights. The strategy was based always on passenger transport because the returns in economics and in politics terms are higher. Also, Spain has a very good highway net with large public inversions year to year. The result of the combination of these two public strategies through time is already mentioned percentage between road and train freight transportation.

In the year 2005 (Ministerio de transportes, movilidad y ayuda urbana), the market was opened for private capital, as a result, other companies entered to play the game. However, although the theory says that the market should be more competitive, and the cake should be distributed, the reality is completely different.

In Spain, freight railway transport can be competitive comparing to road transport when a minimum distance is overcome and the supply chain is fed with the necessary load. Also, the goods to be transported must meet certain characteristics. Otherwise, there will not exist an opportunity for railway transportation.

Consequently, to be sustainable in terms of the supply chain of the companies, freight railway transport has to adapt to the rules of the current logistic markets. Nowadays, the freight rail sector is not flexible enough to compete with the road one with the “market rules” of the logistic supply chain.

Definitively, the challenge to succeed is that the freight rail transportation would be competitive in order to reliability, cost and supply chain adaptation.

2. OPERATIONAL FEATURES

Freight railway transport needs a minimum distance to be competitive versus road transport. Moreover, the efficiency of the AF will depend on a daily minimum quantity of freight to be transported. Hence, in order to ensure the sustainability of the AF, a minimum distance, a big quantity of goods and a perfect adaption to the current supply chain are important and necessary features.

The selection of nodes of Algeciras and Zaragoza, as a part of the AF, is born out of these necessities. The distance is optimal for rail transportation and the freight to move via semi-trailers is daily and large enough. Furthermore, Algeciras and Zaragoza belong to the Ten-T Core Network and Atlantic and Mediterranean corridors are involved between both cores.

Fig. 2 – Ten-T core network corridors. Source: European Commission's Ten-T portal

Therefore, for the complete analysis of the technical and operational capacity of the AF between the nodes of Port of Algeciras and the Intermodal terminal of Plaza-Zaragoza) several critical issues have to be analysed.

The infrastructure of the railway (slopes, electricity, …), the infrastructure nodes (terminals), the technical system for loading semi-trailers, typology of wagons, selection of the railway traction, characteristics of the supply chain of the goods to be transported, etc.

2.1 Infrastructure

2.1.1 Railway Infrastructure

The railway infrastructure that joins Algeciras with Zaragoza consist of 1.074 km with Iberian width. Currently, all the line has got energy (catenary) except the path between Algeciras and Bobadilla which is planned to be ready in the short term (this issue is in ADIF´s planning department).

One of the singularities of the infrastructure is that the maximum slope of the line is 24´´.

This fact is very relevant in terms of traction or maximum load to be transported and it will have a significant importance in terms of operational profitability. Besides, the maximum length of the composition (traction and wagons) is, for the moment, 550 meters. It is because of the maximum length of the railway sidings.

The table below reflects the characteristics of the railway infrastructure.

Length	1.074 km
Width	1.668 mm
Catenary	3 Kv (except Algeciras – Bobadilla. It will be 25 Kv)
Maximum length	550 m (railway sidings)
Maximum slope	24´´ Bobadilla - Algeciras
Rail gauge	Analysing by Technical department of ADIF

Table 1 – Main characteristics of the railway infrastructure. Source: Compilation based on the public information from ADIF

The main problem to make available the infrastructure for the combination of wagon and semi-trailer (P400 or more) is the tunnel gauge for the rolling stock. The nature of this problem is because of two aspects. The first one is that, currently, there does not exist regulation for this type of rail gauge in terms of safety. The responsible for this regulation is the State Agency for Railway Safety (Department of Transport, Mobility and Urban

Agenda of the Spain Government). And the second aspect is the need to analyse whether physically the current tunnels permit or not the traffic of the combinations of wagons and semi-trailer. If not, it will be necessary to study the investments needed for improving the infrastructure (tunnels, platforms, etc) in order to permit the pass of the "new" railway set (extra low wagons and semi-trailers P-400 or more).

2.1.2 Terminals Infrastructure

The multimodal (road-train) terminals based on Zaragoza (Plaza) and Algeciras (Port of Algeciras) are already in service. The maximum length of the railway is 750 m in both cases, and these have all the characteristics to house the rail service system for providing "trailer on flatcar".

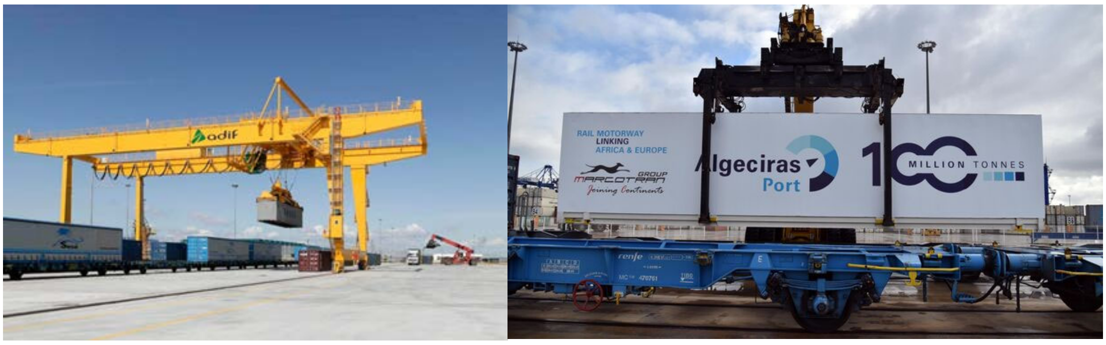

Fig. 3 - Left: Rail terminal of Plaza. Right: Rail terminal of Port of Algeciras

On the other hand, it will be necessary to adequate the terminals for the singularities of the operations of the AF. For instance, access to a big number of semitrailers, new digital systems, space for the "trailer on flatcar" system, etc.

2.2 "Trailer on flatcar" system

In Europe, there exist several systems operating combined transport, which objective is to load semi-trailers on wagons. The most common systems are: Modalohr, CargoSpeed System, Load-unload semi-trailer systems through cranes, bimodal bogies, … All of them have benefits and disadvantages in comparison with the others.

For the present study, the system which has been chosen is Load-unload semi-trailer system through cranes because of its flexibility, initial investment (the lowest), space necessary in terms of demanded surface and reutilization in case of other possible projects.

2.2.1 Wagon

Wagon must be special in terms of height in order to fulfil the requirements of tunnel gauge. For this reason, wagon must be low-floor. Currently, there are no Iberian gauge low-floor wagons. They must be designed, produced, and certificated for Spanish rail-tracks. Besides, it is important that these wagons could be compatible with different uses. Although, the AF has been thought for loading P-400 (or more) semi-trailers, it is important that other types of load could be carried (maritime containers, etc).

2.2.2 Platform to load semi-trailers

Generally, road transport companies do not use crane trailers. This fact make necessary a special platform in order to load the semi-trailer on the wagons. This piece will travel with each semi-trailer from terminal to terminal.

This platform must fit with the wagon.There are different alternatives in the market.

2.3 Composition of the train

The maximum slope of the railway track (24”), the maximum length permitted (around 550 m) and the maximum load (TBR; gross tons towed) are the technical variables that have an influence in the decision of the selection of the rail traction. The following table shows the information of the different alternatives.

	SLOPE & TONS		
RAIL TRACTION	16´´	17´´	24´´
253	1.180	1.130	860
253 DT (hight resistance hooks)	2.130	2.040	1.550
EURO 4000 (335) Diesel	1.490	1.410	1.060
EURO 4000 (335) Diesel (DT)	2.680	2.540	1.910

Table 2 – Different rail traction alternatives. Source: Compilation based on the public information from ADIF, Bombardier and Vossloh

In addition, in order to select the rail traction and respecting the maximum length that is permitted on the rail infrastructure (550 m) the factors to be analysed are: mix of container (semitrailer vs maritime container) and average load of each container. There are many different combinations as a result and all of these have different consequences in the economic part of the analysis. (The hypothesis considered for the analysis are 22 tons of average load for semi-trailers, the low-floor wagon is the standard gauge T-3000 and the platform is the Krona).

COMPOSITION	NUMBER OF WAGONS	LENGTH (m)	WEIGHT (Tons)
Simple traction + 8 wagons (SR) + 4 wagons (UTI)	12	430	1.230
Simple traction + 10 wagons (SR) + 3 wagons (UTI)	13	467	1.448
Double traction + 10 wagons (SR) + 3 wagons (UTI)	13	491	1.571
Simple traction + 11 wagons (SR) + 3 wagons (UTI)	14	502	1.550
Double traction + 11 wagons (SR) + 3 wagons (UTI)	14	525	1.673

Table 3 – Examples of different possible combinations of train compositions. Source: Compilation based on the public information

2.4 Availability of Traffic (Railway Capacity of the infrastructure)

To fulfil parameters defined for being an AF, certain capacity (railway operation of trains) on the infrastructure is needed. This capacity must permit to enhance the needs of the current supply chain. Otherwise, the success of the AFAZ will fail. One relevant aspect of the supply chain between these points are schedules agreed of the freights.

3. TRADE FLOWS

The AF makes economic sense if the trade between Africa; through Tanger Med Port of Morocco; and Spain and Europe; via Zaragoza; is economically sustainable, enhance the current supply chain and can be transported via rail.

3.1 Trade Flows

With the flows studied in the point 3.1, it will be considered that the trade flows are optimal in terms of this project.

Besides, the main flows that could be captured will be coming from RO-RO. The table below describe the forecasting for these flows.

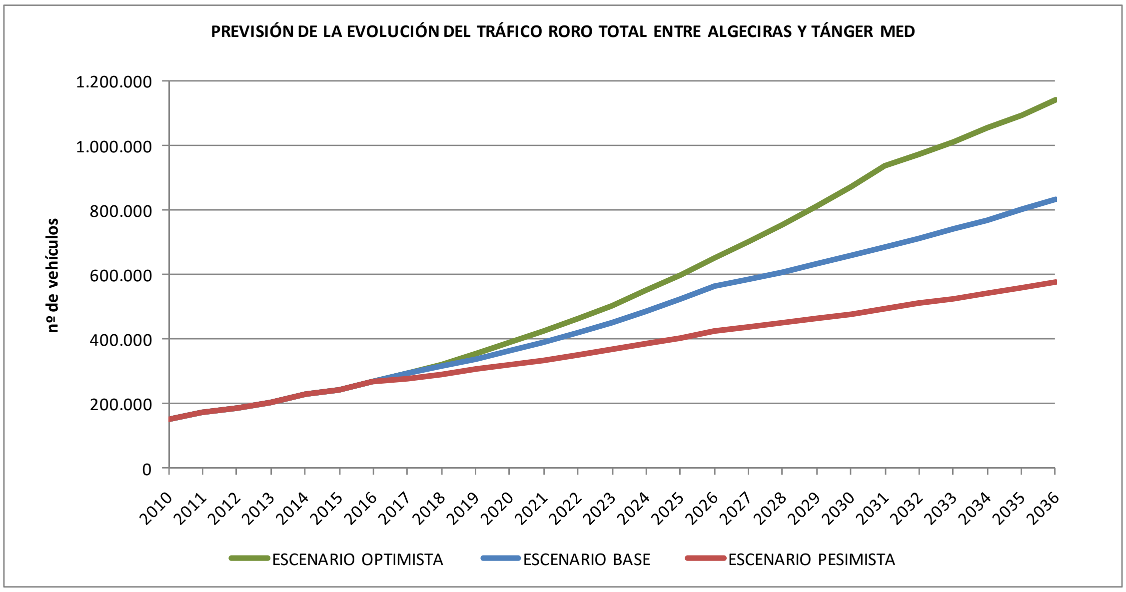

Fig. 4 – Evolution forecast of RO-RO traffic between Algeciras and Tanger Med. Source: Autoridad Portuaria Bahía Algeciras

With this scenario it is logical stablish that the freight to be transported is big enough. It will be necessary an exhaustive analysis in order to know which kind of loads (sectors) are more interesting to be carried by train.

3.2 Supply Chain

After several meetings with important road transportation companies that operate currently between Algeciras and Zaragoza (both directions), there is one variable that is repeated constantly:

The most important feature of the supply chain is the concerted time for the freight, principally in the area of Zaragoza, in the direction Algeciras-Zaragoza. Therefore, Adif has to offer the possibility to use the infrastructure with these requirements.

4. COST EFFECTIVINESS

4.1. Economics

Although a precise model is being realized in this moment as a part of a PhD in the Mechanical Engineering (Transports) of the University of Zaragoza, an example of a Profit and Loss forecast results is expressed in the next table. The main inputs, for the moment, are simple. The combination of the rail traction and wagons are the same in all path. So the mix of the freight is formed by traction, 17 wagons and Nikrasa platforms. The averaged for the load is 24 ton. It is a non-stop in Madrid or other place in order to load or unload goods. The considered occupation is a 70%,80%,100% of the total wagons in the first, second and third year respectively. The costs are based in the cost publications and consultants and the sales are based on the different scenarios.

	ECONOMIC RESULTS (millions of euro)								
TRACCION	Euro 4000 DT -> Euro 4000 (524.84/501.82 m)			253 DT -> 4000 (550.8/536.02 m)			253DT->253DT (550.8 m)		
YEARS	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3
SALES	10,6	11,3	12,0	11,4	12,2	12,9	11,4	12,2	12,9
COSTS	11,5	11,6	11,7	12,1	12,3	12,4	12,7	12,8	13,0
INCOMES B.T.	-0,9	-0,3	0,3	-0,7	-0,1	0,5	-1,3	-0,6	-0,1

Table 4 – Forecast P&L (years 1 to 3)

With these inputs, it is possible to find combinations that permit an economic sustainability operations model.

4.2 External cost

Nowadays, it is very important for different reasons, such as environmental, safety, etc., to keep in mind that rail transport is more ecological than road transportation. With a unique frequency (Algeciras-Zaragoza and Zaragoza-Algeciras) and considering the short train of the analysis (8 wagons for semitrailers and 4 wagons for maritime containers) the train transport will absorb 48 trucks per day. The number of annual kilometers (just for this composition) would be 14.396.429.

5. CONCLUSIONS

On one hand, considering all technical aspects, AF (with Iberian gauge) in Spain between Algeciras and Plaza is possible. The limitations in the infrastructural aspects such as slopes, static, cinematic and dynamic gauges, catenary and terminals do not limit the possibility to run the AF services between Algeciras and Zaragoza.

At the same time, the main operational features (wagons, traction, and systems to load and unload semitrailers) are running in the European market. Therefore, from the perspective of the operations, the AF between Algeciras and Zaragoza is feasible.

On the other hand,currently, there is a big amount of semitrailers in both directions and it will be increased in the short time. And make sense, if the supply chain of the principal players is not altered, that the logistic market accepts a new channel with attractive attributes.

Finally, it has to be mentioned that AF between Algeciras and Zaragoza is a sustainable economic model for private equity with the previous compromise of the public sector.

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AN AGILE AND REACTIVE BIASED-RANDOMIZED HEURISTIC FOR AN AGRI-FOOD RICH VEHICLE ROUTING PROBLEM

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ABSTRACT

Operational problems in agri-food supply chains usually show characteristics that are scarcely addressed by traditional academic approaches. These characteristics make an already NP-hard problem even more challenging; hence, this problem requires the use of tailor-made algorithms in order to solve it efficiently. This work addresses a rich vehicle routing problem in a real-world agri-food supply chain. Different types of animal food products are distributed to raising-pig farms. These products are incompatible, i.e., multi-compartment heterogeneous vehicles must be employed to perform the distribution activities. The problem considers constraints regarding visit priorities among farms, and not-allowed access of large vehicles to a subset of farms. Finally, a set of flat tariffs are employed to formulate the cost function. This problem is solved employing a reactive savings-based biased-randomized heuristic, which does not require any time-costly parameter fine-tuning process. Our results show savings in both cost and traveled distance when compared with the real supply chain performance.

1. INTRODUCTION

Feeding pigs in the pork production industry is a highly relevant activity to achieve successfully the supply chain goals (Rodríguez, 2014). Such activity requires a precise logistics from the production plant to the farms where the pigs are raised. Hence, our work consists in designing a set of vehicle routes that meet the feed demand of a set of pig farms, considering the real case of a pork production company in Spain. From an academic point of view, the analyzed problem can be considered as a rich vehicle routing problem (RVRP) (Caceres-Cruz et al., 2014), since: *(i)* vehicles are heterogeneous and have multiple compartments to separate different types of incompatible products that must be distributed to a set of farms; *(ii)* each farm may require multiple products; *(iii)* some farms admit only that a small-medium vehicle deliver the feed; *(iv)* a visit priority must be met, which indicates that some farms must be visited as soon as possible, whereas other farms must be the last to be served; and *(v)* the cost function considers a set of flat tariffs, which depend on both the location of the farm and the number of farms visited in the same route.

A flexible and enriched heuristic is then proposed to address this problem. Apart from the multi-product and multi-compartment RVRP, this heuristic must be able to deal with an objective function that relies on a flat-rate policy instead of the traditional distance-based minimization. Then, this enriched savings-based heuristic is extended into a biased-randomized algorithm (BRA), which is able to provide multiple solution configurations in short computational times. As described in Grasas et al. (2017), biased-randomized techniques are based on the introduction of an oriented (non-uniform) randomization process inside the constructive stage of a given heuristic. By doing so, a deterministic heuristic is transformed into a randomized algorithm that can be run multiple times (either in sequential or in parallel) without losing the logic behind the heuristic. Hence, the main contributions of our paper can be stated as follows: *(i)* the consideration of a flat-rate cost function, together with multi-product and multi-compartment characteristics; *(ii)* the design of a flexible and agile heuristic, which enriches the traditional savings heuristic, to solve a rich and real-life problem in the agri-food distribution industry; *(iii)* the extension of the former heuristic into a biased-randomized algorithm capable of providing, in short computational times, a set of alternative solution configurations to the problem, each of these including different dimensions; and *(iv)* the introduction of a reactive (automatic) fine-tuning process for the main parameter of the biased-randomization process.

Rich vehicle routing problems have been increasingly addressed by the academic community, since they incorporate highly realistic constraints, especially when these are considered simultaneously (Azadeh and Farrokhi-Asl, 2019). Characteristics regarding input data, decision management components, vehicles, time constraints, among others, turns a classical VRP into a rich VRP (Lahyani et al., 2015b). For instance, Alemany et al. (2016) combine the well-known savings heuristic (Clarke and Wright, 1964) with Monte Carlo simulation to solve a heterogeneous-fleet, multi-depot, multi-compartment, multi-product, and multi-trip VRP. In general, vehicles can be classified according to their physical characteristics, e.g., they can be homogeneous or heterogeneous, or compartmentalized or not. The relevance of considering compartmentalized vehicles emerges whenever different types of products are demanded and they are incompatible, i.e., products must be carried separately into the same vehicle and not be mixed. Despite the practical applications of this strategy for addressing real-world problems, the multi-compartment VRP has been scarcely studied (Derigs et al., 2011). Both theoretical and real-world cases can be found in the multi-compartment VRP literature. Silvestrin and Ritt (2017) and Muyldermans and Pang (2010) show examples of the former.

These works propose metaheuristic approaches given the combinatorial nature of this problem. Regarding real-world cases, products as diverse as apparel, fuel, food, and waste require the use of compartmentalized vehicles for performing an appropriate transport (Wang et al., 2014; Reed et al., 2014; Vidovic et al., 2014; Coelho and Laporte, 2015).

Agri-food supply chains represent also a field where the multi-compartment VRP has been addressed. These chains have special characteristics that should be taken into account in its modelling, such as products perishability (Tordecilla-Madera et al., 2018) or supply and demand seasonality (Vlajic et al., 2012). For instance, Lahyani et al. (2015a) propose a branch-and-cut algorithm to solve a multi-period and multi-compartment VRP with heterogeneous vehicles. A real case from the olive-oil collection process in Tunisia is considered, where compartments cleaning activities are considered. Oppen et al. (2010) address also cleaning activities in a multi-compartment VRP where inventory constraints are considered. Different types of animals are transported in this case, as well as a heterogeneous fleet and multiple trips. An exact method based on column generation is used as solving approach. Alternatively, employing approximate methods is a usual approach in agri-food multi-compartment VRPs. For instance, Caramia and Guerriero (2010) propose a hybrid approach combining mathematical programming and local search techniques to solve a real-life case regarding the collection of different types of milk in Italy. Finally, the number and capacity of compartments can also be a variable to consider, i.e., compartments are flexible. For instance, a large neighborhood search algorithm is proposed by Hübner and Ostermeier (2019) to solve this variant of the multi-compartment VRP. A relevant contribution of this paper is the consideration of loading and unloading costs, which are a function of the number of compartments.

The remainder of this paper is structured as follows: Section 2 shows the main characteristics of our addressed problem, and Section 3 describes the algorithm employed to solve it. Section 4 shows our main found results based on a real case study, and Section 5 shows the concluding remarks and future work.

2. PROBLEM DESCRIPTION

The part of the supply chain addressed in this paper is that in charge of distributing the animal food from central depots to the farms, as displayed in Figure 1. We consider each day as an independent instance, where the subset of farms requiring service can be different. Each farm generates an order, and each order may be composed of different types of feed, e.g., Figure 1 displays circles, hexagons and triangles representing three different products. In general, products can be classified in medicated and non-medicated.

Also, the characteristics of each type of product depend on the growth stage of each herd, i.e., the required diet mix is different according to the age (in weeks) of each individual.

The demand of each product in each farm is deterministic. The feed distribution is carried out from a depot through a set of compartmentalized heterogeneous vehicles. For instance, Figure 1 shows two types of vehicles with three and four compartments, respectively.

Compartments are also heterogeneous, i.e., each compartment has a different known capacity. The demanded quantity per product and farm is at most the capacity of a vehicle.

Hence, each vehicle can visit multiple farms in the same route, as long as the aggregate demand does not exceed the vehicle's capacity. Split deliveries are not allowed, i.e., a single farm must be served by a single vehicle. The objective of using compartmentalized vehicles is to separate each type of feed, since they cannot be mixed during a trip. In addition, if the demand of a product is higher than the capacity of a single compartment, it can be split into two or more compartments in the same vehicle. Nevertheless, in general, medicated feed cannot be transported in the same route as non-medicated feed. Not all types of vehicles can visit all customers, since some farms have access constraints. That is, a subset of farms can be served by all types of vehicles, whereas another subset cannot be served by large vehicles. An additional constraint assigns a sanitary priority indicator, which determines a specific order in which a subset of farms must be visited in case they are in the same route. The company classifies the farms into 3 types according to this sanitary priority: *(i)* a subset of farms with an assigned priority according to a consecutive natural number. These farms must always be served in ascending order whenever they are in the same route, e.g., a farm with a priority of 2 must always be visited before a farm with a priority of 5; *(ii)* a subset of farms with no priority; and *(iii)* a subset of farms with a "negative" priority, which indicates that they must be the last to be served in any route.

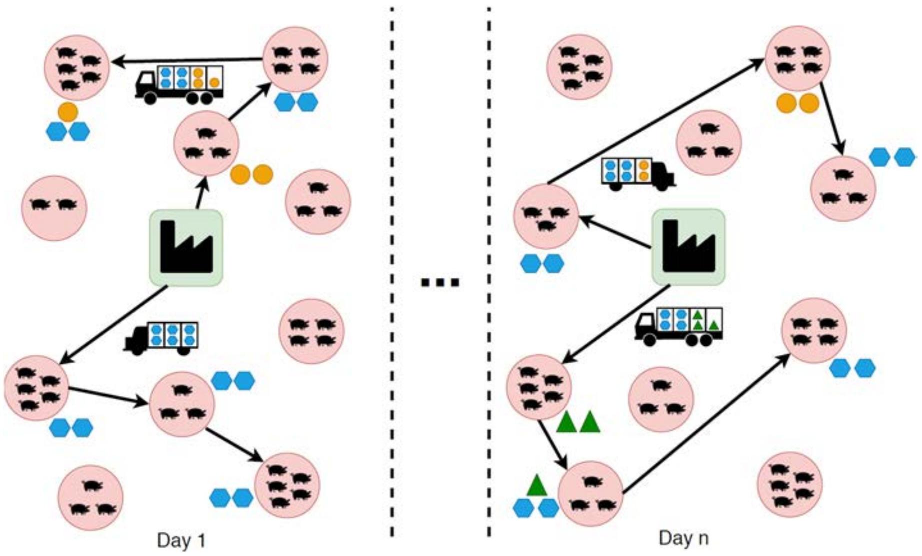

Fig. 1 – Representation of our real-life problem.

Our main objective is to minimize the total distribution cost.

As the company outsources the feed transportation, the distribution cost calculation has been settled in a distribution agreement. This cost is computed as the product of the delivered quantity and a pre-established tariff. The whole distribution region is clustered in zones, so that the tariff $c(n,z)$ depends on both the zone z where the customer is located and the number of farms n visited in the same route. Each customer has three different tariffs according to n (Equation 1), where $c_1(z) < c_2(z) < c_3(z)$.

$$c(n,z) = \begin{cases} c_1(z), & \text{if } n = 1 \\ c_2(z), & \text{if } n = 2 \\ c_3(z), & \text{if } n \geq 3 \end{cases} \tag{1}$$

Figure 2 displays a few examples of tariffs (expressed in €/t) employed by the company.

Figure 2a shows the case in which each farm is the only one visited in its route. Hence, the tariff of all customers in the Zone 1 is $c_1(1) = 7.74$ and the tariff of the customer 4, located in the Zone 2, is $c_1(2) = 8.98$. Figure 2b shows the case in which all customers in the Zone 1 form a single route, therefore, the employed tariff is $c_3(1) = 8.76$. The customer 4's tariff remains the same as in the former case. Finally, Figure 2c shows the case in which customers of different zones form a unique route. Under these circumstances, the distribution agreement indicates that the employed tariff must be the greatest one. Hence, as $c_3(1) = 8.76$ and $c_3(2) = 9.24$, the final distribution tariff for the route in this instance is 9.24 €/t. Since the total satisfied demand is the same in the 3 cases of Figure 2, and the total variable cost depends on the supplied food-load in tonnes, the case in Figure 2b incurs a higher variable cost than the instance in Figure 2a, and the case in Figure 2c incurs the highest variable cost in the example. This means that merging routes increases the variable cost in our problem, which is the opposite of merging routes in traditional routing problems. This behavior is caused by the flat tariffs indicated in the distribution agreement.

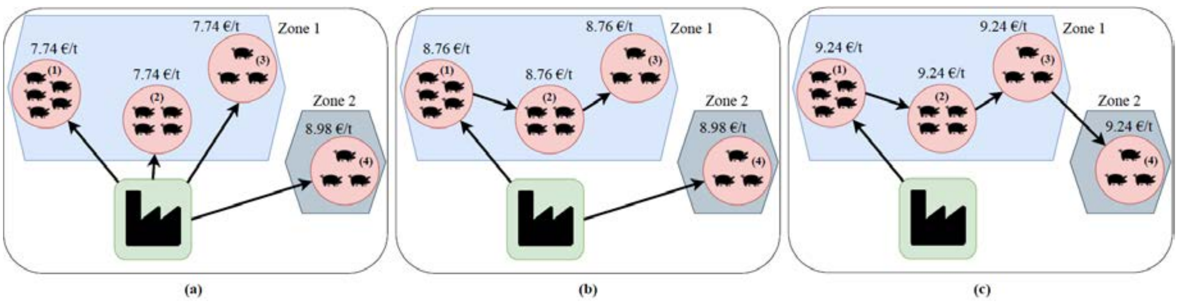

Fig. 2 – Examples of tariffs used by the company.

The considered problem requires that the total delivery cost is not the only key performance indicator (KPI), i.e., the approach used to solve this problem must show enough flexibility to consider additional KPIs, such as the number of designed routes and the total traveled distance.

Despite its non-typical objective function and unique constraints, the problem can be classified as a rich variant of a multi-product and multi-compartment open VRP (RVRP). Hence, it is an *NP-hard* problem and, as such, the use of heuristic-based approaches (Londoño et al., 2020) is justified whenever the size of the problem goes beyond a certain level.

3. FROM A FLEXIBLE AND FAST HEURISTIC TO A REACTIVE BIASED-RANDOMIZED ALGORITHM

This section shows our approach for dealing with the described RVRP. This approach is based on both multi-start (Martí et al., 2013) and biased-randomized algorithms (BR) (Grasas et al., 2017). Algorithm 1 provides a general view of the proposed heuristic to solve the RVRP. The core of our approach is a flexible and fast two-stage heuristic, which includes all problem characteristics considering multiple KPIs. In the stage 1, a first initial solution is generated, in which each customer is assigned to a vehicle in a single round-trip, meeting all the considered constraints. Once this initial solution is generated, the algorithm merges routes in stage 2 as much as possible, reducing the number of used vehicles. Algorithm 2 outlines the stage 2, which consists of the following steps: firstly, it computes the *savings* associated with potential route merges. These savings are computed for every edge and are based on both the distance between farms and the tariff per zone.

Then, a list of edges associated with the savings values is created and sorted in decreasing order. The main loop iterates on the sorted savings list, where each edge is selected to be part of the solution only if it meets the following merging conditions: *(i)* both customers in the origin and the end of the edge belong to different routes; and *(ii)* these customers are adjacent to the depot. Unlike the traditional savings method, we do not consider the total vehicle capacity. Instead, it is evaluated whether the demand of each product fits in the available compartments, considering both their capacity and a feasible layout. When a feasible assignment is found, the algorithm merges the routes and updates the solution; otherwise, the current edge is rejected and the algorithm proceeds to the next iteration with a new alternative. The current solution is updated by removing the routes at both extremes of the selected edge and adding the resulting new merged route. All KPIs are then updated, including the cost, which considers the flat-rate delivery tariffs (Figure 2). Again, notice that this approach is different to the distance-based cost computation employed in most articles on the VRP, which do not consider a flat-rate tariff. Finally, the current edge is removed from the list, and the whole process is repeated until the savings list is empty, returning a complete new solution *sol*.

Algorithm 1 Multi-Start R-BR

```
Require: inputParameters
  sol ← Stage_1(inputParameters)
  β_1, β_2 ← T(0, 0.5, 1)
  newsol_1 ← Stage_2(sol, β_1)
  newsol_2 ← Stage_2(sol, β_2)
  sol, m* ← best(newsol_1, newsol_2), best(β_1, β_2)
  while time not reaches the limit do
      β_s ← T(0, m*, 1)
      newsol ← Stage_1(inputParameters)
      newsol ← Stage_2(newsol, β_s)
      sol, m* ← best(sol, newsol), best(m*, β_s)
      if sol ∉ S* then
          S* ← add(S*, sol)
      end if
  end while
Ensure: S*
```

Algorithm 2 Stage_2

```
Require: sol, β
  savings ← computeSavingsSorted(sol)
  while savings ≠ ∅ do
      edge ← selectNextArc(savings, β)
      savings ← remove(savings, edge)
      if isMergePossible(edge) then
          sol ← updateSolution(sol, edge)
      end if
  end while
Ensure: sol
```

The previous heuristic is extended into a reactive BR algorithm (R-BR). This procedure allows not only to diversify the search for good solutions, but also to generate alternative solutions assessed in terms of multiple KPIs. Our proposed methodology in Algorithm 1 uses both stages 1 and 2 (Algorithm 2) as the base for the R-BR. Previously described steps are followed the same, except for the selection of the next edge in the savings list.

This selection is now performed by considering a skewed probability distribution, which introduces a sort of randomness into this process. In our case, the selection of the next element is performed according to a geometric distribution with parameter $0 < \beta < 1$.

Employing this distribution introduces diversification to explore other regions of the solution space, preserving at the same time the savings heuristic original purpose. Unlike previous works, our algorithm is *reactive*, since the parameter β is automatically fine-tuned. The R-BR implementation procedure is described next: firstly, initialize parameters β_1 and β_2 using a symmetric Triangular probability distribution with mode $m = 0.5$. Secondly, generate two complete solutions using β_1 and β_2, respectively.

Then, compare the yielded costs (or any other KPI) to obtain the best-found mode m^* and the best-found solution *sol* so far. Then, the algorithm iterates while the time limit is not reached. For each iteration, a new β_s is computed using a Triangular distribution with mode equal to m^*.

Later, generate a new complete solution *newsol* using β_s. Again, obtain the best-found mode m^* and solution *sol*. Finally, introduce the new solution *sol* in the pool of solutions S^*.

4. CASE STUDY

Real-world instances representing multiple products demands from 44 workdays have been provided by the company. They represent daily deliveries made to 214 farms. Currently, the company performs a delivery only when the customer generates an order. Hence, only a subset of farms is served each day. Furthermore, the delivered product mix also changes every day, and each customer may require multiple types of food at the same day. The feed shelf life is greater than one day; therefore, perishability is not included in our case study.

The number of vehicle types are 3: a vehicle type with 6 compartments and a total capacity of 26 t, a vehicle type with 6 compartments and a total capacity of 21 t, and a vehicle type with 5 compartments and a total capacity of 21 t. A single product demand can vary between 1 t and 26 t. Our approach yields 4 KPIs: *(i)* total distance, computed as an approximation by employing the Euclidean distance between two farms, considering their real Cartesian coordinates; *(ii)* total cost, computed employing the flat tariffs described in Section 2; *(iii)* total number of routes; and *(iv)* average utilization of vehicles, computed considering the utilization percentage of every vehicle used in every route of a complete solution. The algorithm is implemented in Python 3 and executed in a personal computer with 16 GB RAM and a 2.8 GHz Intel Core i7-1165G7 processor.

Table 1 shows the average results after running our biased-randomized algorithm employing 44 instances. This table compares the results obtained when considering a non-reactive and a reactive biased-randomized (BR) heuristic. The latter refers to the procedure described in Section 3. The former refers to the case already described in the literature, in which the parameter β of the geometric probability distribution must be fine-tuned by hand. In our experiments, our manual fine-tuning process found the best results when β follows a uniform probability distribution between 0.01 and 0.40. Both BR procedures employ a time limit of 60 seconds. Table 1 also shows the results obtained by the company in its real daily operations. Obviously, these results are independent of our both BR procedures. Four types of solutions are generated, where each one is the best-found solution assessed in terms of each aforementioned KPI. For instance, the *Best-distance* solution is the one that achieves the minimum distance. Hence, the reached value of the KPI *Distance* is underlined for this solution.

The reasoning in this example can be extended for the rest of the KPIs. The greater the utilization, the better. The other KPIs have an opposite interpretation. Values obtained by the non-reactive BR are only slightly better than the ones yielded by the reactive BR, i.e., differences are minimal. Nevertheless, the non-reactive BR requires a few work hours for performing the fine-tuning process, whereas the reactive BR is automatic and does not require any fine-tuning.

The average percentage difference between our solution and the company solution is shown in the columns *Gap* of Table 1. This indicator is computed considering the gap between each KPI obtained for each instance. A negative gap indicates that our solution outperforms the company's. If the gap is positive, then the smaller the gap, the better.

Hence, a few results can be highlighted. Firstly, our heuristic always reaches a smaller cost than the company, regardless of the type of solution. Secondly, savings in distance provided by our heuristic are high when considering the *Best-distance* solution. Thirdly, the company slightly outperforms our algorithm when considering the number of routes and the vehicle utilization. Finally, the cost is a KPI whose behavior is opposite to the rest of the indicators', i.e., when the cost improves, the other KPIs worsen. This behavior is a result of considering the flat tariffs explained in Section 2.

Type of solution	Non-reactive BR				Reactive BR			
	KPI				KPI			
	Distance	Cost	#Routes	Utilization	Distance	Cost	#Routes	Utilization
Real company	1153.6	5555.5	23.9	95.8%	1153.6	5555.5	23.9	95.8%
Best-distance	<u>1104.0</u>	5541.7	24.7	92.5%	<u>1106.6</u>	5540.6	24.8	92.3%
Best-cost	1201.3	<u>5495.7</u>	26.7	86.2%	1196.9	<u>5497.5</u>	26.8	86.1%
Best-#routes	1178.8	5544.3	<u>24.2</u>	94.1%	1173.3	5542.4	<u>24.3</u>	93.8%
Best-utilization	1168.5	5549.6	24.2	<u>94.8%</u>	1174.7	5548.6	24.3	<u>94.6%</u>
	Gap				Gap			
Best-distance	<u>-4.4%</u>	-0.2%	3.5%	3.3%	<u>-4.1%</u>	-0.3%	3.7%	3.5%
Best-cost	4.3%	<u>-1.1%</u>	12.3%	9.6%	4.0%	<u>-1.1%</u>	12.6%	9.6%
Best-#routes	2.0%	-0.2%	<u>1.4%</u>	1.7%	1.5%	-0.2%	<u>1.7%</u>	2.0%
Best-utilization	1.1%	-0.1%	1.4%	<u>1.0%</u>	1.7%	-0.1%	1.7%	<u>1.2%</u>

Table 1 – Average results considering different KPIs.

The best-found distance and best-found cost gaps between our solution and the company solution for the 44 instances are displayed in Figure 3. This figure also shows a comparison between our both tested heuristics, i.e., non-reactive BR (NR-BR) and reactive BR (R-BR). Regarding the distance, only a few instances exceed the 0% limit, i.e., our agile approach is able to outperform the company’s distance results for the vast majority of instances. Furthermore, our approach always reaches a negative gap in costs, which is a great result considering the tough restriction imposed by the flat tariffs. Finally, Figure 3 also shows that our reactive BR is able to yield solutions highly similar to the ones achieved by the non-reactive BR.

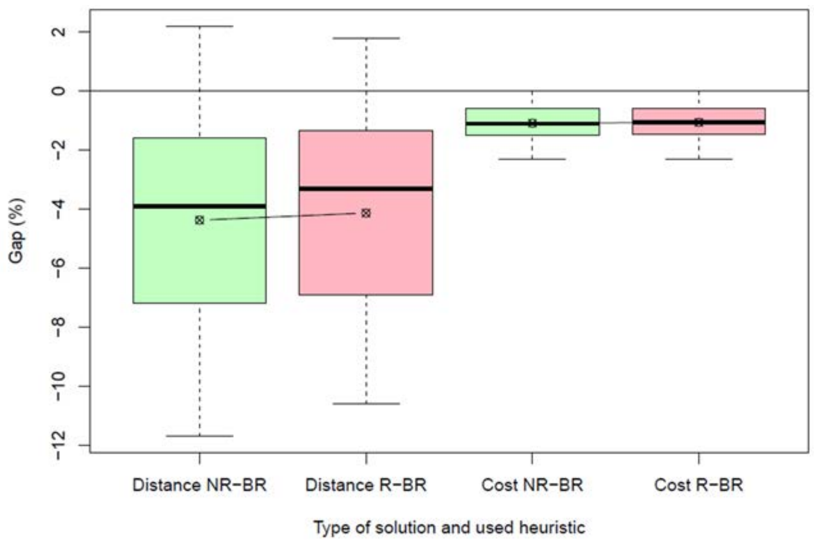

Fig. 3 – Distance and cost gaps of our best-found solutions with respect to the company’s.

4. CONCLUSIONS

This work has proposed a reactive biased-randomized heuristic to solve a real-world rich vehicle routing problem for the distribution of animal food. A set of complex constraints have been considered, such as multi-compartment heterogeneous vehicles, flat tariffs, visit priorities, among others. Four KPIs have been proposed to assess the solutions quality.

Advantages of employing our agile approach are mainly twofold. Firstly, our yielded results outperform the real company's outcomes in terms of traveled distance and distribution cost. These results are obtained in only a few seconds, whereas designing these routes by the company takes a few work hours. Secondly, results yielded by our reactive biased-randomized algorithm are highly competitive when compared with a non-reactive one. However, the latter requires a time-costly fine-tuning process, whereas our proposed heuristic does not require to perform this procedure. Future work includes considering inventory planning jointly with the vehicle routing. In this case, both food perishability conditions and a multi-period planning can be included.

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PROMOTING SUSTAINABLE AND INTELLIGENT FREIGHT TRANSPORTATION SYSTEMS IN THE BARCELONA METROPOLITAN AREA

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ABSTRACT

The growth of e-commerce and the on-demand economy in urban and metropolitan areas has been accelerated by the recent COVID-19 pandemic. As a consequence, logistics and transportation operators are subject to a noticeable pressure to develop efficient delivery systems. These systems are also influenced by the global trend towards more sustainable transportation and mobility, which implies changes in urban policies and technological innovations --$e.g.$, the substitution of traditional diesel petrol-drive vehicles by electric ones. This paper analyzes the current and predicted needs of logistics operators in the Barcelona metropolitan area. To do so, urban regulations are analyzed and key shareholders are interviewed. The analysis of these interviews promote a discussion on how the use of new `agile' optimization algorithms --which are based on the combination of biased-randomized heuristics, computer parallelization techniques, and IoT / 5G technologies-- can contribute to enhance urban distribution practices. Finally, we present a case study in which the effect of different configurations of working/resting times and parking areas availability on routing solutions is studied. Our research aims to provide comprehensive knowledge to managers and policy-makers, and to offer them with powerful tools capable of generating real-time solutions to complex last-mile delivery challenges under dynamic conditions.

1. INTRODUCTION

Currently, more than 50% of the world's population lives in urban areas and this figure will increase up to 68% by the year 2050 (United Nations, 2019). As the world population increases, the demand for goods and commodities will increase. The transportation and mobility sectors have become indispensable for meeting these demands.

However, these sectors emit alarming amounts of carbon dioxide (CO_2) into the Earth's atmosphere. The emitted CO_2 accounts for most transformed climate conditions in regions where climate patterns were once consistent. Respiratory and cardiovascular complications, as well as increased mortality rates have been associated with air contamination.

To alleviate this concern, an innovative paradigm for mobilizing people within urban areas, as well as for developing and sustaining healthier cities while decarbonizing and minimizing the emission of CO_2 is urgently needed. Although preventing the complete mobilization of people would be impractical, exploring environmentally sustainable alternatives such as employing zero-emission electric and unmanned vehicles, and adopting ride-sharing ordinances to reduce idle capacity could have promising results. Nevertheless, adopting technological advances for mobilizing people entails complex operations challenges that need to be properly addressed as well.

As with the mobility of people, the supply of goods is crucial to meeting the United Nations' sustainable development goals. More population implies greater flows, but it also occurs at a time of transformation of the urban business model and related supply chains.

With the emergence of e-commerce, an increasing number of consumers are switching to the online channel, and most are opting for home delivery. This means that the packaging sector is constantly booming, with more vehicles and more companies operating day after day in cities. Thus, the Urban Freight Distribution (UFD) has important implications in terms of both traffic and parking. On the one hand, it significantly contributes to congestion and the emission of polluting particles in urban environments. On the other hand, it strains the demand for parking, filling the reserved spaces and making it difficult to drive through irregular parking practices.

This work aims to investigate the problems emanating from the UFD, and in particular on the public policies imposed at the municipal level to regulate it. Each municipality has a certain infrastructure and dictates its conditions, leaving an extremely fragmented scenario that needs to be taken into account by operators.

The first contribution of this work is an analysis of the logistics conditions in the Barcelona (Spain) metropolitan area. This analysis is based on interviews to key shareholders from different sectors, which allows us to claim the need for agile optimization algorithms (Martins et al., 2021a).

These algorithms constitute an intelligent approach that relies on the combination of biased-randomized heuristics, computer parallelization techniques, and IoT/5G technologies in order to deal with the requirements of large-scale, dynamic, and complex last-mile distribution problems.

A second contribution of the paper is the inclusion of a numerical case study, which allows us to study in more detail the economic and environmental impact that a non-harmonized regulation might have on logistics and transportation operations.

The rest of the paper is structured as follows: Section 2 provides a brief review on related work. Section 3 summarizes a study in which several managers of transportation companies have been interviewed to identify their needs. Section 4 discusses how 'agile' optimization algorithms can contribute to fulfil some of the identified needs.

Section 5 describes a case study regarding the density of parking spots in the city of Barcelona. Section 6 performs a series of computational experiments over the previously described case study. Section 7 analyzes the obtained results and incorporates some managerial insights to be considered. Finally, Section 8 summarizes the main contributions of this study.

2. RELATED WORK

In recent years there has been a huge expansion in e-commerce, with high growth rates of up to two digits in most developed countries. Added to this gradual increase over time are the knock-on effects of the COVID-19 pandemic. Aside from any short-term impacts of the self-isolation and lockdown periods imposed in many countries, the very structure of the market may be undergoing a deep transformation and accelerating the digitization process (Kim, 2020). Thus, for example, in the region of Catalonia (Spain) the online purchases have grown by 27.7% compared to before the pandemic, and 44.6% more than in 2018 (Generalitat de Catalunya, 2020). This increase in e-commerce, in turn, will magnify externalities associated with urban freight logistics and transportation, i.e.: pollution, noise, traffic congestion, as well as the management of parking space.

2.1 UFD Management

Urban freight logistics are made up of the flow of goods circulating throughout a city. In general, an urban transportation system can be defined as the set of transportation elements –both public and private– that involve the mobility of people and goods within the metropolitan area: infrastructure, management, means of transport, entities, service providers, and users (Gonzalez-Feliu et al., 2018). The goal of urban freight distribution is to supply specific items on time and in the right way, guaranteeing low costs and offering good customer service. The recent boom in e-commerce has led to a sizable increase in home delivery packages, with a huge surge in the number of orders shipped and, hence, in urban freight traffic.

In addition, UFD (and especially last-mile delivery) lay bare the conflicting interests of the different stakeholders involved (Rai et al., 2017; Gatta and Marcucci, 2016; Bjerkan et al., 2014). These stakeholders can be classified into three categories: private enterprises (haulage and shipping companies, small retailers, large retailers, and logistics operators), public administrations, and citizens. Public administrations need to take on a leading role in this matter. Local authorities are the ones who have competences for city mobility.

They must have a comprehensive understanding of the complexity of city logistics to identify and implement measures, as well as to create packages of policy tools that facilitate, limit, or manage the distribution of e-goods on different levels of regulation, hence promoting a stronger link between transport planning and land use (Bjørgen et al., 2019; Kiba-Janiak, 2019). Dialogue between all the stakeholders is crucial.
Public policies should be drafted on a consensual basis, especially when logistics operators are the ones that are directly affected by them. Trying to impose specific unilateral measures tends to have unexpected and, more importantly, undesired outcomes (Viu-Roig and Alvarez-Palau, 2020).

Therefore, the goal of the city council is to regulate the use of public space in order to minimize the conflicts that might result from freight transportation in a town, and make this more sustainable (Anderson et al., 2005). The local authorities combat these negative impacts of UFD with different actions, e.g.: by preventing carriers from parking illegally, thus reducing the traffic congestion factor (Cherrett et al., 2012); by enabling enough areas for loading and unloading, thus minimizing the impact on the delivery of goods (Roca-Riu et al., 2017); by imposing vehicle size restrictions in some areas; by creating goods consolidation points or establishing distribution time windows (Rushtonet al., 2014); or by invigorating pollution restriction policies using license plate recognition to avoid the circulation of some vehicles, especially in historic quarters of the city (Liu et al., 2018).

2.2 Loading and Unloading areas

One of the main problems that council cities have to face is the dimensioning of their loading and unloading(L/U) areas, as well as the size of urban land allocated for this purpose (Muñuzuri et al., 2017). Recent researches come to the conclusion that the absence of L/U areas or their poor management causes double parking (Figliozzi and Tipagornwong, 2017).

This mismanagement can sometimes be related to non-commercial use of the L/U zones, such as the use of these by individuals. Something that required greater control for the optimization of the L/U zones (Alhoet al., 2018). In their research, the authors studied the reduction of double parking of cargo vehicles by changing the spatial configuration of the L/U areas and the level of compliance with the parking rule of non-cargo vehicles. Its conclusions show the impact that this mismanagement has on delivery delays and on slow urban traffic. Therefore, the efficiency and effectiveness in the UFD is related, among other things, to the spaces available in the towns for L/U operations (McLeod and Cherrett, 2011; Jaller et al., 2013).

2.3 Time Windows

One of the options used by the council cities to optimize the L/U areas is the implementation of time windows, thus restricting the interval in which delivery vehicles can circulate in various parts of the city (Muñuzuri et al.,2005).

As the time window pressure increases, the number of store deliveries that can be combined in one round-trip decreases, i.e.: the retail chain (who stores and sells the goods) is forced to use extra trucks and cover longer distances to accomplish the store deliveries, which results in an increase of the retailer’s cost.

Furthermore, time windows change over time, and for a retailer it is difficult and costly to accommodate to all these changes. For this reason, many retailers consider time window policies as one of the major problems in urban freight logistics (Quak, 2008). The city council determines their time windows individually, they hardly cooperate and generally copy each others’ municipalities’ regulations regardless of their characteristics (Muñuzuri and Van Duin, 2014).

Another issue that arises in vehicle routing problems or VRPs (Vidal et al., 2019) is the appearance of electric vehicles that require areas to charge the batteries (Juan et al., 2016).

The literature shows some routing examples that would minimize this problem, such as Hiermann et al. (2016) or Keskin and C ̧ atay (2016). The former propose a mixed routing/location problem in which some charging stations are available to allow recharging the vehicle’s batteries during its journey. The latter present a model in which partial recharging of the batteries is assumed to save route times. More recently, Reyes-Rubiano et al. (2019) propose a model for routing electric vehicles that considers limited driving ranges and stochastic travel times.

2.4 Urban Vehicle Access Restrictions

There are many city councils that have limited the entry and circulation of large trucks or polluting vehicles in their cities, since these vehicles have a greater impact on the environment. Several studies show how these policies reduce the environmental impact (Muñuzuri et al., 2005; Anderson et al., 2005).

However, these decisions do not take into account that many more smaller vehicles will be required to transport the same amount of goods or, in the case of license plate recognition, it will force logistics companies to always have to maintain the same fleet entrance into the city, something that will difficult the management of routes (Browne et al., 2008). This will most likely increase the number of vehicles required, as well as the total number of trips (Quak and De Koster, 2005).

Major cities, such as Barcelona, face multiple problems caused by delivery operations in UFD. The urban freight distribution problem in Barcelona has been studied in some works. Thus, for example, Roca-Riu et al. (2015) used mathematical programming optimization models for solving the parking slot assignment problem in the city, while Fernandez-Barcelo and Campos-Cacheda (2012) tried to quantify the social cost (emissions, congestion, and noise)of the urban freight distribution.

As a first goal of this work, we want to analyze the needs of private and public stakeholders in the metropolitan area of Barcelona. To achieve this goal, key actors of urban freight logistics were interviewed, as discussed in the next section.

3. THE VIEW OF THE LOGISTICS SECTOR

According to Taniguchi et al. (2010), decision support tools are needed to help public decision makers and practitioners to deal with city logistics externalities (mainly traffic congestion, greenhouse gas emissions, as well as air and soil pollution). These tools can take the form of decision support systems. These systems are mainly based on modeling, optimization, simulation, and evaluation procedures. In order to devise the optimization model that we present in this research, we first need to know the opinion of the main logistics agents, as well as of the public administrations, that operate in the metropolitan area of Barcelona. Through their opinion and experience, we could know the main concerns that should be taken into account when designing the illustrative case study that considers the different urban restrictions that logistics agents face in their daily activity.

Thus, we interviewed 16 entities that intervene in the UFD in the metropolitan area of Barcelona, bringing together both private companies and public administrations. In our interviews we contemplate different sectors, including: food distribution (Condis), construction (Laymet), transportation (Transcalit), hospitality sector (ADISCAT), and the public administrations (Generalitat, AMB, ATM, or Diputació de Barcelona). We did the interviews by video-conference to comply with the restrictions derived from the health crisis caused by COVID-19. At the end, we accumulated a total of 815 minutes of recordings, with an average duration of about 51 minutes per interview. The following notes summarize the main conclusions of the interviewing process:

- The current loading and unloading areas of the towns do not contemplate the complexity and the different casuistry of each sector. For example, the time required for a parcel delivery door-to-door ranges between 20and 25 minutes, while the time required for the hospitality sector delivery person ranges between 60 and 90minutes.
- e-Commerce growth has altered UFD operations, multiplying the number of destinations and reducing the average size of the parcels.
- The lack of parking availability and its restrictions are leading to increasing illegal parking practices.
- Time windows restrictions for entering the city and for loading and unloading of goods make it difficult for the routes to be efficient.
- The lack of a criteria consensus when considering ordinances among the different towns limits the efficiency of routing plans.
- The restriction of the tonnage of goods delivery vehicles force an increase in the number of trips to make the same route.
- The public administrations recognize the above problems, but they do not have the powers to act on them. They derive this responsibility to each city council. In this sense, if each city council legislates without considering the rest, the inequality of criteria is promoted, thus entering an infinite loop.

4. AGILE OPTIMIZATION ALGORITHMS

Agile optimization (AO) algorithms allow us to process large amounts of data while supporting real-time decision making (Martins et al., 2021b). These algorithms permit a coordinated and effective use of electric autonomous vehicles in modern cities, as well as the development of concepts and solutions which contribute to transform smart cities into sustainable ones (Juan et al., 2020). Using technologies as 5G, data is gathered in real-time via electronic devices mounted onto vehicles and structures, transmitted over the Internet, and analyzed through intelligent algorithms. These algorithms predict the evolution of traffic conditions and allow for making pre-analyzed decisions. The incorporation of low-emission vehicles in last-mile delivery activities raises additional challenges from a planning, operational, and environmental perspective (Juan et al., 2016). For instance, cities are required to provide charge stations for electric vehicles. Thus, investment decisions regarding station numbers, location, and capacity must be addressed. Similarly, the limited driving range and load capacity of most electric vehicles impose additional constraints when designing distribution and collection routes (Londoño et al., 2020). Significant reductions of CO_2 emissions could be reached if carriers embrace the benefits of carefully designed strategy and mobility concepts.

Traditional optimization algorithms are widely applied for coping with optimization problems that assume a fixed time horizon and non-dynamic inputs and constraints. These particular optimization methods might sometimes be insufficient when dealing with real-time transportation problems in modern cities. With the emergence of the Internet of

Things, large amounts of data are generated in smart cities. These cities have continuously evolving conditions, such as: traffic, vehicle location, accidents, and disruptions. The lack of real-time optimization methods raises challenges on the integration of smart mobility innovations, such as unmanned and electric vehicles.

To address these problems, the AO paradigm aligns biased-randomized heuristic algorithms (Estrada-Moreno et al., 2019), which are extremely responsive, parallelizable, flexible, parameterless, effective, and accessible online. As new streams of data are provided, the AO paradigm will embrace the dynamism of real world large-scale scenarios, while offering real-time solutions which re-optimize every few milliseconds. AO algorithms will support environmentally applicable decision making, thus leading the way towards zero-emission transportation activities.

This, in turn, will generate environmental, economic, and social progress via the emergence of new business models like car-sharing and ride-sharing (Martins et al., 2021a), while improving citizen's quality of life (Beneicke et al., 2019). Moreover, the AO paradigm will support current European strategies for low-emission mobility.

5. AN ILLUSTRATIVE CASE STUDY

In order to illustrate the concepts introduced in the previous sections, we have designed a realistic case study based on the city of Barcelona. In this example, two different carriers have to visit a series of customers scattered across the city. Each carrier has its own set of customers and no horizontal cooperation practices (Serrano-Hernández et al., 2017) –or other strategies that can speed up the distribution tasks– are considered at this time.

Therefore, vehicles from different carriers might compete for the available parking spaces in the city. Regarding the availability of these unloading areas, three scenarios are considered: low availability, medium availability, and high availability. For our numerical experiments, we have assumed that this availability level is negatively correlated with the average service time, i.e.: the more parking spaces available in the city, the shorter the average times requested to complete the delivery, and vice versa.

In particular: a low availability scenario assumes that the average service time is 15 minutes, a medium availability scenario is associated with an average service time of 10 minutes, and a high availability scenario implies an average service time of 5 minutes. For each carrier, the associated distribution process is modeled as a VRP.

Vehicle routing problems are very popular in the transportation literature, since they allow to model many different distribution activities (Faulin et al., 2008; Juan et al., 2009). Typically, the goal is to minimize total distribution costs while satisfying all customers' demands and additional capacity constraints. In this case, loading capacity of vehicles is not a constraint –i.e., the transported goods are small in size and, if necessary, they can be piled up inside the vehicles, so loading capacity is not a hard constraint. However, there is a time-capacity constraint for each route, i.e.: no route should exceed a time threshold, t_{max}, given by the carrier. In our experiments, this time threshold is a design parameter that can take different values: $t_{max} \in \{6,7\}$. Figure 1 shows a map of Barcelona together with the depots associated with both carriers and their customers. In Figure 2, a potential solution (set of routes) is drawn.

The aforementioned setting of the VRP is based on the real-life case oriented to deal with the collection of sanitary items – produced using personal 3D printers – from individual houses in Barcelona during the first months of theCOVID-19 pandemics.

The computational experiment will allow us to investigate how different levels of loading/unloading areas in the city will affect the number of trucks needed to complete all visits and, as consequence, the total time that these vehicles are circulating around the city –which is a direct cause of CO2emissions and traffic congestion, apart from being the main factor in the cost function of the carriers.

Our solving approach is based on the algorithm proposed in Tordecilla et al. (2020). This algorithm has been implemented in Python 3.7, and a maximum computational time of 60 seconds has been set for executing each instance of the problem. The experiments were run on a Windows 10 operating system using a computer with the following characteristics: an Intel(R) Core (TM) i7-8750H CPU at 2.20GHz and 16 GB of RAM.

6. COMPUTATIONAL EXPERIMENTS

The results of the case study described in the previous section are shown in Table 1. The first four columns identify the company (1 or 2), the configuration of the time threshold in hours (6+2 or 7+1), as well as the parking areas availability and the service time in minutes: high (5), medium (10, or low 15). The next six columns describe the performance of the best solution found for each case: number of routes (where each route requires one vehicle and driver), time of the longest route, distance of the longest route, total time and total distance (considering all routes), and CO_2 emissions. These emissions have been estimated using the calculator of *myclimate* (https://www.myclimate.org/), which depends on the distance, the fuel type (petrol in our case), and fuel consumption or vehicle type (van). *myclimate* is a non-profit organization and one of the world's quality leaders in voluntary CO2compensation measures. It has a large number of partners, such as *energiapro* or *WWF Switzerland*. The last row of the table shows the average measures.

Based on this data, Figure 3 displays a parallel coordinates plot of the main performance indicators. The data has been added up for each scenario (that is, for each configuration of working/resting times and parking areas availability). It can be concluded that the level of parking area availability has a great effect on the number of routes (which range around 15).

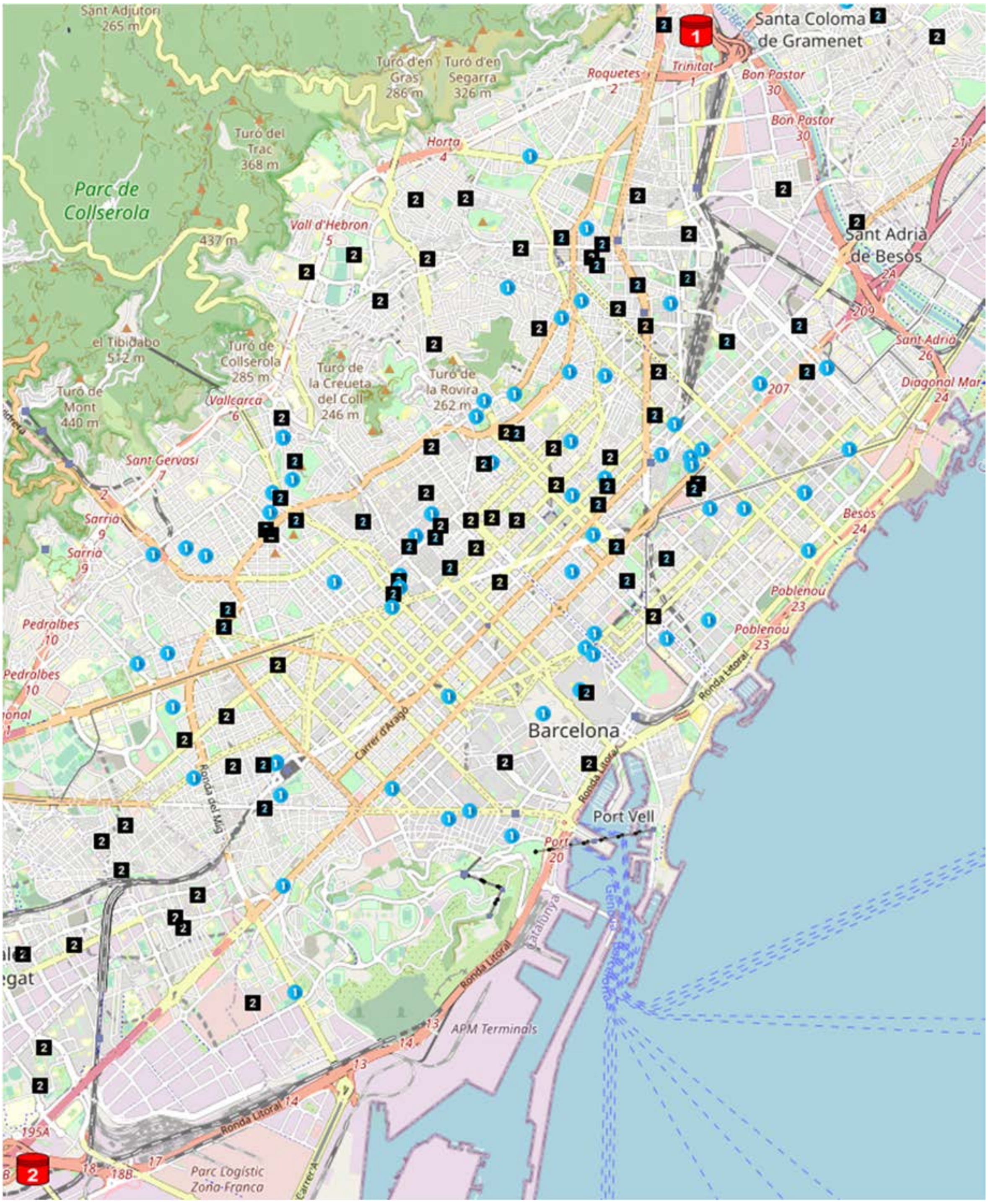

Fig. 1 – Illustrative example in the city of Barcelona. There are two depots corresponding to different carriers (represented by cylinders) and a set of customers for each carrier (represented by circles and squares).

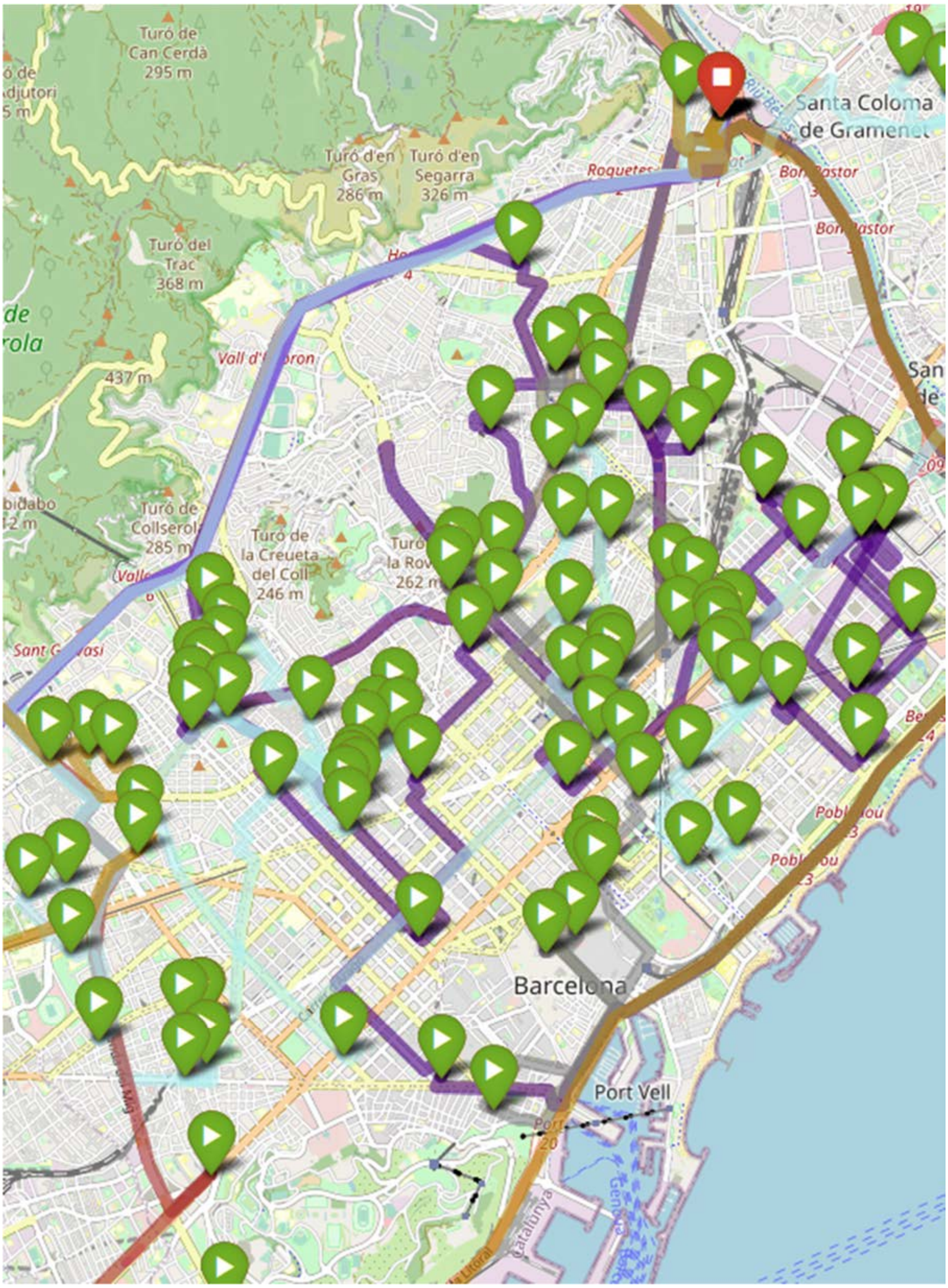

Fig. 2 – Design of routes for an illustrative case study.

Company	Timetable (h)	Parking Areas Availability	Service Time (min)	# Routes	Time Max Route (h:m)	Distance Max Route (km)	Total Time (h:m:s)	Total Distance (km)	CO_2 Emissions (t)
1	6 + 2	high	5	8	5:48	101.46	41:30:34	630.53	0.26
2	6 + 2	high	5	10	5:52	174.95	50:17:15	845.22	0.34
1	7 + 1	high	5	7	6:48	86.28	41:10:20	603.87	0.25
2	7 + 1	high	5	8	6:41	127.55	48:48:42	796.65	0.32
1	6 + 2	medium	10	13	5:45	140.74	66:19:17	843.81	0.34
2	6 + 2	medium	10	14	5:56	110.96	74:14:32	1019.38	0.42
1	7 + 1	medium	10	11	6:39	61.72	64:34:59	742.39	0.3
2	7 + 1	medium	10	12	7:00	110.47	72:19:30	913.74	0.37
1	6 + 2	low	15	17	5:54	59.44	90:24:51	1038.46	0.42
2	6 + 2	low	15	20	5:49	108.02	97:59:10	1174.85	0.48
1	7 + 1	low	15	15	6:51	50.04	87:48:21	873.43	0.36
2	7 + 1	low	15	16	6:49	102.56	95:44:40	1050.8	0.43
			Avg	12.58	6:19	102.85	69:16:00	877.76	0.36

Table 1 – Performance indicators of routes for different configurations of working/resting times and parking areas availability

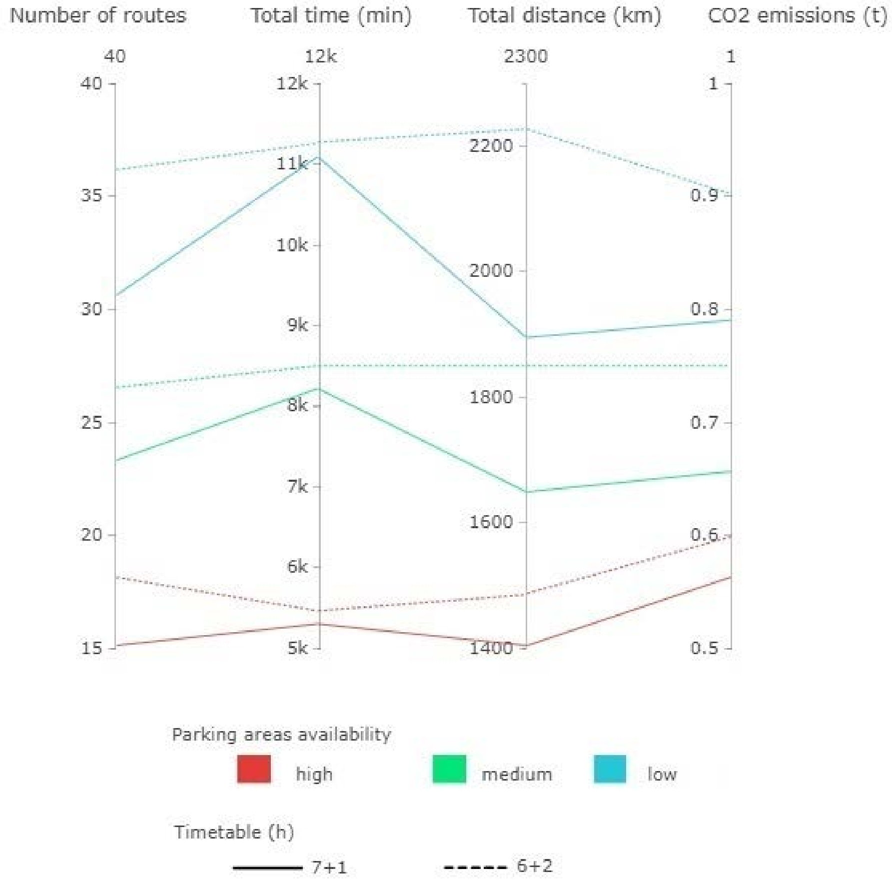

Fig. 3 – Parallel coordinates plot of the main performance indicators.

	Number of routes	Total time	Total distance	CO_2 emissions
Number of routes	1			
Total time	0.966	1		
Total distance	0.994	0.943	1	
CO_2 emissions	0.995	0.946	0.9996	1

Table 2 – Correlation matrix of performance indicators.

	Dependent variable		
	Time	Distance	CO_2 emissions
Intercept	11158.5 ***	2068.8 ***	0.845 ***
Availability - medium	-2834.3 ***	-309.1	-0.13
Availability - high	-5705.0 ***	-630.6 *	-0.26 *
$\bar{R}^2$	0.996	0.763	0.775

Table 3 – Linear regression models (codes for the significance tests: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1).**

37), the total time (from 5,399 minutes to 11,304), the total distance (from 1,400 to 2,213 kilometers), and the amount of CO_2 emissions (from 0.57 to 0.90). The effect of the maximum time per route is also relevant. From this figure, it is clear that there is a positive correlation between these performance indicators. The correlation matrix is displayed in

Table 2. A linear regression analysis is carried out to quantify the effect of the availability on the routing solutions. A summary of the results is displayed in Table 3. Three models have been estimated and, in all of them, the availability constitutes the independent variable (being 'low' the baseline). Each model has a different dependent variable: total time, total distance, and CO2emissions, respectively. The table includes the coefficient estimates, whether they are statistically significant, and the adjusted coefficient of determination. It can be concluded that the parking areas availability explains a high percentage of the variability of the dependent variable in the three models. Moreover, almost all the coefficients are statistically significant (for a standard significance level, i.e., $\alpha=0.05$).

7. ANALYSIS OF RESULTS AND MANAGERIAL INSIGHTS

The analysis of this case study has revealed the important effect that the ordinances may have on the routing solutions and the performance indicators. Regarding parking areas, a medium or low availability level has a noticeable impact on the economic profitability of the companies (since they require the use of longer routes in terms of both time and distance), the environment (more pollution), and the social welfare (congestion, risk of accidents, etc.).

In addition, we have quantified the effect of varying the maximum time per route (that is, the maximum number of hours that a driver is allowed to drive). While reducing this maximum time may have a positive effect on the drivers' welfare, it also has a great impact on the sustainability of the routes. For that reason, a policy based on the reduction of the maximum time should be compensated with other measures. All in all, it has been shown that, when combined with optimization algorithms, visualization techniques and statistical analyses may be a powerful tool to assess/quantify the effects of changes in the ordinances.

8. CONCLUSIONS

Logistics and transportation operators are subject to an increasing pressure to design efficient delivery systems as a consequence of: *(i)* the growth of e-commerce (goods) and the on-demand economy (services) in urban, peri-urban, and metropolitan areas; and *(ii)* a global trend towards more sustainable transportation and mobility. In this context, we have analyzed the needs of logistics operators in the Barcelona metropolitan area by interviewing 16 key shareholders from different sectors. It is concluded that the next factors significantly affect the efficiency of deliveries: *(i)* current loading and unloading spaces; *(ii)* time windows restrictions for entering the city and for loading and unloading; *(iii)* restriction of the tonnage of goods delivery vehicles; and *(iv)* the lack of a unified criterion for the ordinances. Based on the insights, especially *(i)* and *(ii)*, we discuss the need for agile optimization algorithms. An illustrative case study is carried out, which allows us to quantitatively compare several scenarios with different configurations of working/resting times and parking areas availability. The results support, with numerical evidence, the capability of the proposed methodology to measure the impact of different logistics policies and strategies. Several lines of future research stem from this work. We have explored the problems emanating from the UFD, but an extension of this study could help to assess whether the needs and views differ between private companies and public administrations, or among different sectors (food distribution, construction, etc). It could also be possible to specify and prioritize policies that allow us to boost the efficiency of delivery systems. Regarding the illustrative case study, an enriched approach could consider not only economic and environmental dimensions, but also the social one with indicators such as traffic, accident risks, driving near schools, etc. Likewise, a richer approach could consider the incorporation of fleets of electric vehicles –which might generate additional constraints regarding driving ranges–, or autonomous vehicles, which might allow distribution during the night hours.

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A PARALLEL PROGRAMMING APPROACH TO THE SOLUTION OF THE LOCATION-INVENTORY AND MULTI-ECHELON ROUTING PROBLEM IN THE HUMANITARIAN SUPPLY CHAIN

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ABSTRACT

Disasters around the world are becoming more frequent, diverse, complex and extremely challenging, causing millions of casualties and affecting both human development and available resources. Consequently, the present study addresses a multi-objective location, inventory and multi-scale routing (2E-LIRP) problem, which supports comprehensive decision making, so that the logistics network designer and manager can obtain adequate strategic planning in the face of uncertainty and the negative impact that an adverse event can generate.

Moreover, the problem is formulated as an integer linear programming model, having as main objectives to minimize private logistics costs and maximize the welfare of the affected areas, considering dynamic demand, multiple products and heterogeneous fleet.

Due to the computational complexity associated with the model, a new solution approach is proposed, based on the design of evolutionary metaheuristic algorithms; the first one, known as Non-dominated Sorting Genetic Algorithm version II (NSGA-II), the second one, Strength Pareto Evolutionary Algorithm version II (SPEA-II) and the third one, called Genetic Algorithm (GA), programmed in parallel and executed individually under a cooperative environment. Finally, the experimentation carried out on a test set, composed of twenty instances of varying complexity, allows inferring that the parallel-cooperative and purely parallel approach applied to NSGA-II, substantially improves the processing times and the number of non-dominated solutions, if compared to the results obtained by SPEA-II, designed under identical conditions. Moreover, by building a GA with these same characteristics, it improves up to 50% of the solutions, in terms of social costs (logistic and humanitarian costs), with computation times similar to its sequential counterpart.

1. INTRODUCTION

The occurrence of natural disasters and their devastating consequences are a reality experienced year after year around the world. Approximately 75% of the world's population lives in regions affected at least once between 1980 and 2017 by an earthquake, tropical cyclone, flood or drought. As a consequence of these phenomena, more than 184 people die every day in different parts of the world and they result in a toll that includes the destruction of fixed assets, physical capital, the interruption of production, trade and the decrease in public and private savings and investments, which wipe out progress in economic development (Nagurney et al., 2019). This problematic has generated a deep interest in seeking and establishing the most efficient mechanisms, which allow improving the response to emergency situations, thus giving rise to the emergence of humanitarian logistics as a means to cope with the negative effects of adverse events that put at risk the integrity or the very life of the human being.

Despite research and technological progress, it is still not possible to predict when and where a natural disaster will occur in advance; therefore, activities or actions before, during and after its occurrence are important to reduce the associated losses. Moreover, when a disaster occurs in a certain part of the world, many organizations come forward to provide the required relief items, e.g., food, water, medicine, among others, to the affected people. In these situations, coordination between the different members is crucial and it becomes difficult for a single organization to carry out all the necessary activities, such as repairing damaged infrastructure and delivering relief items.

Moreover, humanitarian logistics becomes a complex network with different actors, including, non-governmental organizations (NGOs) of local or international origin, donors, armed forces, corporations and private companies; each of them with different and sometimes, conflicting interests, obligations, capabilities, budget allocation structure and logistical skills (Nikkhoo et al., 2018).

For this reason, the design and management necessary in the logistics network during the pre- and post-disaster phases cannot be improvised; they must be the result of a correct and rigorous planning, in which very important aspects can be identified and established in advance, such as, the location of facilities, the availability and quality of resources through proper inventory management, flexibility in route plans according to the established budget, among others, which ultimately allow guaranteeing an optimal response when the deployment of humanitarian operations is carried out.

1.1 Justification

Currently, disasters, regardless of their origin (whether natural or human), are considered social phenomena whose damages could be prevented and mitigated to reduce or at least control their effects (Cecchini et al., 2017).

The difficulty in predicting the place where it will occur, the time and magnitude with which it will occur, in addition to the uncertainty associated with the characteristics of the population, the existing infrastructure conditions and the demand required to meet the emergency situation, give rise to one of the greatest challenges in humanitarian logistics, such as unpredictability, defined as the occurrence of unexpected events (Balcik et al., 2010). L'Hermitte et al. (2016) state that unpredictability creates barriers and affects efficiency in the supply chain.

Thus, the proper management of the logistics supply chain for disaster relief and humanitarian support becomes a very important challenge worldwide, since it is responsible for estimating, providing, storing, storing, transporting and distributing personnel, resources and services required to the affected areas (Talebian Sharif & Salari, 2015), through a set of activities carried out in different instances of time, which are intended to assist the survivors after a disaster, reduce its impact and maintain social stability (Aghajani et al., 2020; Vahdani et al., 2018).

For this reason, the need arises to develop a model capable of providing sufficient information to the logistics network manager to make the best decisions related to the location, distribution and inventory management, which ultimately guarantee a timely delivery of goods (products or services) to the stakeholders (affected areas), thus minimizing the negative economic and social impacts caused by the occurrence of adverse events. This model is associated with the 2E-LIRP, which integrates three types of very important decisions within the comprehensive planning of humanitarian logistics, as stated by Rafie-Majd et al. (2018), i.e., strategic decisions: with long-term effects (location and allocation of facilities); tactical decisions: medium-term (inventory control and transportation) and operational decisions: daily or weekly (scheduling and routing), which ultimately determine the responsiveness, flexibility, efficiency and effectiveness of the supply chain.

2. LITERATURE REVIEW

By way of summary, the most common solution techniques used to solve multi-echelon location, inventory and routing problems are presented below; in parallel, some characteristics (see Table 1-2) considered to be of great relevance in the different studies found to date are described.

Convention	**Interpretation**
1	Mathematical formulation
2a	Mono-objective
2b	Multi-objective
3a	Multi-period
3b	Multi-product
4a	Deterministic parameters
4b	Stochastic parameters
4c	Fuzzy parameters
5	Method / Solution algorithm
6a	Parallel programming techniques
6b	Paradigm of cooperation between metaheuristics
7	Deprivation costs in the model

Table 1 - Characteristics associated with multi-echelon LIRP

Author (year)	**1***	**2**		**3**		**4**			**5***	**6**		**7**
		a	**b**	**a**	**b**	**a**	**b**	**c**		**a**	**b**	
(Tavakkoli-Moghaddam et al., 2013)	MINLP		**X**				**X**		LINGO			
(Bozorgi-Amiri & Khorsi, 2016)	MILP		**X**	**X**	**X**		**X**		ε-CM			
(Ghorbani & Akbari Jokar, 2016)	MILP	**X**		**X**	**X**	**X**			HIC-SA			
(R. Tavakkoli-Moghaddam & Raziei, 2016)	MILP		**X**	**X**	**X**			X	GAMS CPLEX			
(Zhalechian et al., 2016)	MINLP		**X**	**X**	**X**		**X**	X	SGA/VNS			
(Nakhjirkan & Mokhatab Rafiei, 2017)	MINLP	**X**			**X**		**X**		GA			
(Rayat et al., 2017)	MINLP		**X**	**X**	**X**		**X**		AMOSA			

(Zhao & Ke, 2017)	MILP		**X**			**X**	TOPSIS			
(Guo et al., 2018)	MINLP	**X**				**X**	GA/SA			
(Tavana et al., 2018)	MILP		**X**	**X**	**X**	**X**	ε-CM NSGA-II RPBNSGA-II			
(Vahdani et al., 2018)	MILP		**X**	**X**	**X**	**X**	NSGA-II MOPSO			
(Yuchi et al., 2018)	MINLP		**X**			**X**	TS/ SA			
(Fatemi Ghomi & Asgarian, 2019)	MINLP		**X**	**X**		**X**	PSO BBO HBBO			
(Ghorashi et al., 2019)	CMIP		**X**	**X**	**X**	**X**	MOGWO MOPSO NSGA-II			
(Nakhjirkan et al., 2019)	MINLP	**X**			**X**	**X**	GA/NDEA			
(Saragih et al., 2019)	MINLP	**X**				**X**	SA			
(Biuki et al., 2020)	MILP		**X**	**X**	**X**	**X**	GA/PSO		**X**	
Current study	MILP		**X**		**X**	**X**	NSGA-II SPEA-II GA	**X**	**X**	**X**

Table 2 - Classification of studies related to multi-echelon LIRP

*Note.**MILP= Mixed Integer Linear Programming; MINLP = Mixed Integer Non-Linear Programming; CMIP=Constrained Mixed Integer Programming; ε-CM= Epsilon Constraint Method ε; HIC-SA= Hybrid Imperialist Competitive-Simulated Annealing; SGA = Self-adaptive Genetic Algorithm; VNS= Variable Neighborhood Search; GA= Genetic Algorithm; AMOSA= Archived Multi-Objective Simulated Annealing; TOPSIS= Technique for Order of Preference by Similarity to Ideal Solution; SA= Simulated Annealing; NSGA-II= Non-dominated Sorting Genetic Algorithm II; RPBNSGA-II= Reference Point Based Non-dominated Sorting Genetic Algorithm II; MOPSO= Multi-objective Particle Swarm Optimization; TS= Tabu Search; PSO= Particle Swarm Optimization; BBO= Biogeography-Based Optimization; HBBO= Habitat Biogeography-Based Optimization; MOGWO= Multi-Objective Gray Wolf Optimizer; NDEA= Network Data Envelopment Analysis.

3. PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

The following is a schematic representation, with the purpose of facilitating the interpretation and understanding of the problem addressed (see Figure 1).

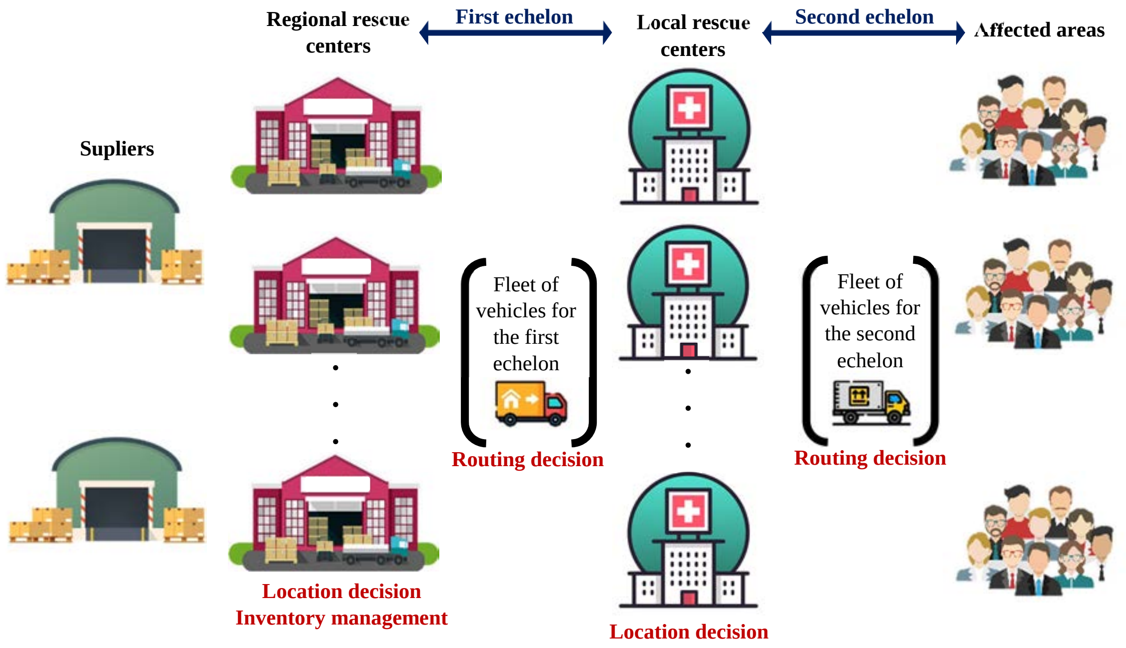

Fig 1 - Graphical illustration of 2E-LIRP

Taking as a reference the research developed by Pérez-Rodríguez & Holguín-Veras (2016), Tavana et al. (2018), Cotes & Cantillo (2019) and Dai et al. (2019), in addition to taking into account the considerations established by the researcher, the mathematical model is formulated as presented below.

3.1 Sets

R = Set of possible regional rescue centers
L = Set of possible local rescue centers
C = Set of areas affected (AA) by a disaster
V = Set of vehicles for first level routes
W = Set of vehicles for second level routes
P = Set of products required in the AA
T = Humanitarian deployment time periods

3.2 Indexes

r = Index for possible regional rescue centers
l = Index for possible local rescue centers
c = Index for areas affected (AA) by a disaster
v = Index for first level vehicles

w = Index for second level vehicles
p = Index for products required in the AA
t = Index for time periods

3.3 Parameters

K_{ip} = Facility capacity $i \in R \cup L$, for product $p \in P$
H_{ip} = Vehicle capacity $i \in W \cup V$, for product $p \in P$
F_i = Cost of opening the facility $i \in R \cup L$
G_i = Cost of using the vehicle $i \in W \cup V$
D_{cp}^{t} = Customer demand $c \in C$, for product $p \in P$, in period $t \in T$
S_{ij} = Cost of traveling between node i and node j for the first echelon
E_{ij} = Cost of traveling between node i and node j for the second echelon
CS_{p}^{t} = Cost of buying the product $p \in P$ in period $t \in T$
CT_{pr}^{t} = Unit cost of transporting the product $p \in P$ from the supplier to the regional rescue center $r \in R$ during the period $t \in T$
CMI_{pr} = Unit cost of keeping the product $p \in P$, in inventory at the regional rescue center $r \in R$
I_{pr}^{0} = Initial inventory of product $p \in P$, at the regional rescue center $r \in R$
F_{jt} = Deprivation time presented by the affected area $j \in C$ in the period $t \in T$
TV_{ij} = Travel time between node i and node j, for $i \wedge j \in L \cup C$
P_j = Number of individuals at the point of demand (affected area) $j \in C$
VP_{j}^{t} = Average economic value of well-being perceived by an individual in the affected region $j \in C$ (it is possible to take as a base value, the GDP per capita of the last year) for the period $t \in T$
$(VP_{j}^{t} * F_{jt}^{-1} * P_j)$ = Deprivation function (DF)
$(VP_{j}^{t} * TV_{ij}^{-1} * P_j)$ = Impact function on distribution (IFD)

3.4 Decision variables

$$y_i = \begin{cases} 1 & \text{If the facility } i \in R \cup L \text{ is open} \\ 0 & \text{Otherwise} \end{cases}$$

$$m_{ijt}^{v} = \begin{cases} 1 & \text{If the vehicle } v \in V, \text{travels from node } i \in R \cup L, \text{to node } j \in R \cup L, \text{on the first level route, during the period } t \in T \\ 0 & \text{Otherwise} \end{cases}$$

$$n_{ijt}^{w} = \begin{cases} 1 & \text{If the vehicle } w \in W, \text{travels from node } i \in L \cup C, \text{to node } j \in L \cup C, \text{on the second level route, during the period } t \in T \\ 0 & \text{Otherwise} \end{cases}$$

$$L_{rl}^{t} = \begin{cases} 1 & \text{If the local rescue center } l \in L, \text{is assigned to the regional rescue center } r \in R, \text{in the period } t \in T \\ 0 & \text{Otherwise} \end{cases}$$

$$P_{rc}^{t} = \begin{cases} 1 & \text{If the affected area } c \in C, \text{ is assigned to the local rescue center } l \in L, \text{ in the period } t \in T \\ 0 & \text{Otherwise} \end{cases}$$

$$q_{i}^{t} = \begin{cases} 1 & \text{If the vehicle } i \in W \cup V, \text{ is used on a route, in the period } t \in T \\ 0 & \text{Otherwise} \end{cases}$$

FN_{prlv}^{t} = Product flow $p \in P$ to be transported, from the regional rescue center $r \in R$ to the local rescue center $l \in L$ in vehicle $v \in V$, for period $t \in T$

Q_{pr}^{t} = Quantity of product $p \in P$ to be purchased at regional rescue center $r \in R$, in period $t \in T$

I_{pr}^{t} = Units of product $p \in P$ in inventory, for regional rescue center $r \in R$, during period $t \in T$

Z_1 = Total logistics cost (Private Costs)

Z_2 = Total wellness of the areas ($-Z_2$ = External Costs/ Human suffering)

3.5 Objective function

$$Minimize\{Z_1\} = Minimize\left\{\sum_{r\in R} F_r * y_r + \sum_{l\in L} F_l * y_l + \sum_{t\in T}\sum_{v\in V} G_v * q_v^t + \sum_{t\in T}\sum_{v\in V} G_w * q_w^t + \sum_{t\in T}\sum_{(i,j)\in R\cup L}\sum_{v\in V} S_{ij} * m_{i\ jt}^{v} + \sum_{t\in T}\sum_{(i,j)\in L\cup C}\sum_{w\in W} E_{ij} * n_{i\ jt}^{w} + \sum_{p\in P}\sum_{r\in R}\sum_{t\in T} CS_p^t * Q_{pr}^t + \sum_{p\in P}\sum_{r\in R}\sum_{t\in T} CT_{pr}^t * Q_{pr}^t + \sum_{p\in P}\sum_{r\in R}\sum_{t\in T} CMI_{pr} * I_{pr}^t \right\} \quad (1)$$

$$Maximize\{Z_2\} = Maximize\left\{\sum_{w\in W}\sum_{t\in T}\sum_{(i,j)\in L\cup C}\left[VP_j^t * p_j * \left(F_{jt}^{-1} + TV_{ij}^{-1}\right)\right] * n_{ijt}^{w}\right\} \quad (2)$$

3.6 Constraints

3.6.1 Second echelon constraints

$$\sum_{l\in L} P_{lc}^t = 1; \quad \forall c \in C \wedge \forall t \in T \quad (3)$$

$$\sum_{c\in C} D_{cp}^t * P_{lc}^t \le k_{lp} * y_l; \quad \forall l \in L, \forall p \in P \wedge \forall t \in T \quad (4)$$

$$\sum_{w\in W}\sum_{j\in L\cup C} n_{jct}^{w} = 1; \quad \forall c \in C, \forall t \in T \wedge j \ne c \quad (5)$$

$$\sum_{h\in L\cup C} n_{hjt}^{w} - \sum_{h\in L\cup C} n_{jht}^{w} = 0; \quad \forall j \in L \cup C, \forall w \in W, \forall t \in T \wedge h \ne j \quad (6)$$

$$\sum_{i\in A'}\sum_{j\in A'} n_{ijt}^{w} \le |A'| - 1; \quad \forall w \in W, \forall t \in T, A' \subseteq A, |A'| \ge 2 \wedge i \ne j \quad (7)$$

$$\sum_{i\in L}\sum_{j\in C} n_{ijt}^{w} \le 1; \quad \forall w \in W \wedge \forall t \in T \quad (8)$$

$$\sum_{b\in L\cup C} n_{cbt}^{w} + \sum_{b\in L\cup C} n_{lbt}^{w} - P_{lc}^t \le 1; \quad \forall l \in L, \forall c \in C, \forall w \in W, \forall t \in T, c \ne b \wedge l \ne b \quad (9)$$

$$\sum_{c \in C} \sum_{j \in L \cup C} D_{cp}^{t} * n_{cjt}^{w} \leq H_{wp} * q_{w}^{t}; \quad \forall w \in W, \forall t \in T, \forall p \in P \wedge c \neq j \tag{10}$$

3.6.2 First echelon constraints

$$\sum_{r \in R} L_{rl}^{t} = y_{l}; \quad \forall l \in L \wedge \forall t \in T \tag{11}$$

$$\sum_{l \in L} K_{lp} * L_{rl}^{t} \leq K_{rp} * y_{r}; \quad \forall r \in R, \forall p \in P \wedge \forall t \in T \tag{12}$$

$$\sum_{h \in R \cup L} m_{hjt}^{v} - \sum_{h \in R \cup L} m_{jht}^{v} = 0; \quad \forall j \in R \cup L, \forall v \in V, \forall t \in T \wedge h \neq j \tag{13}$$

$$\sum_{i \in Q'} \sum_{j \in Q'} m_{ijt}^{v} \leq \left|Q'\right| - 1; \quad \forall v \in V, \forall t \in T, Q' \subseteq Q, \left|Q'\right| \geq 2 \wedge i \neq j \tag{14}$$

$$\sum_{i \in R} \sum_{j \in L} m_{ijt}^{v} \leq 1; \quad \forall v \in V \wedge \forall t \in T \tag{15}$$

$$\sum_{s \in R \cup L} m_{lst}^{v} + \sum_{s \in R \cup L} m_{rst}^{v} - L_{rl}^{t} \leq 1; \quad \forall r \in R, \forall l \in L, \forall v \in V, \forall t \in T, l \neq s \wedge r \neq s \tag{16}$$

$$\sum_{r \in R} \sum_{v \in V} FN_{prlv}^{t} - \sum_{c \in C} D_{cp}^{t} * P_{lc}^{t} = 0; \quad \forall l \in L, \forall t \in T \wedge \forall p \in P \tag{17}$$

$$H_{vp} \sum_{h \in R \cup L} m_{lht}^{v} - FN_{prlv}^{t} \geq 0; \quad \forall v \in V, \forall d \in D, \forall l \in L, \forall p \in P, \forall t \in T \wedge l \neq h \tag{18}$$

$$H_{vp} \sum_{h \in R \cup L} m_{rht}^{v} - FN_{prlv}^{t} \geq 0; \quad \forall v \in V, \forall r \in R, \forall l \in L, \forall p \in P, \forall t \in T \wedge r \neq h \tag{19}$$

$$\sum_{r \in R} \sum_{l \in L} FN_{prlv}^{t} \leq H_{vp} * q_{v}^{t}; \quad \forall v \in V, \forall p \in P \wedge \forall t \in T \tag{20}$$

$$I_{pr}^{t} = I_{pr}^{0}; \quad \forall p \in P, \forall r \in R \wedge t = 0 \tag{21}$$

$$I_{pr}^{t} = I_{pr}^{t-1} + Q_{pr}^{t} - \sum_{v \in V} \sum_{l \in L} FN_{prlv}^{t}; \quad \forall p \in P, \forall r \in R \wedge \forall t \in T \tag{22}$$

$$I_{pr}^{t} \leq k_{rp} * y_{r}; \quad \forall p \in P, \ \forall t \in T \wedge \forall r \in R \tag{23}$$

$$I_{pr}^{t} = 0; \quad \forall p \in P, \ \forall r \in R \wedge t = T \tag{24}$$

3.6.3 Variable decision constraints

$$y_{l} \in \{0,1\}; \quad \forall l \in L \tag{25}$$

$$n_{ijt}^{w} \in \{0,1\}; \quad \forall i \in L \cup C, \forall j \in L \cup C, \forall w \in W \wedge \forall t \in T \tag{26}$$

$$P_{lc}^{t} \in \{0,1\}; \quad \forall l \in L, \forall c \in C \wedge \forall t \in T \tag{27}$$

$$q_{w}^{t} \in \{0,1\}; \quad \forall w \in W, \wedge \forall t \in T \tag{28}$$

$$y_{r} \in \{0,1\}; \quad \forall r \in R \tag{29}$$

$$m_{ijt}^{v} \in \{0,1\}; \quad \forall i \in R \cup L, \forall j \in R \cup L, \forall v \in V \wedge \forall t \in T \tag{30}$$

$$L_{rl}^{t} \in \{0,1\}; \quad \forall r \in R, \forall l \in L \wedge \forall t \in T \tag{31}$$

$$q_{v}^{t} \in \{0,1\}; \quad \forall v \in V \wedge \forall t \in T \tag{32}$$

$$FN_{prlv}^{t} \in \mathbf{Z}^{+} \cup \{0\}; \quad \forall v \in V, \forall l \in L, \forall r \in R, \forall p \in P \wedge \forall t \in T \tag{33}$$

$$I_{pr}^{t} \in \mathbf{Z}^{+} \cup \{0\}; \quad \forall p \in P, \forall r \in R, \wedge \forall t \in T \tag{34}$$

$$Q_{pr}^{t} \in \mathbf{Z}^{+} \cup \{0\}; \quad \forall p \in P, \forall r \in R, \wedge \forall t \in T \tag{24}$$

3.7 Optimization model interpretation

Equation (1) minimizes the private costs, related to the opening of regional rescue centers (first term) and local rescue centers (second term), the use of vehicles at the first and second level (third and fourth terms), the routing at each echelon (fifth and sixth terms) and, in addition, the costs caused by managing the inventory at the first level facilities (regional centers), composed of the quantity purchased (seventh term), transported (eighth term) and in inventory (ninth term).

Moreover, equation (2) maximizes the total welfare of the demand points, which for convenience, is translated into a deprivation cost function (DCF), understood as the welfare that can be foregone by an affected area, given a deprivation time (F_{jt}) and a time required to supply humanitarian goods (TV_{ij}) to that area; thus obtaining two very important components: the deprivation function (first sub-terms, $VP_j^t * P_j * F_{jt}^{-1}$) and the distribution impact function (second sub-terms, $VP_j^t * P_j * TV_{ij}^{-1}$), which together represent the DCF, when the route plan is defined at the second echelon (third sub-terms, n_{ijt}^{w}).

On the other hand, equation (3) guarantees the assignment of each affected area to a single local rescue center; equation (4) ensures that the demand of the regions assigned to the same local rescue center does not exceed the capacity of that facility; equation (5) imposes that each affected area must be visited by exactly one second echelon vehicle; equation (6) allows each vehicle in use to return to the same local center from which it departed.

Furthermore, equation (7) prevents the formation of sub-tours or illegal routes in the second echelon; equation (8) ensures the unique assignment of a vehicle to a specific local rescue center, if it is enabled; equation (9) ensures that the local rescue center r serves the affected region c, if and only if there is a vehicle w leaving r and arriving at c and equation (10) allows that the demand satisfied by a vehicle in the second echelon does not exceed its capacity, if it is used in a facility during period t.

Continuing with the interpretation of the model, equation (11) allows the assignment of each enabled local rescue center to a single regional rescue center; equation (12) refers to the capacity restriction in the regional centers, since, as can be seen, the capacity of an enabled regional center must be greater or equal to the capacity of the local centers assigned to it; equation (13) guarantees the return to the same regional rescue center, the vehicle v assigned. Equation (14) avoids the formation of sub-tours or illegal routes in the first echelon; equation (15) allows a vehicle to be assigned to at most one regional rescue center, if it is used; equation (16) ensures that regional center r serves local center l, if there is a vehicle v leaving r and arriving at l; equation (17) is associated with the conservation of the flow in the local rescue center l, taking into account that the amount of product p entering it must be equal to the total demand of the assigned areas/regions.

Equations (18) and (19) guarantee that the amount of flow in a vehicle v from a regional rescue center r to a local rescue center l is positive if and only if both the regional center and the local rescue center are visited by the same vehicle v; equation (20) is related to the capacity limitation for a vehicle v (the flow or amount of product p transported in a vehicle v from a regional center r to a local center l must be less than or equal to the capacity of that vehicle). Equation (21) allows to include an initial inventory level for each of the products, in the regional centers r enabled; equation (22) represents the inventory balance, which in other words, means that the amount of inventory for a period t, is equal to the units stored in the previous period, plus the purchases made in t, minus the amount transported to each point of demand; Equation (23) prevents the units in inventory for each of the humanitarian products from exceeding the capacity tied to the first level facilities, and equation (24) imposes a zero inventory level for the last period of humanitarian aid in the different facilities (regional rescue centers).

Finally, equations (25)-(35) establish the nature of the decision variables considered in the mathematical model, which as can be seen are mostly binary (25-32) and a small portion take values in the set of positive integers (32-35), thus allowing to address an Integer Linear Programming (ILP) problem.

4. CONSTRUCTION OF EVOLUTIONARY ALGORITHMS

Taking as a reference the logical procedure of each of the chosen algorithms, in addition to the proposed scheme to generate and represent an individual or solution k, it is possible to build a parallel and cooperative version of each technique, using the paradigm of *"distributed systems or islands"* (see Figure 2), which basically consists of the use of a coordinator or collector C (*multi-processing variable*), which fulfills a mediating function in the exchange of information generated by each of the islands. In order to understand its role in the algorithmic process, a summary of its structure is presented below, taking into account the applied technique.

4.1 Parallel-cooperative algorithms

1. **Coordinator *p*-GA_V1**

1.1. Module for the reception and transfer of information generated in island 1

1.2. Module for the reception and transfer of information generated in island 2

1.3. Storage module (starts operation once the stop criterion is met)

1.3.1. Sub-module that stores the set of best individuals obtained in island 1 during each generation $[S^1(T)]$

1.3.2. Sub-module containing the set of best individuals obtained in island 2 during each generation $[S^2(T)]$

2. Coordinator *p*-NSGA-II_V1

2.1. Module for the reception and transfer of information generated on island 1

2.2. Module for the reception and transfer of information generated on island 2

2.3. Storage module (It is activated once the iterative process is finished)

2.3.1. Sub-module that stores the final population $[P_T^1(N/2)]$ of island 1

2.3.2. Sub-module containing the final population $[P_T^2(N/2)]$ of island 2

3. Coordinator *p*-SPEA-II_V1

3.1. Module for reception and transfer of information generated in island 1

3.2. Module for the reception and transfer of information generated in island 2

3.3. Storage module (Executed once the iterative process is finished)

3.3.1. Sub-module storing the final external population $\left[P_{E_1}^T\right]$ of island 1

3.3.2. Sub-module containing the final external population $\left[P_{E_2}^T\right]$ of island 2

4.2 Pure parallel algorithms

4. *p*-NSGA-II _V2

4.1. Module in charge of storing the final population $[P_T^1(N/2)]$ obtained in island 1

4.2. Module in charge of storing the final population $[P_T^2(N/2)]$ obtained in island 2

5. *p*-GA_V2

5.1. Module that stores the set of best individuals obtained in island 1 during each generation $[S^1(T)]$

5.2. Module that stores the set of best individuals obtained in island 2 during each generation $[S^2(T)]$

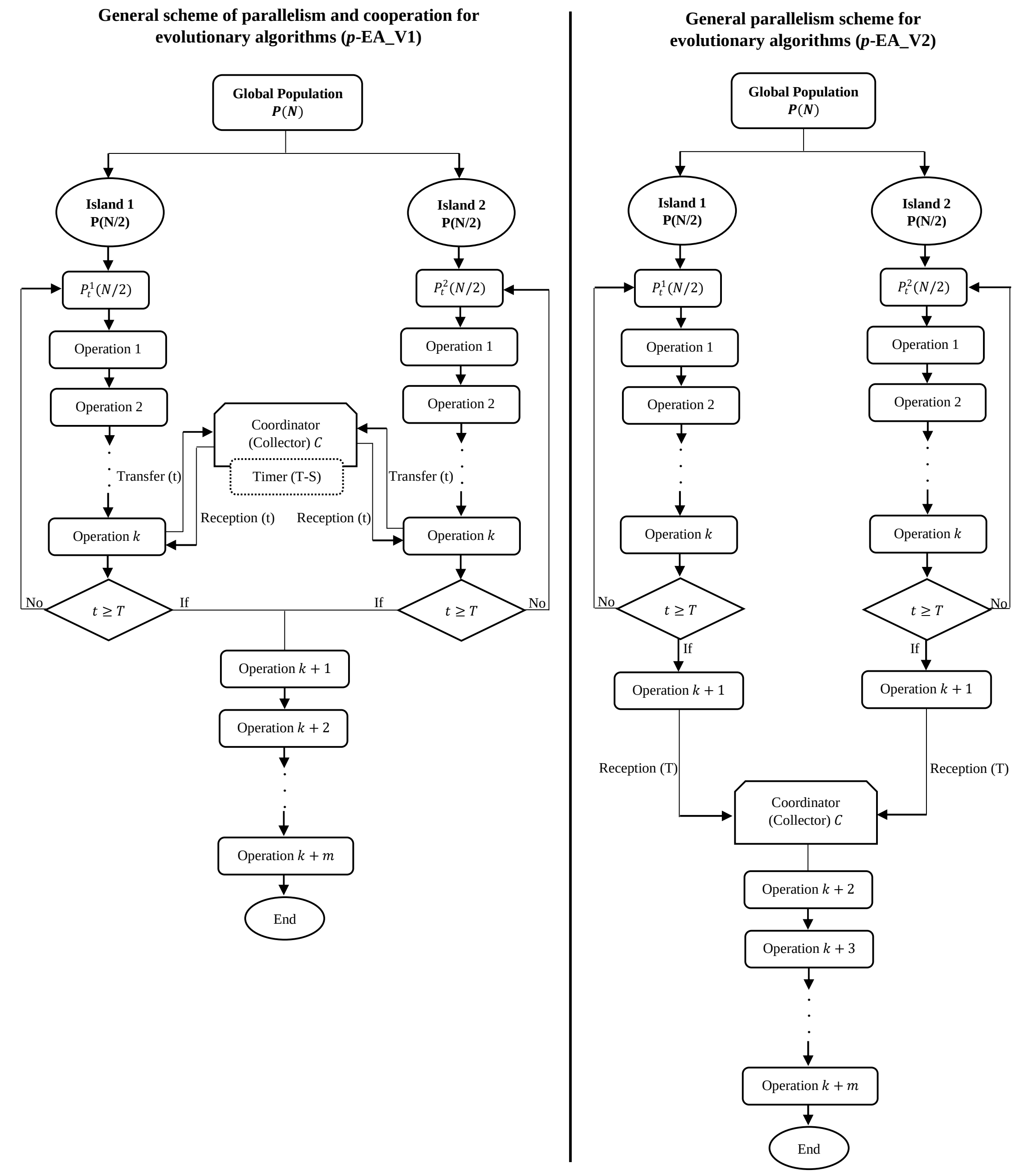

Fig 2 - General operation of parallel-cooperative and purely parallel evolutionary algorithms

5. EXPERIMENTATION

Once the solution techniques have been coded in the Python programming language, it is essential to validate them, in order to verify consistent outputs, depending on the problem addressed and the assumptions established.

To carry out this procedure, it was necessary to create a set of test instances (testbed), taking into account those designed by Albareda-Sambola et al. (2005) and Prodhon (2006), since there are currently no easily adaptable scenarios in the literature; these instances are consolidated under the nomenclature presented in Table 3.

Type of Instance	Nomenclature							Reference
	C	L	R	W	V	P	T	
1	30	10	7	11	6	8	7	I1_30C-10L-7R-11W-6V-8P-7T
2	50	8	4	10	6	3	4	I2_50C-8L-4R-10W-6V-3P-4T
3	100	20	14	30	22	4	3	I3_100C-20L-14R-30W-22V-4P-3T
4	65	12	9	17	12	2	2	I4_65C-12L-9R-17W-12V-2P-2T
5	26	9	5	10	8	6	3	I5_26C-9L-5R-10W-8V-6P-3T
6	40	12	12	11	7	5	3	I6_40C-12L-12R-11W-7V-5P-3T
7	57	10	12	14	10	11	2	I7_57C-10L-12R-14W-10V-11P-2T
8	32	11	9	14	14	5	5	I8_32C-11L-9R-14W-14V-5P-5T
9	125	8	11	13	9	2	2	I9_125C-8L-11R-13W-9V-2P-2T
10	91	6	7	16	10	3	2	I10_91C-6L-7R-16W-10V-3P-2T
11	75	7	6	9	8	4	4	I11_75C-7L-6R-9W-8V-4P-4T
12	140	5	3	12	11	2	2	I12_140C-5L-3R-12W-11V-2P-2T
13	45	15	10	7	5	7	2	I13_45C-15L-10R-7W-5V-7P-2T
14	60	4	8	8	4	3	4	I14_60C-4L-8R-8W-4V-3P-4T
15	80	7	13	12	8	3	3	I15_80C-7L-13R-12W-8V-3P-3T
16	35	6	7	9	5	4	5	I16_35C-6L-7R-9W-5V-4P-5T
17	70	16	16	13	9	2	3	I17_70C-16L-16R-13W-9V-2P-3T
18	38	5	7	8	10	6	4	I18_38C-5L-7R-8W-10V-6P-4T
19	54	3	10	15	13	5	5	I19_54C-3L-10R-15W-13V-5P-5T
20	28	4	8	10	7	9	6	I20_28C-4L-8R-10W-7V-9P-6T

Table 3 - Set of instances for validation of AEs

Note. C= Number of clients, L= Potential local centers, R= Potential regional centers, W= Second tier vehicles, V= First tier vehicles, P= Products and T= Relief periods.

Once the errors have been corrected and the codes debugged, it is possible to move on to the calibration process, which consists of identifying the main variables influencing the performance (solution quality and computational time) of the algorithms (GA, *p*-GA_V1/V2 *p*-NSGA-II_V1/V2 and *p*-SPEA-II_V1);

Therefore, it is decided to use a 2^k factorial design (DOE), composed of the parameters of the evolutionary algorithms (factors), i.e., population size (PS), number of generations (NG) and mutation probability (MP); taking into account as response variables, the best solution found (BS), if the methodology is of the single-objective type, the number of non-dominated solutions (NDS), for multi-objective approaches and a variable common to both techniques, the computational time (CT) required. On the other hand, the configurations established for this experiment are shown in Table 4 and Table 5, where the levels or treatments were chosen based on the experimentation and the review of previous studies.

Factors	Levels	
	Low (-)	**High (+)**
PS	100	200
NG	150	300
MP	0,05	0,10

Table 4 - Factorial design for the single-objective techniques

Factors	Levels	
	Low (-)	**High (+)**
PS	240	480
NG	50	100
MP	0,05	0,10

Table 5. Factorial design for the multi-objective techniques

It is important to mention that the tests were performed on a laptop computer with a Core i5-1035G4 processor, 8 GB RAM memory and solid-state hard disk, using a total of 5 replicates for each of the possible combinations of the levels of the main factors; in addition, the hypotheses of significance for the BS and NDS variables were contrasted under a confidence level equivalent to 80% and for the case of CT, a level equal to 95% was taken into account.}

In order to choose the best configuration of levels for the evolutionary factors (initialization parameters) and to allow adequate outputs, taking into account the set of instances tested on each technique, it was decided to use the response optimizer that Minitab 19 has in the section: "DOE>Factorial>Optimizer". Once this tool has been executed, under the same level of importance between test scenarios, the structure shown in Table 6 is obtained, which will serve as a starting point when executing any test instance.

Algoritmo	Best combination of treatments associated with the response variable (Optimizer)					
	BS/NDS			**CT**		
	PS	**NG**	**MP**	**PS**	**NG**	**MP**
GA	200	300	0,05	100	150	0,10
p-GA_V1	200	300	0,05	100	150	0,10
p-NSGA-II_V1	480	50	0,10	240	50	0,10
p-SPEA-II_V1	480	50	0,10	240	50	0,10
p-NSGA-II_V2	480	50	0,10	240	50	0,10
p-GA_V2	200	300	0,05	100	150	0,10

Table 6 - Optimal combination of factors associated with AEs

Taking as reference the configuration of the evolutionary parameters obtained previously by means of the factorial design, the testbed is executed on each algorithm, with the purpose of obtaining sufficient data to verify the preliminary statements, associated to the performance; which is represented in the case of the mono-objective techniques, by the variable: best solution found (BS) and for the multi-objective approaches, the variable defined as: number of non-nominated solutions (NDS), taking into account in turn, the computational time (CT). To carry out this procedure, it was necessary to use a sample size equivalent to thirty (30) per instance tested and to apply the t-test statistic with joint equality of variances, for differences between two means. The results of each technique are presented in Table 7-10, using an algorithmic contrast or GAP.

Instance	Algorithm				GAP	
	***p*-NSGA-II_V1**		***p*-SPEA-II_V1**		**(*p*-NSGA-II_V1-*p*-SPEA-II_V1)**	
	NDS	**CT**	**NDS**	**CT**	**NDS**	**CT**
I1	6,100	399,550	5,900	477,034	0,200	-77,484
I2	8,567	223,042	8,167	299,973	0,400	-76,932
I3	5,867	348,650	6,967	421,611	-1,100	-72,961
I4	6,633	163,684	8,167	233,694	-1,533	-70,009
I5	8,867	117,551	9,633	188,416	-0,767	-70,865
I6	9,200	188,290	9,200	257,267	0,000	-68,977
I7	5,567	181,082	6,400	252,590	-0,833	-71,507
I8	8,167	230,756	9,600	296,181	-1,433	-65,425
I9	5,200	238,188	6,533	303,023	-1,333	-64,835
I10	8,900	178,006	8,867	250,924	0,033	-72,918
I11	8,533	294,992	8,400	361,875	0,133	-66,883
I12	9,767	211,720	10,800	281,523	-1,033	-69,803
I13	11,100	111,218	12,667	165,437	-1,567	-54,219
I14	6,533	228,217	7,233	271,475	-0,700	-43,258
I15	6,533	259,037	6,200	296,033	0,333	-36,996
I16	9,200	214,804	9,400	265,671	-0,200	-50,867
I17	6,067	263,645	6,500	308,835	-0,433	-45,190
I18	6,400	208,508	7,633	267,172	-1,233	-58,665
I19	6,300	287,443	7,233	348,707	-0,933	-61,264
I20	5,900	242,527	7,533	305,711	-1,633	-63,184

Table 7 - GAP between algorithms *p*-NSGA-II_V1 and *p*-SPEA-II_V1(n = 30)

Note. The results correspond to an average and the computational time (CT) is given in seconds.

Instance	Algorithm				GAP (*p*-GA_V1-GA)	
	p-GA_V1		GA			
	BS	CT	BS	CT	BS	CT
I1	-2608329,808	693,339	-2621485,630	620,700	13155,822	72,639
I2	-118843,322	402,573	-119472,111	343,335	628,789	59,239
I3	-2666872,956	585,832	-2687137,125	535,088	20264,169	50,744
I4	-3977960,852	276,149	-3986844,367	243,198	8883,515	32,951
I5	-1421596,543	204,778	-1422258,866	178,447	662,323	26,331
I6	-1598128,210	324,961	-1597821,753	285,487	-306,457	39,474
I7	-427842,676	315,004	-436876,559	281,402	9033,883	33,603
I8	-3020121,145	398,285	-3022902,409	355,207	2781,264	43,077
I9	-4452441,767	402,390	-4460707,077	352,999	8265,310	49,391
I10	-10437775,724	299,961	-10435912,098	269,714	-1863,626	30,248
I11	-5797773,828	499,006	-5800601,257	457,315	2827,429	41,691
I12	-9914707,692	374,540	-9921649,955	331,951	6942,263	42,589
I13	-1875211,244	172,358	-1876014,889	153,123	803,645	19,234
I14	-3081713,774	361,084	-3086399,139	325,763	4685,365	35,321
I15	-4233694,198	405,131	-4240697,709	367,707	7003,511	37,424
I16	-3571773,645	355,100	-3571430,187	317,716	-343,458	37,384
I17	-3975248,726	422,269	-3987212,763	385,487	11964,037	36,781
I18	-1418874,253	341,502	-1430756,336	311,764	11882,083	29,738
I19	-2936430,644	491,022	-2939044,696	455,393	2614,053	35,630
I20	-3442215,098	414,514	-3445306,281	382,268	3091,183	32,246

Table 8 - GAP between algorithms *p*-GA_V1 and GA (n = 30)

Note. The results correspond to an average and the computational time (CT) is given in seconds.

Instance	**Algorithm**				**GAP (*p*-NSGA-II_V2-*p*-SPEA-II_V1)**	
	***p*-NSGA-II_V2**		***p*-SPEA-II_V1**			
	NDS	**CT**	**NDS**	**CT**	**NDS**	**CT**
I1	6,767	389,762	5,900	477,034	0,867	-87,272
I2	9,233	221,183	8,167	299,973	1,067	-78,791
I3	6,300	341,345	6,967	421,611	-0,667	-80,266
I4	6,667	159,942	8,167	233,694	-1,500	-73,752
I5	10,267	117,456	9,633	188,416	0,633	-70,960
I6	9,967	186,027	9,200	257,267	0,767	-71,240
I7	6,333	178,663	6,400	252,590	-0,067	-73,927
I8	8,967	223,228	9,600	296,181	-0,633	-72,953
I9	6,100	230,447	6,533	303,023	-0,433	-72,576
I10	8,933	176,165	8,867	250,924	0,067	-74,758
I11	9,533	291,936	8,400	361,875	1,133	-69,939
I12	11,067	215,053	10,800	281,523	0,267	-66,469
I13	13,267	100,823	12,667	165,437	0,600	-64,614
I14	7,467	206,141	7,233	271,475	0,233	-65,334
I15	7,767	234,765	6,200	296,033	1,567	-61,269
I16	10,500	204,194	9,400	265,671	1,100	-61,477
I17	6,500	247,296	6,500	308,835	0,000	-61,539
I18	8,100	197,680	7,633	267,172	0,467	-69,492
I19	7,400	281,774	7,233	348,707	0,167	-66,933
I20	8,533	234,325	7,533	305,711	1,000	-71,386

Table 9 - GAP between algorithms *p*-NSGA-II_V2 and *p*-SPEA-II_V1 (n = 30)

Note. The results correspond to an average and the computational time (CT) is given in seconds.

Instance	Algorithm				GAP (*p*-GA_V2-GA)	
	p-GA_V2		GA			
	BS	CT	BS	CT	BS	CT
I1	-2619906,796	679,429	-2621485,630	620,700	1578,834	58,729
I2	-119153,886	382,557	-119472,111	343,335	318,225	39,223
I3	-2679250,089	581,146	-2687137,125	535,088	7887,036	46,057
I4	-3985067,370	271,852	-3986844,367	243,198	1776,997	28,654
I5	-1423644,349	196,921	-1422258,866	178,447	-1385,483	18,474
I6	-1597800,833	314,473	-1597821,753	285,487	20,921	28,986
I7	-435757,645	315,684	-436876,559	281,402	1118,914	34,282
I8	-3020996,654	390,588	-3022902,409	355,207	1905,756	35,380
I9	-4457008,689	393,371	-4460707,077	352,999	3698,388	40,373
I10	-10437311,884	297,082	-10435912,098	269,714	-1399,786	27,368
I11	-5799699,320	504,373	-5800601,257	457,315	901,938	47,057
I12	-9918961,427	366,633	-9921649,955	331,951	2688,527	34,682
I13	-1875070,324	169,132	-1876014,889	153,123	944,566	16,009
I14	-3084389,255	360,077	-3086399,139	325,763	2009,884	34,314
I15	-4239894,080	390,638	-4240697,709	367,707	803,629	22,931
I16	-3572521,077	346,914	-3571430,187	317,716	-1090,890	29,198
I17	-3986816,770	418,637	-3987212,763	385,487	395,993	33,150
I18	-1421781,899	339,794	-1430756,336	311,764	8974,437	28,029
I19	-2937575,106	492,697	-2939044,696	455,393	1469,590	37,305
I20	-3445063,335	414,627	-3445306,281	382,268	242,946	32,359

Table 10 - GAP between algorithms *p*-GA_V2 and GA (n = 30)

Note. The results correspond to an average and the computational time (CT) is given in seconds.

6. DISCUSSION

The experimentation carried out points to the algorithms *p*-NSGA-II_V1 and *p*-NSGA-II_V2 as the best alternatives to solve the multi-objective 2E-LIRP problem applied to the humanitarian supply chain, because they obtain the highest average number of non-dominated solutions (NDS), allowing the decision maker to have a prudent set of possible solutions and also, the execution times (CT) are statistically lower than *p*-SPEA_V1.

Despite an approximately equal performance in terms of computational time (CT) or solution quality (BS), by genetic algorithms (GA) programmed in parallel under a cooperative environment or simply with a parallel approach, compared to their sequential counterpart, it is important to mention that there are some considerable improvements for the variable BS, using the *p*-GA_V1 and *p*-GA_V2 techniques, which are valued at 45% and 50% respectively, taking as a reference the testbed, i.e., the *p*-GA_V1 algorithm improves the solutions for 45% of the tested instances, while the *p*-GA_V2 allows to obtain a global improvement, equivalent to 50%.

On the other hand, the algorithms designed under the mono-objective and multi-objective approaches, taking into account sequential, parallel and cooperative characteristics, generally present a reasonable processing time (5 to 10 minutes approximately), thus becoming valid and efficient tools that support integral decision making for the management of the humanitarian supply chain, whose main objective is to attend the areas affected by a disaster in the shortest possible time, thus saving as many lives as possible.

Finally, the results obtained in each of the solution approaches indicate that the present study has fulfilled the general purpose, related to the development of a multi-objective optimization model for the two-echelon location, routing and inventory problem (2E-LIRP) and, consequently, to the design of a set of computational tools (Python code), which allow solving specific instances, providing relevant information to the decision-maker and designing the humanitarian logistics network.

7. CONCLUSIONS

One of the most significant contributions provided by this research is the development of a multi-objective model for the problem of location, inventory and multi-echelon routing, considering dynamic demand, heterogeneous fleet, multiple periods and products, which takes into account the optimization of social costs, due to its humanitarian context and the new approaches in the area of disasters that seek to mediate between private and humanitarian costs, despised so far in much of the existing literature, because they use adaptations of commercial logistics; in other words, the objectives of the mathematical model constructed are to minimize traditional logistics costs (location, inventory and routing) and, at the same time, to maximize the welfare of the affected areas, using a function that represents the impact on the distribution strategy and the time of deprivation experienced.

The parallel-cooperative or purely parallel scheme, acts favorably when constructing solution techniques that follow the methodology proposed by NSGA-II, thus allowing a higher performance, if compared to the SPEA-II algorithm, designed under identical conditions, using as metrics, the computational time (CT) and the number of non-dominated solutions (NDS). Moreover, it is important to mention how the *p*-NSGA-II_V1 and *p*-NSGA-II_V2 algorithms have strictly lower computational times for 100% of the executed instances and at the same time, the number of non-dominated solutions are at least equal or higher than those of *p*-SPEA-II_V1.

The experimentation carried out showed that using parallel programming under the cooperative paradigm or simply the parallel approach, in the design of a single-objective genetic algorithm (*p*-GA_V1 or *p*-GA_V2), for the solution of the 2E-LIRP, allows obtaining at the inferential level solution methods approximately equal, in terms of the variable, best solution found (MS), than its sequential counterpart, the genetic algorithm

(GA). However, it is important to mention that for a set of replicates (sample level), the *p*-GA_V1 and *p*-GA_V2 algorithms significantly improve the solutions obtained by the GA technique, finding approximately 45% (parallel-cooperative algorithm) and 50% (parallel algorithm) of the best global solutions in the testbed executed.

In spite of the effort made to build a parallel-cooperative genetic algorithm that would present an improvement in terms of computational time (CT), the experimentation allows inferring that under the scheme used (distributed system or islands), this purpose is impossible to achieve, since in most of the instances used, the performance obtained was inferior with respect to its sequential counterpart, This is due to two very important aspects, the first, the need to synchronize the two threads (islands) at the time of the transfer of genetic information and the second, the additional operations that it needs to perform in the collector (communication mechanism), to finally obtain a solution (better individual).

The evolutionary techniques used in the present study offered excellent performance (global range between 5 and 10 minutes) when solving the problem addressed, given the computational complexity that demanded the use of adequate tools to obtain good solutions in reasonable computational times. Each proposed technique was validated by applying a testbed, composed of twenty test instances, where the consistency and validity of the outputs were two very important aspects that were evaluated, with the purpose of offering the decision-maker useful tools to support the management of the humanitarian supply chain, taking into account the needs (location, inventory and routing) from an integral viewpoint, the multi-objective approach, which provides a set of possible solutions, which according to some criteria or specific technique, lead to the selection of an alternative, and the mono-objective approach, which allows to mediate or combine the interests under conflict, by applying a level of importance or weight, in order to obtain a single answer.

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FUZZY OPERATIONAL DECISION-MAKING PROCESS IN URBAN FREIGHT TRANSPORT

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ABSTRACT

This article presents a fuzzy process for operational decision-making on the freight pick-up and delivery. It allows assessing the impact of uncertainty conditions presented in urban context variables such as time windows, service time, reacting available time, on the distribution routes. We use the fuzzy decision process to assess customers' requirements on a daily urban freight. The process supports the decision-making for accepting or rejecting the requests. It considers a notable key index, the impact level on the route. This index assesses the current values of the input variables. The changes are accepted when the impact level on the route is lower than 0.25.

1. INTRODUCTION

In urban freight transport (UFT) processes, there are constant changes in customer demand, travel times, and service times, among others (Gómez-Marín, 2020). It is necessary to consider methods that assess the feasibility of reacting quickly to these online changes in terms of additional costs incurred by changing pre-established routes and the impact on the scheduled routes to visit on time for all customers.

The fuzzy inference has been implemented in distribution logistics processes to mitigate the uncertainty and risks that arise in today's business and the constant search to improve the service levels expected by customers (Adarme-Jaimes, Arango-Serna, & Cogollo-Flórez, 2012; Brito, 2011; Lin et al., 2014), to minimize cost and risk on route planning (Pamučar et al., 2016), and to reduce environmental impact of network design (Cirovic, Pamucar, & Bozanic, 2014; Soleimani et al., 2017). It can be used integrating data analysis to assess the UFT system efficiency (Bray et al., 2014; Koohathongsumrit & Meethom, 2021). By using fuzzy inference, stakeholders can make decisions and react to the dynamic context changes and improve the performance of freight transportation systems (Bray et al., 2014; Kuo, Wibowo, & Zulvia, 2016). It allows flexible behaviors or replies to each change. According to Villeta et al., (2012) it is possible to use this tool to model the attitudes and behavior of actors in different scenarios.

Simic & Simic (2011) classify the application of fuzzy inference in UFT into four types: 1) application of expert systems, 2) multi-criteria decision-making processes under uncertainty, 3) routing problems mixed with transportation modes, and 4) process actor selection process. We present an application for a multi-criteria decision-making process to assess the possibility of accepting or rejecting changes based on reached impact level on the distribution plan (route).

This paper proposes a decisional framework to assess a notable key index, the impact level on the route. It considers events of time windows changes and service time changes during the operation day. It also takes into account the moment of the day when the event occurs and the relative customer importance on the route. The paper is organized as follow: at section two, we present the fuzzy decision-making process. In section three, we discuss the results of the fuzzy inference process. Hereafter we present conclusion and propose future works.

2. FUZZY DECISION-MAKING PROCESS

We define four input variables for the fuzzy inference system. These variables represent some possible changes in customer demand conditions and the changes characteristics. The customer sends a request informing the desired changes in time windows and in the service times to the vehicles at loading or unloading activity.

The input variables are defined based on change features and customer order importance.

The output variable is the result of the fuzzy inference process that explores quantifying the impact level on the route considering the changes events to the current route. Figure 1 presents the proposed fuzzy operational decision-making process.

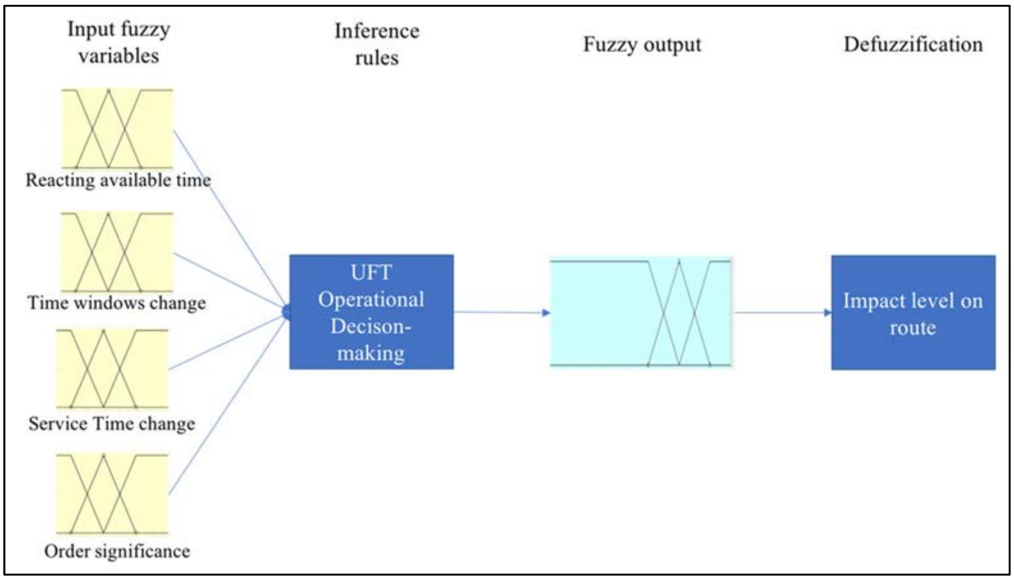


Fig. 1 – Fuzzy operational decision-making process

The selected variables in this fuzzy inference process are used to make decision-making more flexible and promptly and assess the possibility of reprogramming the initial distribution plan. These variables are:

2.1 Input variables

Reacting available time: This variable measures the time availability to react considering the moment when the customer requests the change. The available route time is the difference between the total time for the working day and the moment when the request arrives. Equation (1) shows how to calculate this variable:

$$Reacting\ available\ time = \left(\frac{Available\ route\ time\ (t)}{Total\ time\ for\ the\ working\ day}\right) \quad (1)$$

In the fuzzy parameterization process of the reacting available time, there are three fuzzy sets. Low if the reacting available time is between 0.00 and 0.25; medium, if reacting available time is between 0.125 and 0.375, and high if the reacting available time is greater than and 0.25.

Time windows change: this variable defines the time window increase or decrease, i.e., the new window size requested by the customer measured as a ratio between the change and the initial time window. We do not consider a translation of time window in a different operation time period. The fuzzy sets for the variable parameterization are three: low, when the ratio is lower than 0.25; medium, when this ratio is between 0.125 and 0.375; and high for ratios greater than 0.25. Equation (2) shows how to calculate this variable.

$$Time\ windows\ change = \left(\frac{New\ time\ window\ size}{Initial\ time\ window\ size}\right) \quad (2)$$

Service time change: We consider service time as the waiting time for be served plus the loading/unloading time**.** This variable defines the numerical value of the change in service time location with respect to an established service time, i.e., this variation just can occur when vehicle arrive to customer's location. The pre-established value for service time is 10 minutes. The fuzzy sets for the parameterization of the variable are three: low when the change in service time is negative, that is, the vehicle is served earlier than expected, and can vary between -10 minutes and 5; medium when the additional time that vehicle must wait is between 0 and 10 minutes; and high for changes greater than 5 minutes.

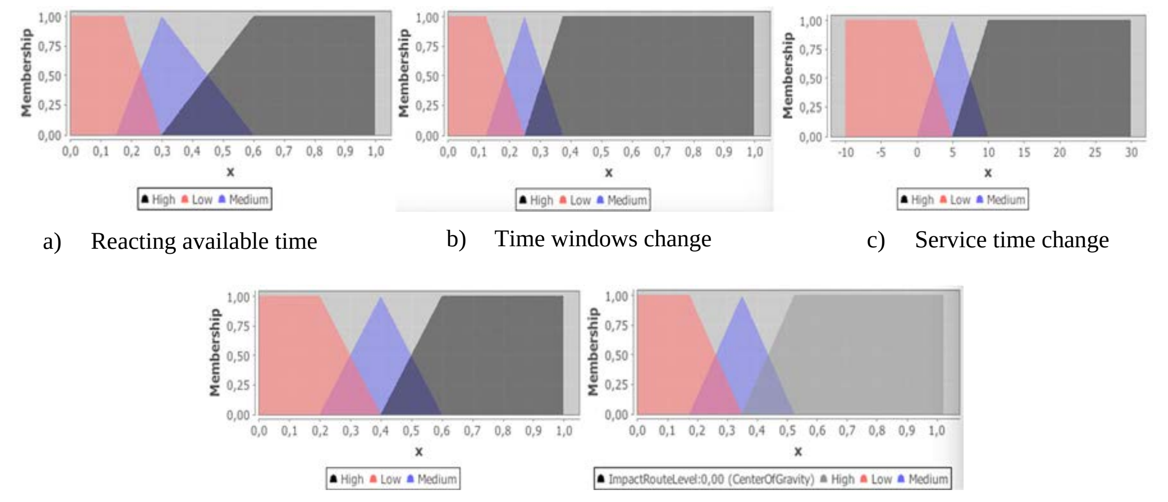
Order significance: This variable measures the ratio between the load quantity for the customer order that requires the change over the total vehicle load. Equation (3) presents the normalization for this variable.

$$Order\ significance\ (i) = \left(\frac{Load\ quantity\ for\ order\ (i)}{Total\ load\ quantity\ at\ vehicle}\right) \quad (3)$$

Order significance variable is bounded by three fuzzy sets. Low, when order significance takes values between 0 and 0.4; medium for significance values between 0.2 and 0.6; and high when the customer has a significance greater than 0.4.

2.2 Output variable:

Impact level on route: this variable measures the impact degree for a set of changes from a customer in the distribution route. This variable has an output range from 0 to 1 in which three fuzzy sets are determined: low, for impact route level values between 0 and 0.35; medium for values between 0.175 and 0.525; and high for impact route level values greater than 0.35. It is expected for values lower than 0.25 the changes can be accepted. Fig.2 presents the membership functions and fuzzy sets for the treatment of the variables.



a) Reacting available time
b) Time windows change
c) Service time change
d) Order significance
e) Impact level on route

Fig. 2 – Membership functions

2.3 Inference rules.

Impact level on route was evaluated on three input variables, which have three fuzzy categories. Therefore, there are $3^4 = 81$ IF-THEN rules in the fuzzy inference system. Table 1, for illustrative purpose, presents the first nine inference rules.

Rule	Service time change	Time window change	Urgency	Customer Significance	Impact level on route
1	High	High	High	High	Low
2	High	High	High	Medium	Low
3	High	High	High	Low	Low
4	High	High	Medium	High	Medium
5	High	High	Medium	Medium	Medium
6	High	High	Medium	Low	Low
7	High	High	Low	High	High
8	High	High	Low	Medium	Medium
9	High	High	Low	Low	Medium

Table 1 – First inference rules

2.4 Deffuzification method.

Since the objective of the work is to make decisions in urban freight transport to react to operational changes in the input variables, it is necessary to defuzzify the output of this inference system. For this purpose, the centroid method was used.

3. RESULTS AND DISCUSSION

The previously described fuzzy operational decision-making process allows to obtain response surface 3D graphs for modeling the relation between the input and output variables in urban freight transport (Figs. 3, 4 and 5). Figure 3 shows that the reacting available time has a greater impact level on route than the order significance. It is possible to obtain low impacts level on route and accept the changes when the reacting available time is below 0.6, regardless of the order significance values. Nevertheless, the impact level on route begins to increase when the available time to react to changes is lower than the approximately half of the total time for the working day.

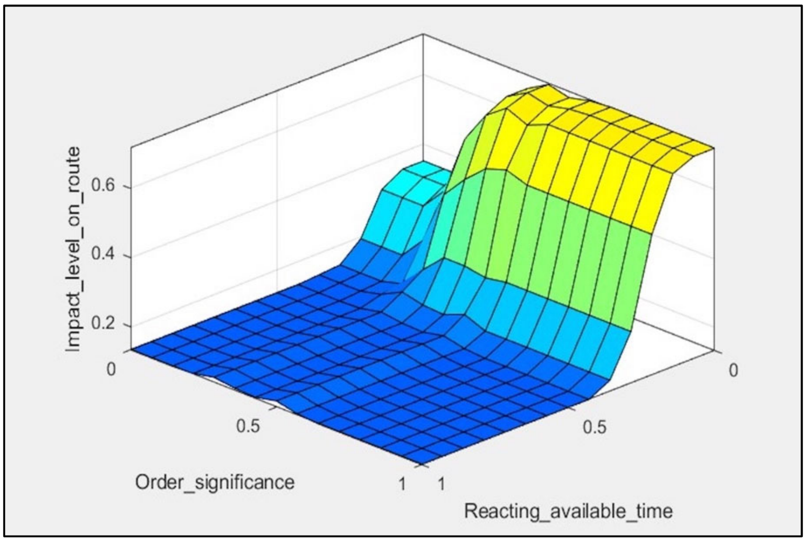


Fig. 3 – The 3D relation between order significance, reacting available time and 3.1 3.1 Impact level on route.

The reacting available time and service time change variables have a greater impact level on distribution route (Figure 4). With reacting available time values above 0.38 and service time change above 17 minutes, impact level on route is higher than 0.25 and the changes should be rejected. When the service time change is below 16 minutes and the reacting available time is more than 0.39, a significant decrease in impact level on route and the changes should be accepted.

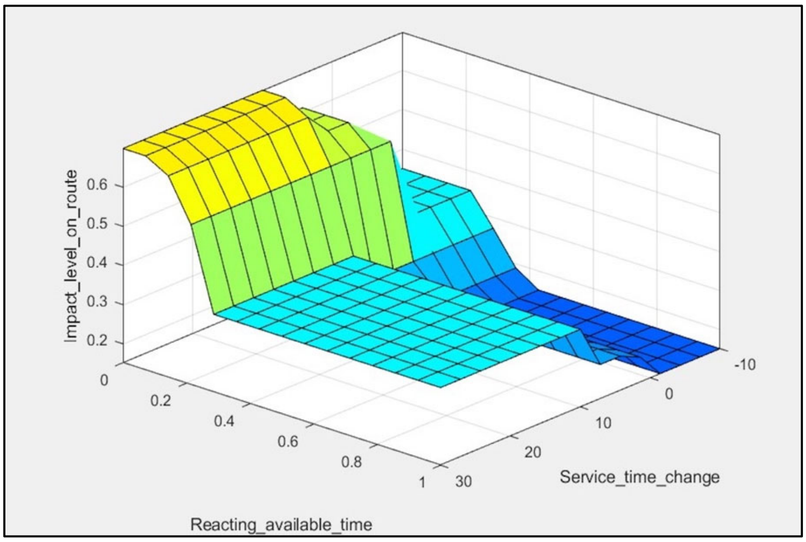


Fig. 4 – The 3D relation between reacting available time, service time change and Impact level on route

Regarding the relationship between order significance and service time change and their impact level on route (Fig. 5), it is possible to obtain high impacts level on route and reject the changes when the service time change is above + 8 minutes, regardless of the order significance values. Additionally, the impact level on route begins to decrease when the service time change is lower than the approximately +7 minutes and the change should be accepted.

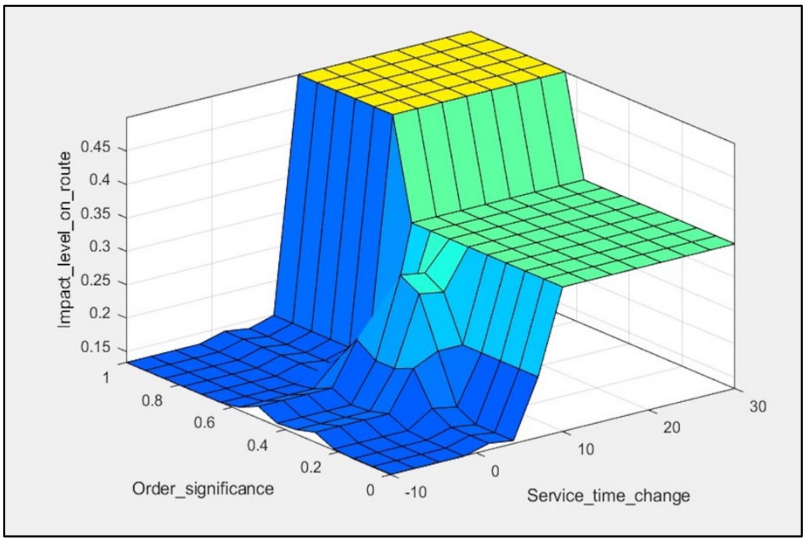


Fig. 5 – The 3D relation between order significance, service time change and impact level on route

4. CONCLUSIONS

The developed system shows that the fuzzy operational decision process is congruent with the reality of the UFT context. When there is more time to react to different changes in the operational context, it is possible to modify the distribution plan and accept the changes obtaining low impacts on routes. When the time to react to changes is relatively short, the change acceptance is affected by the low flexibility to respond to this change.

Additionally, if service times increase, it directly affects the remaining time to visit the customers and produces a higher impact level on the route, decreasing its acceptance. The variables that have a higher impact on the decision process are the reacting available time and the service time change. This work is a product of ongoing research whose objective is a model formulation for planning and evaluating urban freight distribution strategies under uncertain conditions. A future research line is the combination of this decision process integrated with the design of distribution routes and the dynamic vehicle routing problem. Also include some additional variables such as travel times and changes in demand.

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MODELIZACIÓN Y SIMULACIÓN
MODELLING AND SIMULATION

A FINITE ELEMENT APPROACH FOR THE TRAFFIC ASSIGNMENT PROBLEM

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ABSTRACT

Traffic assignment problem (TAP) in static equilibrium conditions is based on the Wardrop´s first principle. The mathematical solution of this problem involves significant computation times for the analysis of large transportation networks, especially in the context of design. Thus, the development of efficient computational methodologies is of the greatest concern.

In this article, a reduced order model for TAP, based on a Finite Element Approach (FEA), is proposed. Such methodology involves four main ideas: a) the TAP formulation including as variables the travel times from any node of the network to the corresponding destination points, b) the solution of the governing algebraic equation system by means of an efficient iterative approach, known as "Physarum", that takes the travel times as the main unknowns, c) the interpolation of travel times in certain urban subdomains, denominated "finite elements", in terms of the values corresponding to some main nodes previously selected (reduced unknowns), d) the use of the Galerkin's method to express the TAP in terms of the reduced unknowns. The model formulation is presented and a numerical example is given to show its efficiency.

1. INTRODUCTION

Estimation of users' choice of routes and the resulting traffic flow on every arc of the transportation network, known as TAP, is a very important task in studies of urban planning. In static equilibrium conditions, this problem is based on the Wardrop´s first principle (Sheffi, 1984). One of the most used approaches for this problem corresponds to the Beckmann's formulation that constitutes a convex optimization problem having the link flows as the main unknowns. The TAP Beckmann's formulation may be appropriately solved by means of the Frank-Wolfe method (FW).

The computational burden to solve this problem increases with the number of network nodes. Accordingly, involved calculation times for large networks are significant, especially in the context of transportation optimal design because the TAP must be solved many times.

For this reason, remarkable research efforts have been directed to the development of efficient methodologies to solve the TAP.

Some investigations were directed to improve the efficiency of the FW, thus originating the conjugated FW and the bi-conjugated FW (Hearn et al., 1985; Mitradjieva and Lindberg, 2013). Also, efficient algorithms based on trajectories were proposed showing faster convergence with respect to arc-based methods but with higher requirements of computational memory (Florian et al., 2009). On the other hand, Xu et al. (2008) presented an improved origin-based algorithm for assignment and distribution problems.

A strategy to improve the efficiency for solving the TAP is the use of parallel computation.

For example, Lotito (2006) proposed an approach to parallelize, by origin-destination pairs, the disaggregated simplicial decomposition algorithm previously developed by Larsson and Patricksson (1992). Another interesting parallelization method for TAP was recently developed by Jafari et al. (2017) consisting in the partition of the transportation network in small sub-networks. The algorithm alternates between the equilibrium of every sub-network and the equilibrium of a simplified version of the whole network.

In the last years, a new model denominated "Physarum" for solving different optimization problems of scientific and technological interest has been proposed (Tero et al., 2007).

This biologically-inspired algorithm is based on an analogy with the foraging behaviour of the slime mould Physarum Polycephalum that consists in generating protoplasmic tubes following the shortest route to the food sources. The mathematical modelling of such behaviour has been conveniently applied to the determination of the shortest path in networks, the reduction of costs in transportation and communication networks, etc. Very recently, the Physarum approach has been extended to the TAP in user equilibrium conditions following the Beckmann´s formulation (Zang, 2018; Xu et al., 2018). As shown in these articles, the Physarum approach may be more efficient than classical methods based on the FW. On the other hand, Cortínez and Dominguez (2018) have demonstrated that Physarum model, when applied to TAP, may be considered as an iterative strategy for solving an alternative TAP formulation based on travel times (Cortínez y Dominguez, 2017).

This interpretation allows the application of the Physarum approach to the generalized traffic assignment problems (including variable demand, multiple user classes, etc.).

Despite these efforts, the computational burden is still very important in the case of optimal design of large transportation networks. Consequently, several methods have been directed to reduce the number of unknowns. Some of these ones consist in eliminating arcs with low vehicular flow, and other techniques consist in aggregating several arcs in another fictitious equivalent link (Raadsen et al., 2020).

Many of these approaches present certain arbitrariness in the selection of the reduced network topology that can lead to inaccuracies in the calculated flows.

Another kind of models conceives the traffic network as an equivalent two-dimensional continuum medium. To solve these models, discretization methodologies, such as finite differences or finite elements, could be applied with a number of unknowns lesser than that of the original network (Sasaki et al., 1990; Ho et al., 2006, Dominguez, 2013, Cortínez and Dominguez, 2013, 2017).

In the present paper, in order to reduce the number of necessary variables to define the TAP, a finite element approach is proposed. This methodology involves four main ideas: a) the TAP formulation including, as variables, the travel times from any node of the network to the corresponding destination points, b) the solution of the governing algebraic equation system by means of an efficient iterative approach known as “Physarum” that takes the travel times as the main unknowns, c) the interpolation of travel times in certain urban subdomains, denominated “finite elements”, in terms of the values corresponding to some main nodes previously selected (reduced unknowns), d) the use of the Galerkin’s method to express the TAP in terms of the reduced unknowns.

The model formulation is presented and a numerical example is given to show its efficiency.

2. TRAFFIC ASSIGNMENT PROBLEM IN TERMS OF TRAVEL TIMES

A traffic urban network during the rush hour, when users travel from their homes distributed over the city to certain destination points d (d=1,2,...Nd), is considered.

The network topology, assumed as a set of nodes i (i=1,2,…Nn) connected by directed arcs a (a=1,2,…Na), and the properties of every arc (capacity, length, maximum speed, etc.) are known. Moreover, trip generation rates q_i^d (veh/h), at every node i of the network to the different destinations d, are known. TAP consists in obtaining the link flows $\bar{g}_a$ (veh/h) and the travel times u_i^d (h), from each node i to the corresponding destinations d, according to the users route choices in equilibrium condition.

In the following, the TAP is formulated incorporating the travel times u_i^d as variables (Dominguez, 2013; Cortínez y Dominguez, 2017).

2.1 Congestion function

Urban traffic congestion may be defined as the increment of the link travel time t_a caused by the increment of the link flow $\overline{g}_a$ (veh/h).

From a mathematical point of view, congestion may be defined by means of the following analytical expression:

$$t_a = t_a(\overline{g}_a) \tag{1}$$

This strictly increasing function (Figure 1a) is known in the literature as cost function. Several empirical functions have been developed for expressing (1) explicitly, such as the well-known BPR formula (Sheffi, 1984).

The total flow $\overline{g}_a$ on a link *a* may be expressed as the sum of the flow directed to a certain particular destination *d*, g_a^d, and the flows going to the rest of destinations, g_{aR}^d. This last one may be denominated residual flow with respect to the destination *d*:

$$g_{aR}^d = \sum_{dd} g_a^{dd} \qquad \forall dd \neq d \tag{2}$$

From (1) and (2), the flow on the link *a* going to *d* may be expressed as:

$$g_a^d = \overline{g}_a\left(t_a\right) - g_{aR}^d \tag{3}$$

where $\overline{g}_a(t_a)$ is the inverse function of (1).

2.2 Wardrop's first principle

Wardrop's first principle (Sheffi, 1984) for user's equilibrium (UE) states that the used paths travel times, between every origin-destination pair, are less than, or equal to, the travel times of the other paths. According to this sentence, the travel time between a given point of the network to the destination point is unique (and the minimum) for all the paths really used.

Then, such principle may also be formulated by postulating that the travel time between a given point (*x*,*y*) of the transportation network until the destination *d* is only a function of (*x*,*y*) and not of the employed trajectory (it is a potential function):

$$u^d = u^d(x, y) \tag{4}$$

being by definition $u^d(x_d, y_d) = 0$, where x_d and y_d correspond to the coordinates of the destination *d*. Then, travel time from node *i* to destination *d* may be written as:

$$u_i^d = u^d(x_i, y_i) \quad (5)$$

Using this potential function, the link travel time can be expressed as:

$$t_a = t_a^d = \left| u_i^d - u_j^d \right| \quad (6)$$

It is important to observe that, in equilibrium conditions, the link travel time t_a is the same for every user circulating on the link independently of its destination.

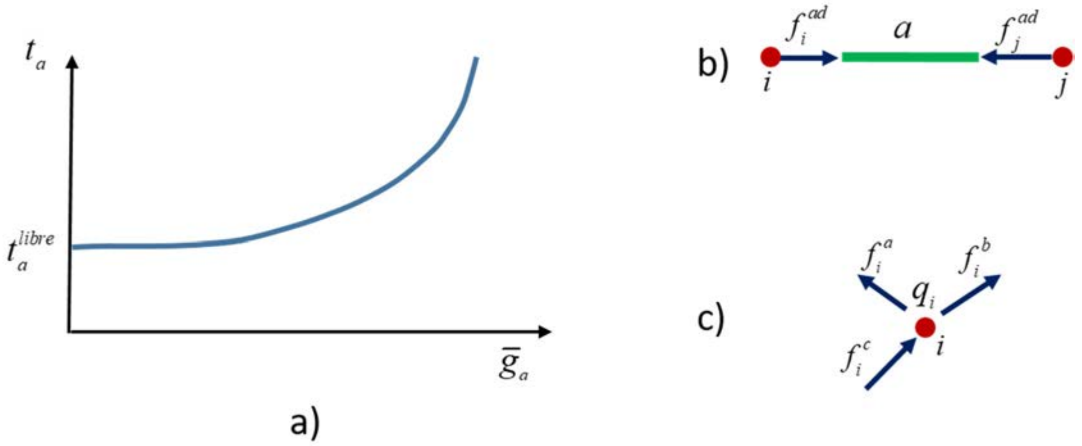

Fig. 1 – Basic definition of UE: a) Cost function, b) flow on link *a*, c) nodal flows at *i*.

2.3 Conservation of vehicles

To formulate the TAP, the conservation of vehicles law at a node must be considered (the number of vehicles entering and exiting a node is a conservative quantity). In order to express such a law, it is convenient to write, making use of (6), the following identity:

$$g_a^d = \frac{g_a^d \left| u_i^d - u_j^d \right|}{t_a} \quad (7)$$

Then, the nodal flows, corresponding to a link *a* (Figure 1b), are defined in the following form:

$$f_i^{ad} = \frac{g_a^d \left(u_i^d - u_j^d \right)}{t_a} = -f_j^{ad} \quad (8)$$

In (8) such flows have been defined positive when they enter the node and negative when they exit. In fact, in (8) $\left(u_i^d - u_j^d\right)$ is positive when the flow is directed from *i* to *j* (in the direction of decreasing *u*). Expression (8) is then useful for non-directed arcs, that is to say those links in which flows can be directed from *i* to *j* or from *j* to *i* according to the sign of $\left(u_i^d - u_j^d\right)$. However, TAP involves directed arcs (one-way links). To define the correct direction of a link *a*, the indicator λ_{ij}^a is introduced:

$$\lambda_{ij}^a = \begin{cases} 1 & i \to j \\ -1 & j \to i \end{cases} \qquad \lambda_{ij}^a = -\lambda_{ij}^a \tag{9}$$

Therefore, the expression for nodal flows corresponding to directed arcs should be re-written, generalizing (8), in the following form:

$$f_i^{ad} = \frac{g_a^d}{t_a} \xi_e^d \left(u_i^d - u_j^d\right) \tag{10}$$

where:

$$\xi_a^d = \begin{cases} 1 & \lambda_{ij}^a \left(u_i^d - u_j^d\right) \geq 0 \\ 0 & \lambda_{ij}^a \left(u_i^d - u_j^d\right) < 0 \end{cases} \tag{11}$$

As can be observed, ξ_a^d has a unit value when the travel time decreases in the allowed link direction and is null in the other case (vehicles cannot flow in a not allowed direction). One can observe that:

$$g_a^d = \left| f_i^{ad} \right| \tag{12}$$

According to expressions (8) and (10), the nodal flows on link *a* going to *d*, may be re-written as:

$$\begin{cases} f_i^{ad} = k_{ii}^{ad} u_i^d + k_{ij}^{ad} u_j^d \\ f_j^{ad} = k_{ij}^{ad} u_i^d + k_{jj}^{ad} u_j^d \end{cases} \tag{13}$$

where the link conductivity matrix has been introduced:

$$k_{ii}^{ad} = k_{jj}^{ad} = \frac{g_a^d \xi_a^d}{t_a^d}; \quad k_{ij}^{ad} = k_{ji}^{ad} = -\frac{g_a^d \xi_a^d}{t_a^d} \tag{14}$$

This matrix depends on $g_a^d(t_a)$ and t_a, and then, according to (6), depends on the potential functions u_i. Expressions (13) involve the travel time corresponding to the considered link *a*. However, it is possible to generalize expressions (13) involving all the nodes of the network by defining in an enlarged form the conductivity matrix. This definition can be performed by adding zeros in those elements connecting two nodes *m*, *n* not belonging to the considered link *a*:

$$k_{mn}^{ad} = 0, \quad m,n \neq i, j \tag{15}$$

In this way, nodal flow to destination *d*, at node *i* of link *a*, can be written as:

$$f_i^{ad} = \sum_{j=1}^{NN} k_{ij}^{ad} u_j^d \tag{16}$$

Therefore, the conservation of vehicles, at generic node *i*, may be expressed by the following equation (Figure 1c):

$$q_i^d - \sum_a f_i^{ad} = 0 \tag{17}$$

In (17), the sum involves all the arcs, although, obviously, the nodal flows are null for the links not connected with node *i* (in agreement with expression 15):

$$f_i^{ad} = 0 \qquad i \notin a \tag{18}$$

Substituting (16) into (17), the vehicle conservation equation may be written in the following form:

$$\sum_j \left(\sum_a k_{ij}^{ad} \right) u_j^d = q_i^d \tag{19}$$

Or, using a matrix notation:

$$\mathbf{K}^d \mathbf{u}^d = \mathbf{q}^d \qquad d = 1, 2, \ldots, Nd \tag{20}$$

In (20), the elements of the global conductivity matrix for vehicles going to *d* have been defined in the form:

$$K_{ij}^{d} = \sum_{a} k_{ij}^{ad} \tag{21}$$

Such system must be complemented with the expressions (corresponding to the definition of travel times):

$$u_{d}^{d} = 0 \qquad d = 1, 2, \ldots, Nd \tag{22}$$

As can be seen in (14), conductivity matrices $\mathbf{K}^{d}$ depend on t_a and g_a^d and, accordingly, expressions (1), (2), (3), (6), (20) and (22), constitute a non-linear algebraic equation system whose unknowns are given by u_i^d, g_a^d, $\bar{g}_a$ and t_a. Cortínez and Dominguez (2017) have shown that this system can be iteratively solved by means a sequence of problems whose unknowns are given by u_i^d. It can be demonstrated that the system (1), (2), (3), (6), (20) and (22) is equivalent to Beckmann's variational formulation (Dominguez, 2013; Cortínez y Dominguez, 2017).

3. NUMERICAL SOLUTION BY USING PHYSARUM APPROACH

The previous system can be iteratively solved by means of a Newton-Raphson technique (Cortínez and Dominguez, 2017). One of the difficulties found with this methodology is due the fact that if some links are decongested, g_a^d tends to zero and then, according to (14), also the conductivity matrix tends to zero.

Therefore, the system becomes indeterminate. This methodology makes use of the Physarum iterative approach (Zhang and Mahadevan, 2018; Xu et al., 2018; Cortínez and Dominguez, 2018), based on an analogy with a biological process, that works appropriately even in presence of decongested links.

The methodology starts with the approximation of the numerator and the denominator of the conductivity matrix elements (see expressions 14 and 15):

$$\begin{aligned} g_a^d \xi_a^d &\to D_a^d \\ t_a &\to L_a \end{aligned} \tag{23}$$

Consequently, expression (10) is approximated as:

$$f_i^{*ad} = \frac{D_a^d}{L_a}\left(u_i^d - u_j^d\right) \tag{24}$$

where f_i^{*ad} is an approximation to f_i^{ad}. Therefore, following (14), matrix k_{ij}^{ad} may be approximated by k_{ij}^{*ad} defined as:

$$k_{ij}^{*ad} = \begin{cases} D_a^d / L_a & i = j \\ -D_a^d / L_a & i \neq j \in a \\ 0 & i, j \notin a \end{cases} \tag{25}$$

Thus, considering (21), system (20) is approximated by the following linear system with unknowns $\mathbf{u}^d$:

$$\mathbf{K}^{*d}\mathbf{u}^d = \mathbf{q}^d \tag{26}$$

Before solving (26), it is necessary to take into account conditions (22). This may be performed easily modifying $\mathbf{K}^{*d}$ by means of a penalization approach (summing very large values to the diagonal elements corresponding to the unknowns u_d^d, Chandrupatla and Belegundu, 2012). One can observe that (26) (modified by 22) constitutes a decoupled system of linear equations for every destination. Formally, the solution may be expressed as:

$$\mathbf{u}^d = \left(\mathbf{K}^{*d}\right)^{-1}\mathbf{q}^d \tag{27}$$

Once determined $\mathbf{u}^d$, better approximations for link flows g_a^{*d} are obtained by means of (12) and (24):

$$g_a^{*d} = \frac{D_a^d}{L_a}\left|u_i^d - u_j^d\right| \tag{28}$$

Then, new approximations for ξ_a^{*d} are calculated using (11). Now, it is possible to obtain updated values for coefficients D:

$$D_a^{d(new)} = \frac{D_a^d + g_a^{*d}\xi_a^{*d}}{2} \tag{29}$$

The new approximation for total flow on the link *a* is obtained as:

$$\bar{g}_a^* = \sum_d g_a^{*d} \xi_a^{*d} \tag{30}$$

Finally, using expression (1), a new approximation for the link travel time t_a^* is achieved and then, the updated coefficient *L* is expressed as:

$$L_a^{(new)} = \frac{L_a + t_a^*\left(\bar{g}_a^*\right)}{2} \tag{31}$$

With the updated values, matrix conductivity $\mathbf{K}^{*d(new)}$ is re-calculated and the procedure is iterated. When convergence is achieved, D_a^d and L_a converge to $g_a^d \xi_a^d$ and t_a, respectively. The fact that, in each iteration, the systems (26) should be solved separately for every destination *d*, allows the application of this methodology in a context of parallel computing.

4. REDUCED MODEL: FINITE ELEMENT METHOD

System (26) for every *d* is often very large for urban or regional networks and, accordingly, very demanding from the computational point of view, because it should be solved many times up to convergence. This is especially true in the context of optimal design. For this reason, it is of interest to develop a model with lesser unknowns being approximately equivalent to system (26). In this section, an approach for reducing unknowns is developed by taking ideas from the Finite Element Method (FEM) commonly used in the field of continuum mechanics (Chandrupatla y Belegundu, 2012).

The methodology starts with the subdivision of the transportation network in subdomains, denominated finite elements (FE), each one containing a part of the network, as shown in Figure 2. The geometrical shapes of such elements may be relatively simple: rectangles, triangles, irregular quadrilaterals, etc.

Over these elements certain nodes are identified corresponding to the main unknowns U_K^d that represent the travel times from each point *K* to the corresponding destination *d*. Inside each FE, travel time from a generic point, with (*x*,*y*) coordinates, to destination *d*, is approximated by means of an interpolation in terms of travel times corresponding to the main nodes U_K^d:

$$u^d(x,y) = \sum_K N_K^e(x,y) U_K^d \tag{32}$$

For a consistency reason, the interpolation functions $N_K^e(x,y)$, must adopt the values $N_K^e = 1$ if $(x,y) = (x_K, y_K)$ and $N_K^e = 0$ if (x,y) correspond to any of the other main element nodes. Moreover, such functions are null outside the considered *e* element: $N_K^e = 0$ if $(x,y) \notin e$. There are many ways to select the interpolation functions (Chandrupatla y Belegundu, 2012). One of them will be presented in the numerical example given below. According to (32), travel time from *i*-node to destination *d* may be approximated as:

$$u_i^d = \sum_K \sum_e N_{iK}^e U_K^d \tag{33}$$

where $N_{iK}^e = N_K^e(x_i, y_i)$. On the other hand, if one defines:

$$N_{iK} = \sum_e N_{iK}^e \tag{34}$$

expression (33) could be written as:

$$u_i^d = \sum_K N_{iK} U_K^d \tag{35}$$

Or, in matrix form:

$$\mathbf{u}^d = \mathbf{N}\mathbf{U}^d \tag{36}$$

That is to say, the travel time u_i^d may be expressed in terms of travel times corresponding to the main nodes U_K^d. It should be observed that, using (36), the number of unknowns are significantly reduced with respect to the original network.

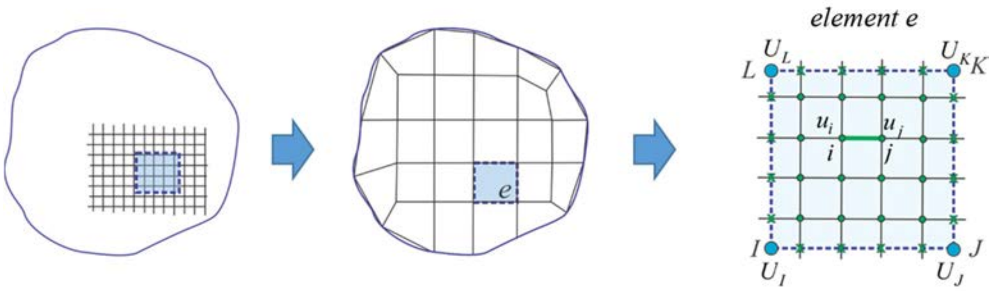

Fig. 2 – Scheme of the finite element reduced model

To obtain the reduced equation system with unknowns $\mathbf{U}^d$, the Galerkin's method is employed (Chandrupatla y Belegundu, 2012; Cortínez y Dominguez, 2017). Accordingly, a virtual vector $\delta\mathbf{u}$ is defined, with arbitrary values at all nodes excepting at those corresponding to destinations *d* where takes zero value. Now, pre-multiplying expression (26) by the transposed of $\delta\mathbf{u}$ one arrives at:

$$\delta\mathbf{u}^T\left(\mathbf{K}^{*d}\mathbf{u}^d - \mathbf{q}^d\right) = 0 \tag{37}$$

Interpolating $\delta\mathbf{u}$ in a form similar to (36), that is to say:

$$\delta\mathbf{u}^d = \mathbf{N}^T\delta\mathbf{U}^d \tag{38}$$

expression (37) can be re-written in the form:

$$\delta\mathbf{U}^T\mathbf{N}^T\left(\mathbf{K}^{*d}\mathbf{N}\mathbf{U}^d - \mathbf{q}^d\right) = 0 \tag{39}$$

Then, taking into account that $\delta\mathbf{U}^d$ is an arbitrary vector, equation (39) is true if:

$$\left(\mathbf{N}^T\mathbf{K}^{*d}\mathbf{N}\right)\mathbf{U}^d = \mathbf{N}^T\mathbf{q}^d \tag{40}$$

This expression may be conveniently re-written as:

$$\mathbf{\Psi}^d\mathbf{U}^d = \mathbf{Q}^d \tag{41}$$

considering the following definitions:

$$\mathbf{\Psi}^d = \mathbf{N}^T\mathbf{K}^{*d}\mathbf{N}, \quad \mathbf{Q}^d = \mathbf{N}^T\mathbf{q}^d \tag{42 a, b}$$

$\mathbf{\Psi}^d$ is a reduced conductivity matrix and $\mathbf{Q}^d$ is a reduced trip demand vector. One should observe that for representing appropriately the network in a reduced form, the destinations *d* must be included among the main nodes. On the other hand, the rest of the main nodes do not need to match with the real nodes. Before solving (41) matrix $\mathbf{\Psi}^d$ should be modified using the conditions (22) by means of the penalization approach described in the previous section.

5. COMPUTATIONAL PROCEDURE

According to the methodology explained in the above sections, the present algorithm to solve TAP is the following:

I) Definition of FE model (reduced model).
   a. Choice of main nodes K.
   b. Definition of nodes and links in each element.

II) Initialization of the iterative process.
   a. Adoption of initial values for g_a^d, ξ_a^d and t_a $\forall(d,a)$.
   b. Determination of the initial values for D_a^d and L_a $\forall(d,a)$ → Expression (23)

III) Iterative calculation up to convergence
   a. Determination of the conductivity matrix for each link k_{ij}^{*ad} $\forall(d,a,i,j)$ → Expression (25).
   b. Determination of the global conductivity matrices K_{ij}^{*d} $\forall(d,i,j)$ → Expression (21).
   c. Determination of the reduced FR conductivity matrices ψ_{IJ}^{*d} $\forall(d,I,J)$ → Expression (42a).
   d. Determination of the reduced EF trip demand vector Q_I^{*d} $\forall(d,I)$ → Expression (42b).
   e. Determination of travel time from main nodes to destinations *d*: U_I^{*d} $\forall(d,I)$. → Solution of system (41) for every destination *d*.
   f. Recovery travel times for the transportation network nodes u_i^{*d} → Expression (35).
   g. Updating of g_a^{*d}, ξ_a^{*d} $\forall(d,a)$ → Expressions (28) and (11).
   h. Updating of $\bar{g}_a^*$ and t_a^* $\forall a$ → Expressions (30) and (1).
   i. Updating of D_a^d and L_a $\forall(d,a)$ → Expressions (29) and (31).
   j. Verification of convergence. If $\max\left|u_i^{*d} - \left(u_i^{*d}\right)_{previous}\right| < Tolerance$ → end of iterative calculation.

6. NUMERICAL EXAMPLE

A fictitious transportation network of 2.9x2.9 km^2 consisting in 1740 one-way links of 100m length and 900 nodes (Figure 3) is analysed. The links, normal one each other, have a BPR cost function given by $t_a = 0.1\left(1+0.15\left(g_a/600\right)^2\right)$, corresponding to a link capacity of 600 vehicles/h and a maximum allowable speed of 60 km/h. Trip demand is assumed to be 6308 trips/h uniformly distributed among all the nodes with an only one destination.

In Figure 3, three paths from different origins to the destination, with arrows showing the circulation direction, are depicted. The nodes and links identified with numbers and letters, respectively, correspond to those used in the following figures to show the numerical results.

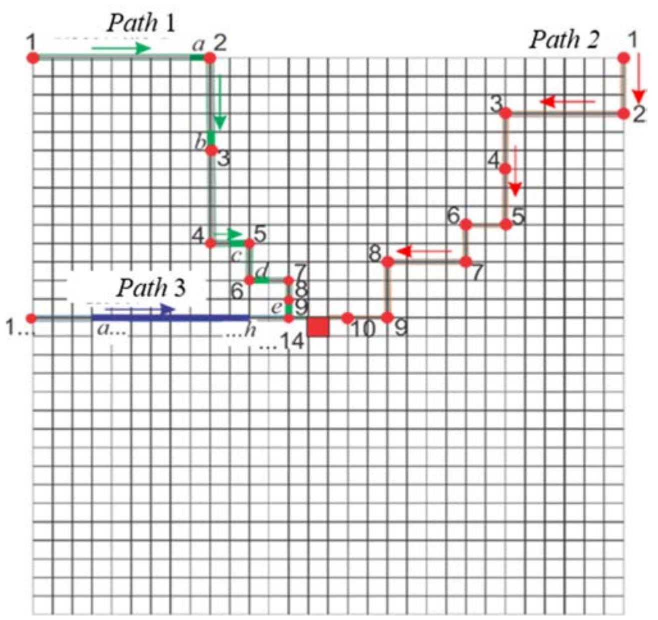

Fig. 3 – Scheme of the transportation network under analysis.

To solve the TAP corresponding to the described network, the explained methodology is applied using two different meshes, one of 16 elements (shown in Figure 4) and the other of 64 elements.

Each element has been assumed to be rectangular, with four main nodes (one per vertex). Bi-linear interpolation functions have been adopted. That is to say, they have the generic form $a_K(b_K - x)(c_K - y)$, where constants a_K, b_K, c_K are determined in such a way the following conditions are verified: $N_K^e = 1$ if $(x,y) = \left(x_K, y_K\right)$, and $N_K^e = 0$ if (x,y) correspond to any other main node.

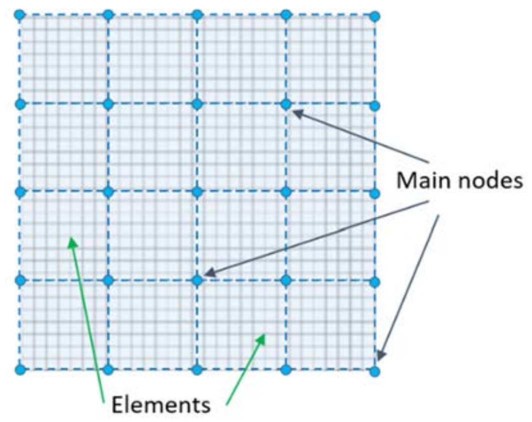

Fig. 4 – Scheme of the reduced model (considering 16 finite elements).

In order to perform a numerical study on the accuracy of the present methodology, TAP has also been solved: a) using the classical Beckmann's formulation along with Frank-Wolfe method (FW) and b) with the iterative Physarum method (Physarum) for the full network. The results of these two methods are considered to be exact.

Observe that Beckmann's formulation involves 1740 link flows as basic unknowns, Physarum solution to the full network involves 900 travel times (one for each node) while the FE reduced models of 16 and 64 finite elements involve only 25 and 81 main unknowns, respectively.

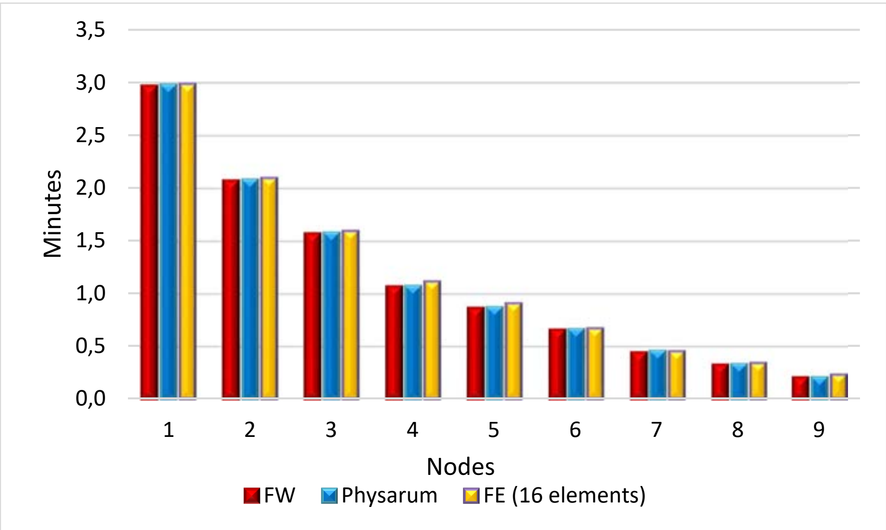

Fig. 5 – Travel times u_i from nodes corresponding to Path 1.

In Figure 5 a comparison of travel times obtained with FW, Physarum and FE (16 elements) for the nodes of Path 1 is shown. A very good agreement between the values obtained with all the models is observed. The same observation is valid for the nodes corresponding to Path 2 (Figure 6).

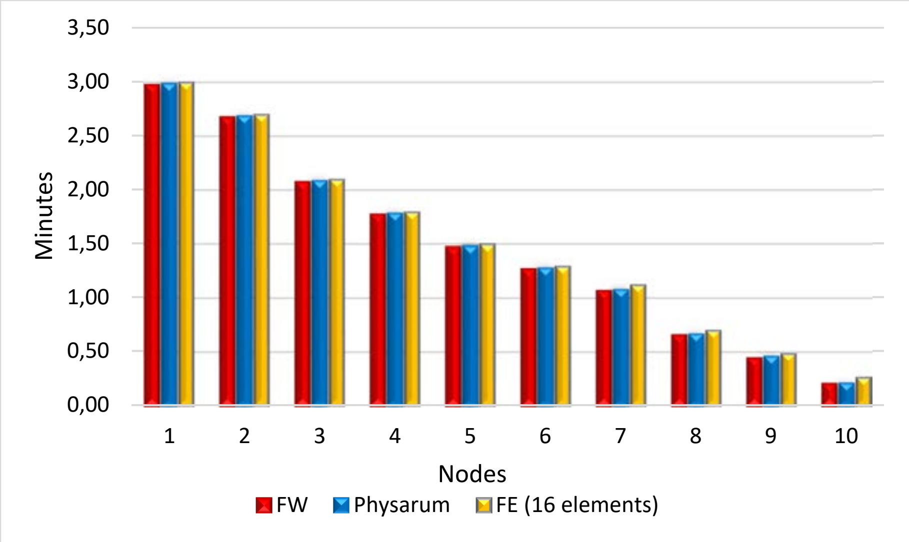

Fig. 6 – Travel times u_i from nodes corresponding to Path 2.

In Figure 7, a comparison for link travel times (expressed as the ratio between link travel time and free link travel time) determined by Physarum and the reduced FE (16 and 64 finite elements) for different links of Path 1, is shown. As observed, the results are almost identical except for link *e*, where the FE reduced model with 16 elements presents an error of approximately 10%, and the FE reduced model, with 64 elements, an error less than 5%.

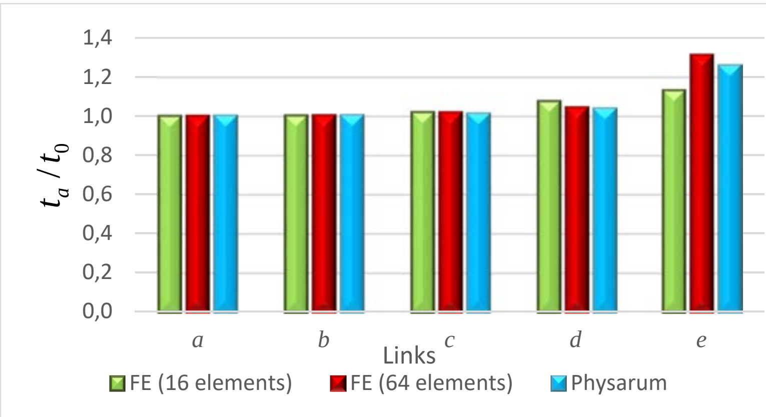

Fig. 7– Ratio between link travel time and free link travel time t_a / t_0 on links of Path 1

On the other hand, in Figure 8, a comparison for the link flows corresponding to Path 1, obtained by means of Physarum and the FE reduced model (64 elements), is shown. The maximum error of the reduced model is of 8% approximately.

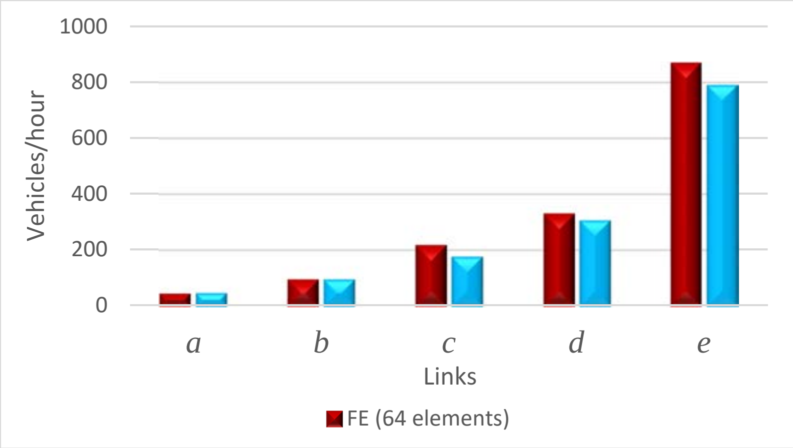

Fig. 8 – Link flows ($\bar{g}_a$) for Path 1.

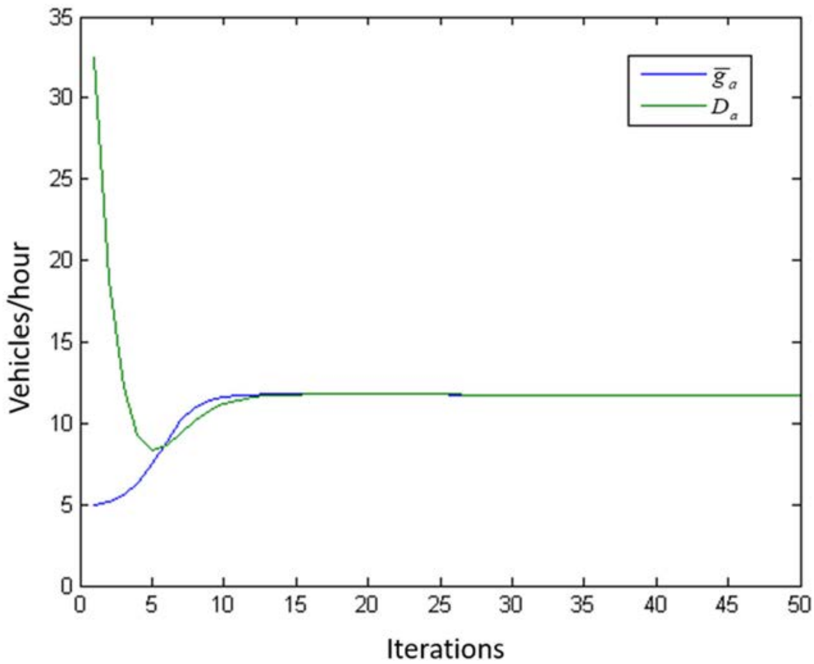

Fig. 9 – Convergence of the methodology in terms of traffic flow on the first link of Path 1 using the 64 FE reduced model.

The iterative procedure converges quickly, as can be observed in Figures 9 and 10. Figure 9 shows the convergence of D_a^d and $\bar{g}_a$ for the first link of Path 1. Convergence is achieved in less than 15 iterations. It is interesting to note that this convergence is reached even when the link is practically decongested. Figure 10 shows a similar information for the last link (*e*) of the same path. Although this link is congested, the convergence is also achieved in the same number of iterations.

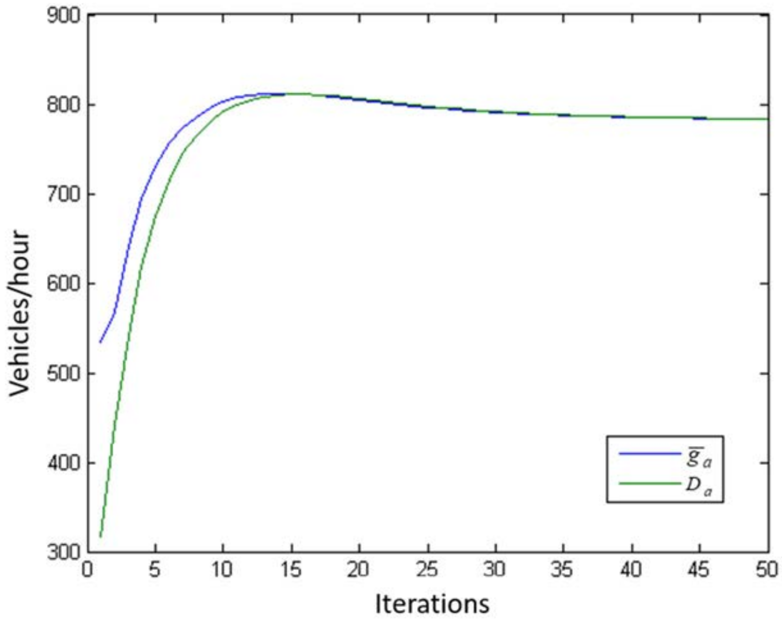

Fig. 10 – Convergence of the methodology in terms of traffic flow on the last link (*e*) of Path 1 using the 64 FE reduced model.

Finally, in Figure 11, a comparison of the convergence behaviour shown by Physarum, 16 FE and 64 FE reduced models, is shown in terms of the travel time from node 1 of Path 3 until the destination. As can be seen, the three approaches show a similar convergence behaviour.

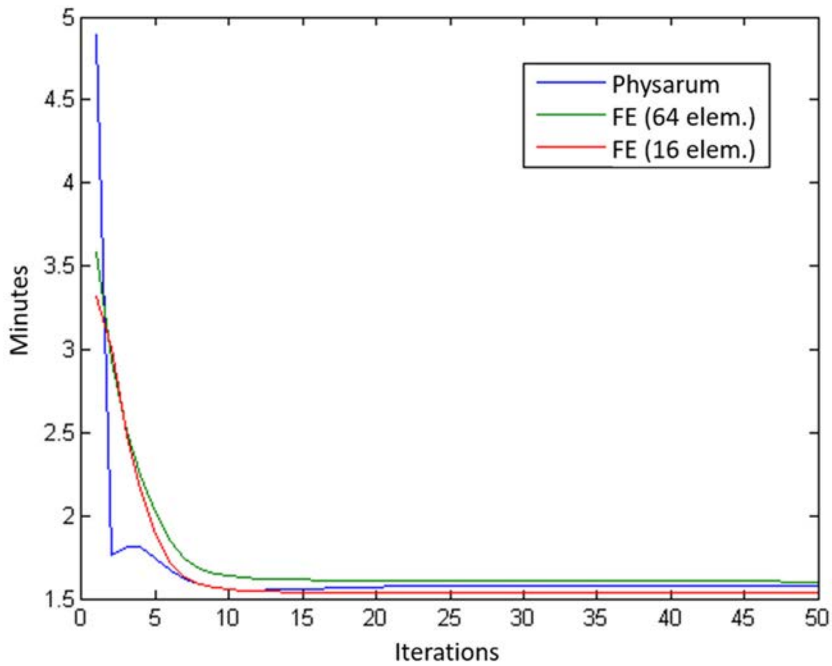

Fig. 11 – Convergence behaviour of travel time at node 1 of Path 3 for Physarum, 16 FE and 64 FE reduced models.

7. CONCLUSIONS

A finite element approach for reducing TAP unknowns is presented. This methodology employs an efficient iterative technique (Physarum analogy) to solve the governing non-linear equation system taking travel times as basic unknowns. This procedure works appropriately, even in presence of links with very low flow (avoiding indeterminacy of the system). The present approach allows a notable reduction of unknowns (more than 100 times in the analysed example), maintaining an accuracy similar to the full model, with an important reduction of the computing time. The methodology can be easily programmed in a context of parallel computing.

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SIMULACIÓN Y ANÁLISIS DE TRÁFICO DENTRO DEL ESTUDIO INFORMATIVO DE LA AUTOVÍA ORBITAL B-40 EN BARCELONA

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RESUMEN

A la hora de planificar nuevas vías, es importante utilizar todas las herramientas que estén a nuestro alcance para optimizar su diseño, de modo que no caigamos en infra o sobredimensionamientos, que pueden provocar un funcionamiento peor al esperado o un coste mucho mayor al necesario, respectivamente. Por ello, las herramientas de macrosimulación de tráfico pueden ser un interesante apoyo para este fin.

En el presente artículo, se va a exponer un caso práctico en el que el empleo de dichas herramientas informáticas ha permitido realizar un dimensionamiento más idóneo en cuanto al número de carriles de una nueva vía. En concreto, se trata del Estudio Informativo de la Autovía Orbital B-40, en el que se han utilizado técnicas de macrosimulación de tráfico para estimar las captaciones de demanda de las diferentes alternativas consideradas, y para finalmente calcular el Nivel de Servicio previsto en cada una de ellas en los diferentes horizontes temporales establecidos.

Los resultados obtenidos han permitido afinar el diseño de dicha Autovía, y la metodología empleada puede ser un ejemplo válido para otros casos de estudio similares.

1. INTRODUCCIÓN

Dentro de los trabajos del Estudio Informativo de la Autovía Orbital de Barcelona B-40 -tramo Terrassa-Granollers (enlace AP-7/C60)-, la empresa GPYO INNOVA, S.L. precisó la realización de un estudio de tráfico analizar las diferentes alternativas a plantear en dicho

Estudio Informativo. Conocida la experiencia del Grupo de Investigación LogIT (Logística e Ingeniería del Transporte) de la Universidad de Burgos en materias de tráfico, se les solicita colaboración para la elaboración del citado Estudio de Tráfico.

Para su realización, el trabajo se ha divido en dos fases, con diferentes alcances

- Fase A:
    - Estudio de antecedentes
    - Recopilación de datos básicos de tráfico, movilidad y socioeconómicos
    - Análisis de planes y programas de transporte
- Fase B
    - Delimitación del ámbito de estudio y planificación de encuestas
    - Realización y codificación de las encuestas, si se considerada necesario
    - Modelización de la situación actual: calibración matriz Origen/Destino, macrosimulación de la red y cálculo de capacidades y Niveles de Servicio por tramos
    - Prognosis de tráfico en distintos horizontes temporales y modelización de las situaciones futuras a considerar: actualización del modelo de macrosimulación para conocer tráfico futuro en cada tramo y cálculo de capacidades y Niveles de Servicio por tramos, en diferentes horizontes temporales, y para cada alternativa
    - Conclusiones

El presente artículo muestra los resultados obtenidos en el citado Estudio de Tráfico, y se estructura en 5 partes fundamentales. Tras una breve introducción y exposición de antecedentes, se incluye un resumen de los antecedentes y la información más relevante recogida en la Fase A. A continuación, se muestran las bases metodológicas seguidas. Por último, se muestran los resultados del modelo de asignación y de los cálculos de Niveles de Servicio. Finalmente, se muestra un resumen de las principales conclusiones extraídas del estudio completo.

2. DATOS BÁSICOS

La denominada autovía Orbital de Barcelona, que discurrirá entre las localidades de Terrassa y Granollers, atravesando diversos municipios del entorno en función de la alternativa finalmente seleccionada, tiene una funcionalidad múltiple, sirviendo para facilitar diversas tipologías de desplazamientos:

- Tráficos entre el centro de España y el Levante con Gerona y Europa.
- Movimientos longitudinales entre localidades del corredor.

- Ofreciendo una nueva vía de circunvalación para el municipio de Barcelona, alejada de la congestión provocada por la ciudad y sus vías de acceso y comunicando los grandes municipios del área (Terrassa, Sabadell y Granollers). El cierre de dicha Ronda es una de las actuaciones previstas en el Plan de Infraestructuras, Trasporte y Vivienda 2012-2024 PITVI (Ministerio de Fomento, 2015), dentro de las obras de circunvalación, así como en el Plan de Infraestructuras del Transporte de Cataluña (Generalitat de Cataluña, 2006).

2.1 Datos socioeconómicos

La población del área de análisis superaba los 670.000 habitantes en 2016, representando prácticamente el 12% de la población de la provincia de Barcelona. Los principales núcleos urbanos de la misma son Terrassa y Sabadell (origen del tramo objeto de estudio) con más de 200.000 habitantes, seguido con Granollers (fin del tramo objeto de estudio) con más de 60.000 habitantes. Estos tres municipios aglutinan el 72% de la población de la zona.

Todos los municipios del entorno han aumentado notablemente su población desde 2016, con tasas de crecimiento superiores al 10-20% en algunos casos. En su conjunto, estos municipios han incrementado su población con una tasa de crecimiento anual acumulada claramente superior a la tasa de la provincia de Barcelona, aunque se aprecia una ralentización en dicho crecimiento a partir del año 2010-2012.

Por otra parte, la tasa de motorización de la zona afectada por el cierre de la Orbital, muestra unas elevadas tasas en todos los municipios directamente afectados por la traza.

Los valores en casi todos los municipios son superiores en el año 2015 a la media de la provincia de Barcelona.

2.2 Datos de movilidad

En cuanto a las pautas de movilidad, el 78,8% de los desplazamientos de Cataluña se producen en día laborable, con una media de 24,4 desplazamientos/día y 3,57 desplazamientos/persona. El tiempo medio de desplazamiento ronda los 15 minutos para los viajes intramunicipales y los 31,50 minutos para los intermunicipales.

Si analizamos el reparto modal, observamos que la proporción en día laborable es de un 40,6% vehículo privado, 14,3% transporte público y 45,1% en modos no motorizados. Pero en día festivo, la proporción de viajes en vehículo privado alcanza un 49,1%, y el transporte público desciende hasta un 6,4%. Las ocupaciones medias de los vehículos (turismos) son de 1,22 personas/vehículo en día laborable, y de 1,40 en sábado y festivo.

Analizando la distribución horaria de los desplazamientos, vemos, en los días laborables, dos grandes puntas: una por la mañana, correspondiendo a las horas de entrada a los lugares de trabajo/estudio, y una por la tarde, en la salida.

En sábados y festivos ese patrón horario se altera bruscamente, siendo la punta de la mañana más suave y además en horas más tardías, distribuyéndose más el tráfico entre las 24 horas del día.

2.3 Planeamiento urbanístico

Finalmente, se ha analizado los diferentes desarrollos urbanísticos de la zona que pueden afectar al tráfico en la Ronda Orbital, no hallándose ninguna incompatibilidad entre los posibles corredores analizados y la planificación urbanística del área de estudio. Tampoco se observan grandes bolsas de suelo urbanizable (residencial o para actividades económicas) que puedan ser especialmente relevantes para el tráfico de la zona (más allá del crecimiento habitual ya observado).

2.4 Datos de tráfico

Para el análisis de tráfico en el entorno, se ha atendido a todas aquellas vías paralelas a la nueva actuación y perpendiculares a la misma, con independencia de su titularidad. Así se ha recopilado datos de 6 estaciones pertenecientes al Ministerio de Fomento (una de ellas secundaria y el resto de cobertura), y de 44 estaciones de la Generalitat de Cataluña (entre las que sí hay estaciones permanentes). Los datos han sido obtenidos del Mapa de Tráfico del 2015 (Ministerio de Fomento, 2016a) y del Plan de Aforos 2015 (Generalitat de Cataluña, 2016).

Las vías de la zona bajo titularidad estatal soportan unos índices de intensidad diaria muy elevados, con elevados porcentajes de pesados, que en algunos casos superan el 20% de la IMD. El tráfico existente en el corredor de la A-7 oscila entre los 83.000 y 138.000 vehículos diarios, siendo superior en el acceso al entorno de Barcelona desde el levante español que desde la frontera francesa. Además, el tramo de mayor intensidad corresponde al que conjuntamente suman la A-7 (ahora AP-7N) en el tronco y la B-30 en las vías de servicio, entre las carreteras de acceso a Barcelona C-16 y C-58, si bien dicho tráfico ha sufrido un importante descenso desde el 2014.

Como complemento, se han analizado de forma exhaustiva los datos concretos de 3 estaciones consideradas de especial relevancia: 2 permanentes (la 10181608, ubicada en la C-58, y la 17-308, en la C-17) y una secundaria (la B-220-2 en la B-30). En ellas se observan las siguientes pautas:

- La intensidad existente en esta estación del corredor cuenta con un tráfico constante a lo largo del año excepto en el mes de agosto que se produce un constante a lo largo del año excepto en el mes de agosto que se produce un descenso debido al periodo vacacional. Además, se producen en diciembre-enero y abril-mayo otros valles aunque menos marcados.
- La distribución del tráfico en la semana es relativamente uniforme en los días laborables, con una punta durante el viernes, y un importante descenso los fines de

semana, especialmente el domingo. Este comportamiento es similar para los vehículos ligeros y pesados, aunque la diferencia en porcentaje sobre la IMD entre laborables y fines de semana es mucho más marcada en el caso de los vehículos pesados.

- Finalmente, de los diagramas de frecuencias acumuladas de intensidades horarias, se observa que el tráfico para la hora 30 (IH-30) ronda el 8% de la IMD.

3. METODOLOGÍA

3.1 Delimitación y zonificación del área de estudio

Los términos municipales directamente afectados por el trazado de los distintos corredores considerados son los siguientes: L'Ametlla del Vallès, Caldes de Montbui, Canovelles, Cardedeu, Castellar del Vallès, Les Franqueses del Vallès, La Garriga, Granollers, Lliçà d'Amunt, Matadepera, Palau de Plegamans, Polinyà, La Roca del Vallès, Sabadell, Santa Eulàlia de Ronçana, Sentmenat y Terrassa. Sin embargo, obviamente el estudio no puede limitarse a considerar dichos municipios, sino que se ha extendido a un ámbito territorial, mucho mayor, que incluye toda la provincia de Barcelona, así como las provincias limítrofes, e incluso el resto de España.

El modelo finalmente elaborado se compone de 38 zonas, con desagregación en términos municipales en la zona de influencia más directa del nuevo tramo de Cierre de la Autovía Orbital de Barcelona, y en menor grado de detalle al alejarse de la zona de la actuación.

Todas las zonas están compuestas por municipios de forma individual o agregaciones de los mismos. La Figura 1 muestra la zonificación empleada.

Fig. 1 – Distribución geográfica de zonas

3.2 Obtención de la matriz origen/destino base

La principal fuente de datos utilizada en el proyecto han sido datos anonimizados de telefonía móvil procedentes de un operador de red. Adicionalmente, se han utilizado datos de usos del suelo y datos de población residente en España. Para ello, se ha contado con el apoyo de Kineo Mobility Analytics, una empresa tecnológica experta en el análisis de datos geolocalizados procedentes de dispositivos móviles y su fusión con otras fuentes de datos para proporcionar información sobre movilidad y demanda de transporte.

Como fuente de datos principal para el análisis de la movilidad general de la población se utilizaron datos anonimizados de telefonía móvil proporcionados por el grupo Orange España (Orange, Jazztel, Amena y Simyo), que cuenta con una cuota de mercado entorno al 27 % (CNMC, marzo de 2018). Estos datos contienen las posiciones geolocalizadas de los dispositivos móviles tanto para eventos activos (llamadas, mensajes SMS, conexiones a Internet) como para determinados eventos pasivos (cambios de áreas de cobertura, actualización de las conexiones a Internet, etc.), proporcionando una granularidad temporal muy elevada, que permite determinar con alto nivel de detalle la localización del dispositivo a lo largo del día.

En cuanto a la resolución espacial, se dispone de información de localización del dispositivo móvil a nivel de antena, lo que supone una precisión espacial de decenas/cientos de metros en ciudad y hasta varios kilómetros en zonas rurales.

Los datos proporcionados por el operador también incluyen información socio-demográfica ligada a los usuarios, como la edad y el género. Los datos utilizados en este estudio se corresponden con la actividad registrada durante el mes de marzo de 2018.

En cuanto a la población, para los procesos de elevación de la muestra se han utilizado los datos procedentes del padrón de habitantes. Se ha considerado a la población residente en España con edad superior a 16 años.

Agregando los diferentes motivos de viaje considerados, se obtuvo una matriz Origen/Destino global para un día laborable medio. Finalmente, atendiendo a los resultados obtenidos en la Fase A, a partir de la encuesta Movilia, observamos que la proporción de viajes en vehículo privado en día laborable es de un 40,6% vehículo privado, y que la ocupación media de los vehículos (turismos) son de 1,22 personas/vehículo en día laborable.

Además, es necesario tener en cuenta el factor K, correspondiente a las intensidades horarias correspondientes a la Hora 30, 50 o 100, que resulta de alrededor de un 8,3% para la zona de estudio (tomando un valor conservador). Teniendo en cuenta todos estos elementos correctores, se obtuvieron las matrices base finales de vehículos ligeros y pesados, que arrojaron valores similares a los obtenidos en la encuesta Movilia para el total de la provincia de Barcelona, lo que aporta confianza en la fiabilidad del proceso empleado para su obtención.

Sin embargo, al aplicar dichas matrices al modelo de red, no se reproducen con exactitud los valores de tráfico registrado en las estaciones reales de aforo. Por tanto, será necesario hacer un último ajuste, que se describirá en capítulos posteriores, una vez esté elaborado el modelo de oferta o modelo de red.

3.3 Modelo de oferta

El horizonte inicial de modelización fue el año 2016, último año con datos completos de tráfico disponibles en la zona. Se incluyó en la modelización la totalidad de las principales infraestructuras viarias comprendidas en el área comprendida por los tramos existentes de la B-40, ronda litoral de Barcelona y el Eje Transversal C-25, que comunica la A-7 al sur de Girona, con la A-2 a la altura de Cervera, en la provincia de Lleida. El escenario se completó con la inclusión de otras vías de la red de carreteras de la provincia de Barcelona, que podrían suponer cierta competencia con la nueva infraestructura, o que pueden influir en los resultados del modelo.

En la Figura 2 se muestra el grafo explicativo de la red actual modelizada en el escenario base, junto con las conexiones de los centroides dicha red.

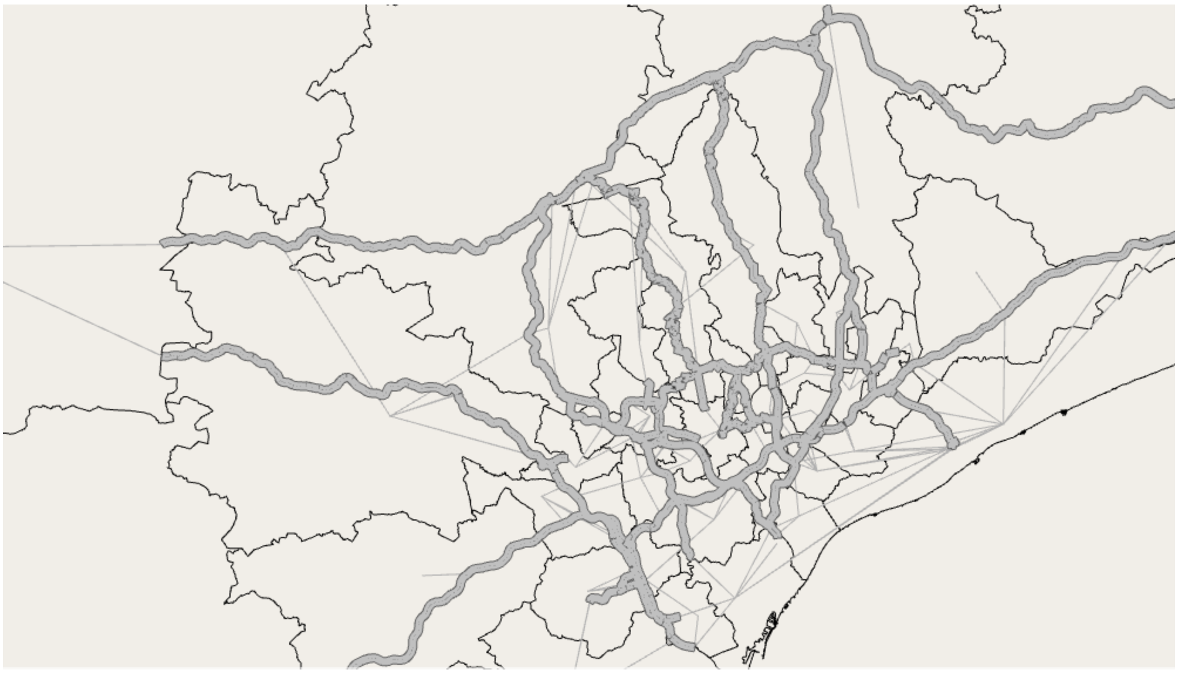

Fig. 2 – Red actual base

En total, la red actual modelizada se compone de 1232 secciones, 519 intersecciones, y de una longitud total de 1593 km (3251 km si desglosamos por carril), lo que muestra el alto grado de detalle conseguido en la misma, máxime si tenemos en cuenta la longitud total de la red de carreteras de la provincia de Barcelona, que era de 3929 km en 2016.

La red prevista para la modelización viaria futura, incluye la red actual, a la que se suma el cierre de la Orbital, desde Abrera hasta Terrassa, y desde Terrassa hacia Granollers (que consistirá en el tramo de actuación que se está evaluando). Además, se han analizado diferentes actuaciones previstas en la red, como el desdoblamiento de la C-59 entre Mollet y Caldes de Montbui, que en los escenarios futuros se ha considerado como una autovía con velocidad de proyecto 120 km/h.

El Estudio Informativo contempla seis posibles alternativas, que se estructuran en torno a dos corredores principales –Norte y Sur–. La Figura 3 muestra las diferentes alternativas consideradas.

Fig. 3 – Alternativas de trazado

3.4 Modelo de asignación

El modelo de asignación se ha llevado a cabo sobre el software AIMSUN, mediante herramientas de macrosimulación, más adaptadas para el tipo de estudio que se describe. Cada tramo de la red se ha ido delineando en dicho software a partir de la información base contenida en la plataforma OpenStreetMap, actualizando en caso necesario las infraestructuras nuevas o modificadas con respecto a la misma, obviamente.

Se ha calculado, para cada tramo, el Coste Generalizado de Viaje, con una expresión similar a la que sigue:

$$CG = \frac{t_{recorrido} \cdot VST}{60} + peaje_{por\ km} \cdot Longitud \quad (1)$$

La variable VST, valor subjetivo del tiempo, se ha extraído de la Nota de Servicio 3/2014, sobre "Prescripciones y recomendaciones técnicas relativas a los contenidos mínimos a incluir en los estudios de rentabilidad de los estudios informativos de la Subdirección General de Estudios y Proyectos", del Ministerio de Fomento.

Se ha considerado un factor de equivalencia para los vehículos pesados inicialmente igual a 3, correspondiente a terreno ondulado. Así, realizaremos la asignación bajo el método de equilibrio simple de distribución estadística con restricciones de capacidad y caminos múltiples, aplicando una función de congestión, que hace que el tiempo de recorrido de cada tramo aumente en función del tráfico que está soportando. Esta función difiere según el tipo de carreteras, y su formulación, tanto para vehículos pesados como para vehículos ligeros, es del tipo:

$$t_{recorrido} = t_0 \cdot máx\left[1 + \alpha \cdot \left(\frac{Vol}{c}\right)^{\beta}; 1 + \alpha \cdot 0{,}985^{\beta} + 15 \cdot \alpha \cdot \beta \cdot 0{,}985^{\gamma} \cdot \left(\frac{Vol}{c} - 0{,}985\right)\right] \quad (2)$$

El tráfico que soporta cada tramo de red influye en la velocidad del mismo, y ésta a su vez vuelve a influir en la idoneidad de dicho tramo, es decir, en el tráfico que capta. Así se genera una situación en la que ambas cuestiones –tráfico soportado y velocidad resultante– deben converger, según lo establecido en los modelos de equilibrio de usuario (Wardrop, 1952).

Dado que en nuestro caso las funciones de coste de cada arco dependen únicamente del flujo en dicho arco, es problema es separable y se puede resolver de una forma relativamente rápida mediante algoritmos como el de Frank & Wolfe (1956). Los criterios de convergencia establecidos fueron un límite máximo de 100 iteraciones o una diferencia de un 0,1% entre una iteración y la siguiente.

3.5 Ajuste de matrices origen/destino a partir de datos de aforo

Una vez que tenemos las matrices base de origen/destino (O/D) y el modelo de red, podemos introducir las primeras en el segundo y determinar el tráfico sobre cada tramo de vía. Sin embargo, es habitual (y nuestro caso no es una excepción) que el volumen de tráfico resultante no coincida con el realmente registrado en las estaciones de aforo dispuestas en la red. Por ello, es conveniente ajustar dichas matrices base, modificándolas ligeramente para que, al asignar el tráfico en la situación inicial, sea similar al realmente detectado en cada vía.

Desde cierto punto de vista, el problema de recalcular las matrices origen/destino a partir de datos de aforo se puede considerar como la inversa a un problema de asignación. En un problema de asignación, se conocen los flujos entre cada par de centroides, así como las características de la red y el modelo de comportamiento de los vehículos, y se busca encontrar el tráfico soportado por cada tramo de red. En el caso contrario, se trata de obtener una matriz O/D modificada, partiendo del tráfico realmente registrado, y teniendo en cuenta las características de la red y los modelos de comportamiento del usuario (Cascetta, 2001).

En nuestro estudio, se ha implementado una metodología de equilibrio de usuario, empleando el algoritmo de Frank & Wolfe (1956) en cada iteración, y estableciendo en este caso un número máximo de 50 iteraciones completas (cada una de ellas conteniendo un ajuste Fran & Wolfe de 100 sub-iteraciones internas). Finalmente, se han obtenido sendas matrices OD ajustadas para vehículos ligeros y pesados para el escenario base del año 2016.

Para validar la fiabilidad de dichas matrices, se han comparado los datos resultantes de la asignación de las mismas con los tráficos registrados en la red, tanto para tráfico ligero como pesado. Así, tal y como establece la Nota de Servicio 5/2014 del Ministerio de Fomento, sobre “Prescripciones y recomendaciones técnicas para la realización de estudios de tráfico de los Estudios Informativos, Anteproyectos y Proyectos de carreteras”, se ha verificado la validación del modelo a través de las dos metodologías que siguen:

- Análisis de regresión. Se elaboró una gráfica de dispersión, con las parejas de valores de volúmenes de tráfico obtenidos en cada tramo mediante la asignación (eje vertical) y mediante la observación real mediante aforos (eje horizontal). Sobre él, se ha ajustado una recta de regresión, de la que se comprueba que el valor de la pendiente es cercano a 1, el valor del intercepto en el eje de ordenadas es cercano a 0 (teniendo en cuenta el volumen de tráfico del que hablamos) y el coeficiente de determinación R^2 es claramente mayor que 0,7.
- Indicador %RMSE (raíz cuadrada del error cuadrático potencial).
  Tal y como se indica en la NS 5/2014 del Ministerio de Fomento, al tratarse de una red compleja y con muchos tramos, se ha dividido el total de observaciones en dos grupos: una muestra de contraste de al menos el 10% (en nuestro caso, del 28%, seleccionados aleatoriamente) y el resto de valores. Para cada grupo, se comprobó cómo ambos valores de %RMSE son inferiores al 30%.

3.6 Prognosis de tráfico y horizontes temporales considerados

Una vez calibrado y ajustado correctamente tanto el modelo como las matrices base Origen/Destino e de vehículos ligeros y pesados, el último paso, antes de proceder a estimar el tráfico a soportar por la nueva vía, es determinar los horizontes temporales a considerar, así como el crecimiento del tráfico previsto.

En cuanto a los horizontes temporales considerados, se parte del año 2025, en que se prevé que pueda estar puesta en servicio la infraestructura analizada, y se proseguirá durante 20 años más, en intervalos de 5 años. Así, los horizontes a calcular son los siguientes: 2025, 2030, 2035, 2040 y 2045.

No es necesario añadir situaciones intermedias a éstas, ya que el resto de actuaciones en el área de estudio se pueden asimilar perfectamente a los períodos anteriores.

Por otra parte, para el crecimiento estimado del tráfico, la Nota de Servicio 5/2014 del Ministerio de Fomento recomienda tener en cuenta los valores incluidos en la Orden FOM/3317/2010, “Instrucción para la mejora de la eficiencia en la ejecución de las obras públicas de infraestructuras ferroviarias, carreteras y aeropuertos” del Ministerio de Fomento. En ésta, se establece que el incremento anual acumulativo debe ser del 1,08% en el período de 2013 a 2016 y del 1,44% desde el año 2017 en adelante. Sin embargo, para analizar si estas tasas de crecimiento son suficientes para el área de estudio, se ha procedido a calcular tasas específicas de crecimiento para cada zona, tanto para vehículos ligeros como pesados, a fin de corregir estos valores en caso necesario.

Así, para analizar el crecimiento del tráfico ligero, se ha optado por extraer las series de población correspondientes a cada zona considerada, y se ha calculado una tasa anual para cada zona, introduciendo un peso mayor para los últimos años, como suele ser habitual. A partir de dicho valor, se han estimado las prognosis de población para los horizontes temporales considerados, y finalmente la tasa de crecimiento con respecto a nuestro escenario base, situado en el año 2016. Aunque las tasas de crecimiento resultantes son inferiores a las propuestas en la NS 5/2014, se considera más recomendable utilizar éstas, ya que se ajustan mejor a la realidad de la zona de estudio, y permiten establecer diferentes tasas de crecimiento para cada zona.

En cuanto al tráfico pesado, se ha procedido de forma similar, aunque en este caso, en lugar de la variable de población, se ha optado por otra mucho más orientada al tráfico de mercancías, como es el Índice de Producción Industrial (IPI), que tiene en cuenta la producción de bienes de consumo (distinguiendo entre consumo perecedero y no perecedero), bienes de equipo, bienes intermedios y energía. Con una formulación similar a la empleada para el tráfico ligero, se ha obtenido una media ponderada. De nuevo, esta tasa de crecimiento anual es inferior a la propuesta en la NS 5/2014, aunque se sigue considerando más conveniente emplear ésta, ya que es un valor más adaptado a la zona de estudio, en lugar de un valor agregado para todo el territorio nacional.

Por último, dado que no se dispone de datos de encuestas, no se ha podido elaborar modelos de generación de viaje sensibles a las variables de accesibilidad. Por ello, se ha optado por emplear la elasticidad media de la demanda respecto al tiempo de viaje en vías de tipo similar para determinar el nuevo tráfico inducido por la apertura de la nueva vía.

Considerando unas elasticidades de la demanda respecto al tiempo de -0,45 y -1,0 a corto y largo plazo, respectivamente, (Guirao, 2000), resultaría que el tráfico inducido es de un 1,69% a corto plazo y un 3,77% a largo plazo, respecto del total de viajes.

Se puede apreciar que el tráfico inducido por la nueva vía resulta un valor relativamente bajo con respecto al total de viajes, lo que resulta comprensible al no existir cambios en los usos del suelo condicionados a la realización de la actuación objeto del Estudio, sino que básicamente se trata de una redistribución de viajes como consecuencia de cambios en destinos.

4. RESULTADOS

Como resultado del proceso anteriormente indicado, se han realizado asignaciones para las seis alternativas seleccionadas en los años 2025, 2030, 2035, 2040 y 2045. Finalmente, en función de las condiciones de circulación, se calculan los Niveles de Servicio, a partir del procedimiento indicado en el Manual de Capacidad (TRB, 2016).

En primer lugar, se calcularon los resultados correspondientes a la hipótesis inicial de disponer suponiendo 2 carriles por sentido a lo largo de todo el recorrido. Sin embargo, se apreció que el Nivel de Servicio en la hora punta del año horizonte (2045) era inadmisible en los tramos iniciales, por lo que la configuración final seleccionada fue la disposición de 3 carriles por sentido desde la conexión con la actual B-40 hasta el enlace de Sabadell Oeste.

Como se puede observar en las Tablas 1 y 2 y en las Figuras 4 a 9, aunque los resultados son similares para todas las alternativas (dado el escaso margen de trazado para las mismas), la IMD global en el año estimado de puesta en servicio (2025) varía entre los 44.300 y los 46.500 vehículos/día, siendo las alternativas de mayor captación la 1 y la 4, es decir, las que discurren más al Sur del corredor. En el escenario del año 2045, los valores de IMD rondan entre los 52.500 y los 55.400 vehículos/día. El volumen de pesados se sitúa, en todos los casos, alrededor del 10-12%, en promedio.

Estos volúmenes implican que la Autovía Orbital de Barcelona sería capaz de captar alrededor de un 30% del tráfico de largo recorrido que actualmente transita por la B-30 y la AP-7 (unos 70.000 vehículos/día), lo que respalda su funcionalidad esperada como catalizadora del tráfico de largo recorrido ajeno a la metrópoli barcelonesa. Además, aporta un importante servicio a las localidades cercanas, al permitir que gran parte del tráfico que discurre entre ellas utilice la nueva vía.

En cuanto a Niveles de Servicio, en el año de puesta en servicio se alcanzaría un Nivel D únicamente en las Alternativas 1 y 4 (aquéllas que más tráfico captan), mientras que, en el año horizonte, 2045, dicha situación es generalizada.

Las únicas excepciones a la Norma 3.1-IC de Trazado son las alternativas 1 y 4, en las que el Nivel de Servicio D en sus tramos inciales no cumple estrictamente lo establecido en la Instrucción de Trazado, aunque no se considera recomendable ampliar la sección en ellos a 4 carriles por sentido.

TRAMO/DETECTOR	SENTIDO	IMD TOTAL 2025						NS 2025					
		Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
conexión B-40 - Terrassa Este	PK desc	69.951	66.228	67.867	69.658	67.620	67.938	B	B	B	B	B	B
	PK asc							C	B	C	C	C	C
Terrassa Este - Sabadell Oeste	PK desc	89.926	86.368	88.022	89.636	87.778	88.058	C	C	C	C	C	C
	PK asc							D	C	C	D	C	C
Sabadell Oeste - Sabadell Este	PK desc	51.210	44.563	47.635	50.518	47.600	47.918	C	B	B	C	B	B
	PK asc							D	C	C	D	C	C
Sabadell Este - Sentmenat B-142	PK desc	48.169	46.243	47.583	48.120	47.516	47.482	C	C	B	C	B	B
	PK asc							C	C	C	C	C	C
Sentmenat B-142 - Caldes de Montbui C-59	PK desc	30.558	27.211	30.571	30.281	30.604	30.552	B	B	B	B	B	B
	PK asc							B	B	B	B	B	B
Caldes de Montbui C-59 - Lliçà d'Amunt BV-1602	PK desc	38.208	38.298	37.367	37.580	37.479	38.254	C	C	C	C	C	C
	PK asc							B	B	B	B	B	B
Lliçà d'Amunt BV-1602 - Canovelles C-17	PK desc	43.984	39.547	43.144	43.357	43.254	44.024	C	C	C	C	C	C
	PK asc							C	B	C	C	C	C
Canovelles C-17 - Les Franqueses del Vallès	PK desc	25.049	28.612	24.857	25.000	24.817	24.915	B	B	B	B	B	B
	PK asc							B	B	B	B	B	B
Les Franqueses del Vallès - C-151	PK desc	32.449	34.946	32.257	32.400	32.216	31.156	B	B	B	B	B	B
	PK asc							B	B	B	B	B	B
C-151 - AP-7	PK desc	35.859	31.242	35.666	35.781	35.608	26.954	B	B	B	B	B	B
	PK asc							B	B	B	B	B	B
PROMEDIO		**45.384**	**43.775**	**44.474**	**45.087**	**44.435**	**43.964**	**B**	**B**	**B**	**B**	**B**	**B**
Tráfico inducido (veh/día)		*767*	*740*	*752*	*762*	*751*	*743*						
Tráfico atraído de otros corredores (veh/día)		*44.617*	*43.036*	*43.722*	*44.325*	*43.684*	*43.221*						

Tabla 1 – Resumen de resultados – año de puesta en servicio (2025)

TRAMO/DETECTOR	SENTIDO	IMD TOTAL 2045						NS 2045					
		Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
conexión B-40 - Terrassa Este	PK desc	78.025	73.066	75.002	78.597	74.290	75.185	B	B	B	B	B	B
	PK asc							C	C	C	C	C	C
Terrassa Este - Sabadell Oeste	PK desc	104.176	99.077	101.192	104.724	100.637	101.360	D	C	C	D	C	C
	PK asc							D	D	D	D	D	D
Sabadell Oeste - Sabadell Este	PK desc	62.596	53.134	57.162	63.069	56.769	57.399	C	C	C	C	C	C
	PK asc							D	C	C	D	C	C
Sabadell Este - Sentmenat B-142	PK desc	55.358	52.218	54.310	55.523	54.396	54.112	C	C	C	C	C	C
	PK asc							D	D	C	D	C	C
Sentmenat B-142 - Caldes de Montbui C-59	PK desc	40.311	33.912	41.495	40.265	41.239	40.995	B	B	B	B	B	B
	PK asc							B	B	B	B	B	B
Caldes de Montbui C-59 - Lliçà d'Amunt BV-1602	PK desc	42.824	44.224	42.406	43.263	43.234	43.554	C	C	C	C	C	C
	PK asc							C	B	C	C	C	C
Lliçà d'Amunt BV-1602 - Canovelles C-17	PK desc	49.895	45.910	49.444	50.353	50.296	50.565	C	C	C	C	C	C
	PK asc							C	C	C	C	C	C
Canovelles C-17 - Les Franqueses del Vallès	PK desc	31.328	36.116	31.068	31.370	31.042	31.313	B	B	B	B	B	B
	PK asc							B	C	B	B	B	B
Les Franqueses del Vallès - C-151	PK desc	41.187	44.320	40.928	41.230	40.901	39.933	C	C	C	C	C	B
	PK asc							C	C	C	C	C	C
C-151 - AP-7	PK desc	45.371	42.757	45.087	45.388	45.146	37.861	C	C	C	C	C	C
	PK asc							C	C	C	C	C	B
PROMEDIO		**53.664**	**51.744**	**52.604**	**53.926**	**52.635**	**52.247**	**C**	**C**	**C**	**C**	**C**	**C**
Tráfico inducido (veh/día)		*2.023*	*1.951*	*1.983*	*2.033*	*1.984*	*1.970*						
Tráfico atraído de otros corredores (veh/día)		*51.641*	*49.793*	*50.621*	*51.893*	*50.651*	*50.277*						

Tabla 2 – Resumen de resultados – año horizonte (2045)

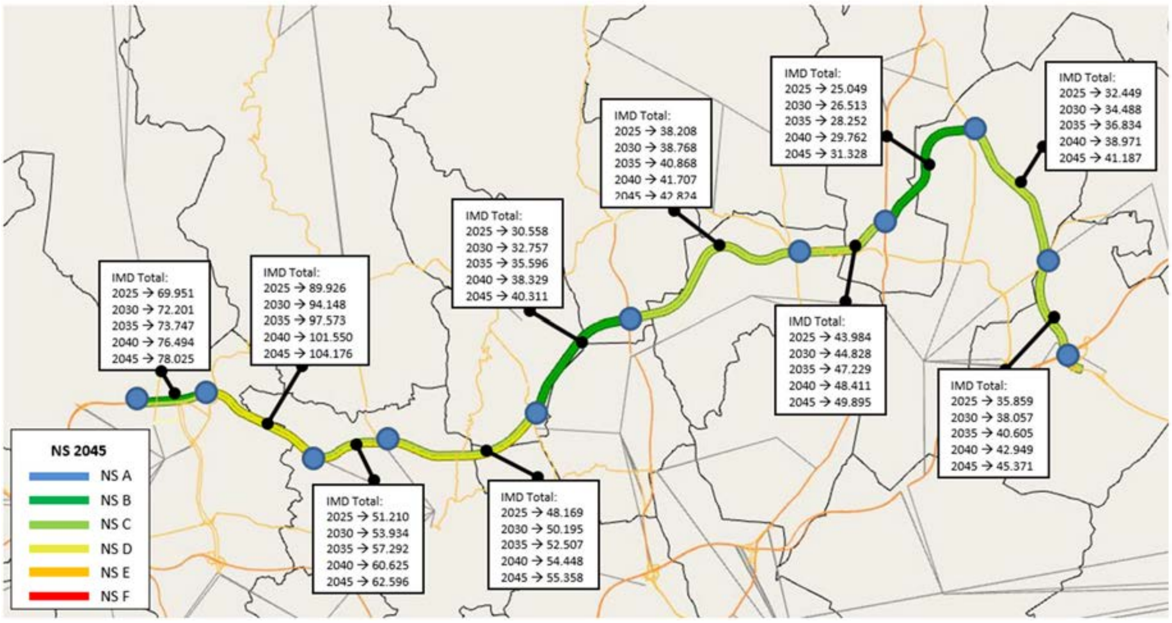

Fig. 4 – Resultados alternativa 1

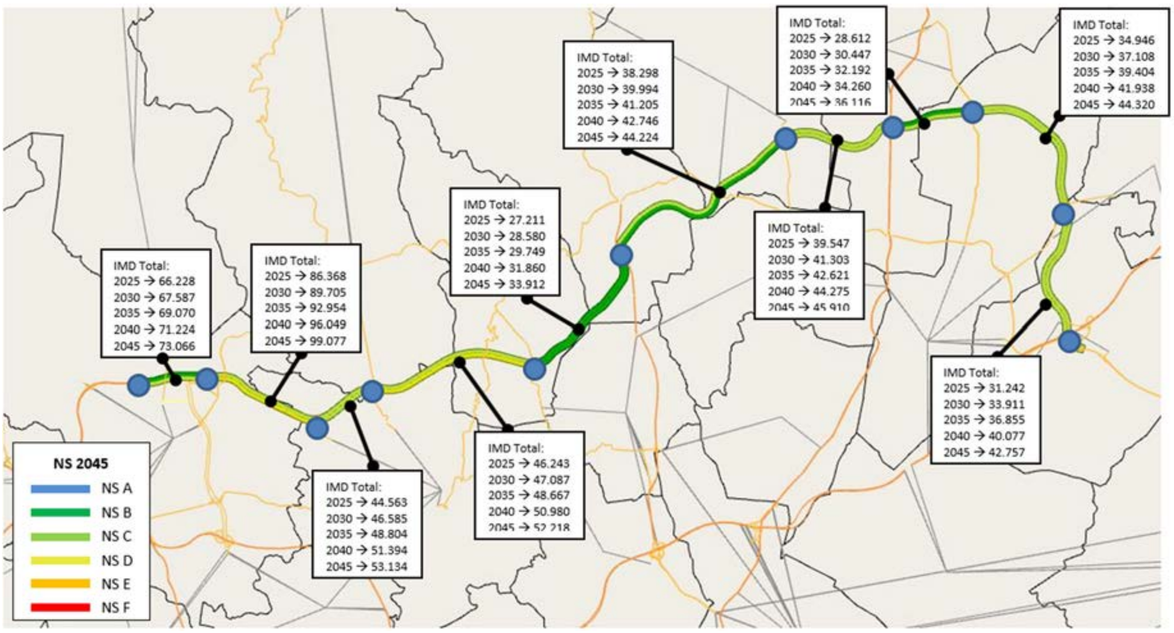

Fig. 5 – Resultados alternativa 2

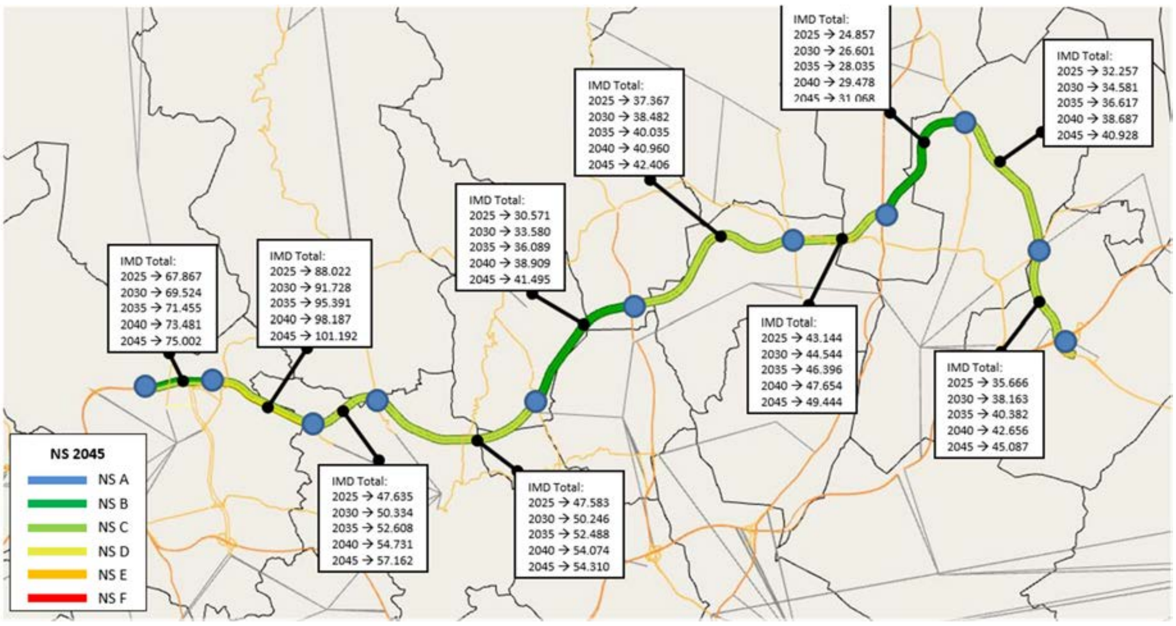

Fig. 6 – Resultados alternativa 3

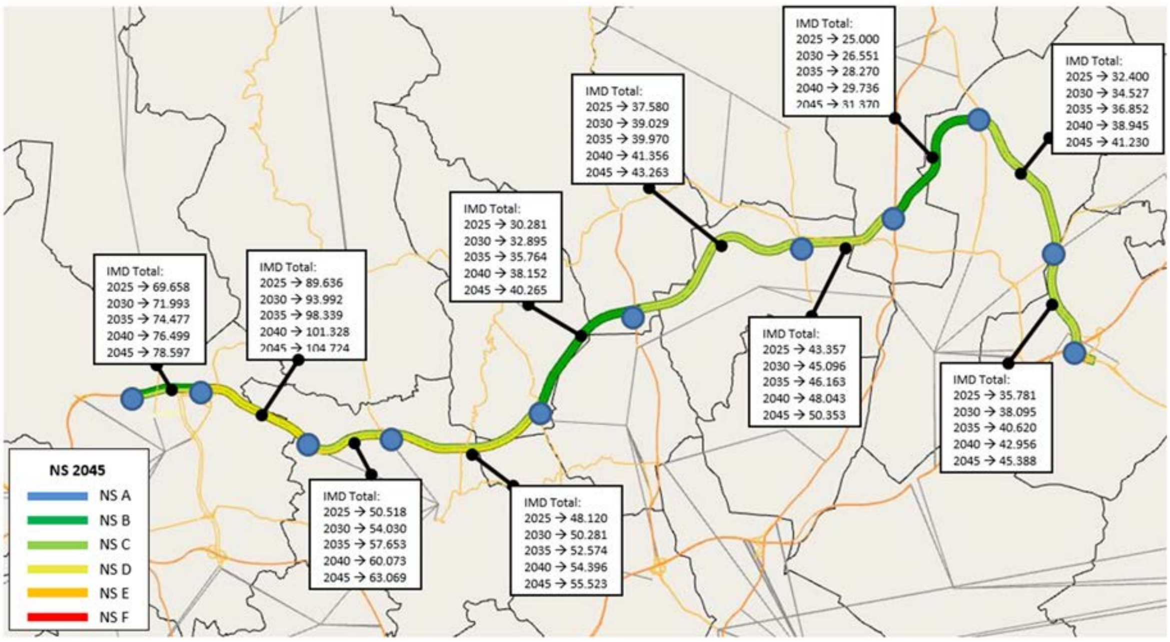

Fig. 7 – Resultados alternativa 4

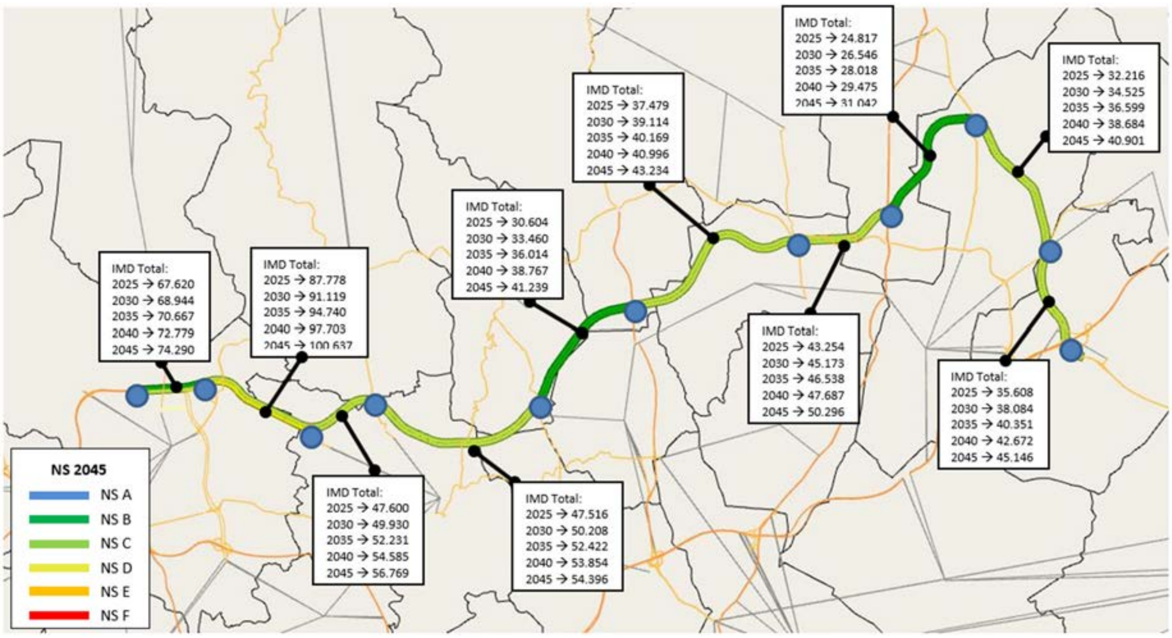

Fig. 8 – Resultados alternativa 5

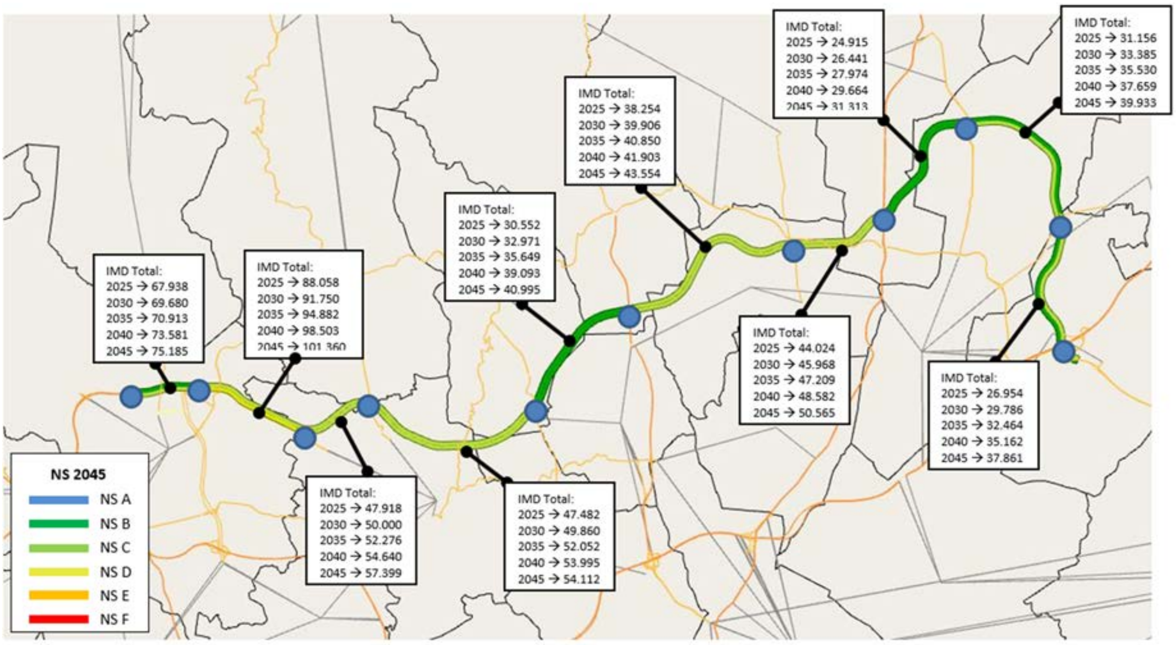

Fig. 9 – Resultados alternativa 6

5. CONCLUSIONES

El estudio informativo en análisis, en su fase A, planteó diversos corredores que discurren por varios municipios entre Terrassa, al inicio del estudio, y La Roca del Vallès, cerca de Granollers, en su final. Existe la previsión de dos grandes corredores, denominados: Corredor 1, que discurre por el Norte, y Corredor 2, por el Sur, que finalmente se han plasmado en 6 alternativas.

En la fase B, se incorporaron técnicas de macrosimulación de tráfico, mediante apoyo de software específico para tal fin, y se modelizaron las diferentes alternativas en varios horizontes temporales, comprendidos entre el año estimado de puesta en servicio, 2025, y el año horizonte, 2045. Con dichas herramientas, se ha podido realizar un mejor dimensionamiento de la red, evitando posibles Niveles de Servicio inadmisibles, y también costes más altos de lo necesario. Es por ello que este tipo de herramientas de simulación pueden aportar valor técnico y económico a la planificación de infraestructuras.

Queda pendiente verificar que los datos estimados se correspondan a las previsiones estimadas mediante la simulación, lo que sin duda aportará un componente de validación -o no- a dichas técnicas. En cualquier caso, resulta evidente que una herramienta de mejora del diseño como las empleadas en el presente estudio siempre va a mejorar la calidad de este tipo de estudios de planificación de nuevas infraestructuras.

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MODELO DE MOVILIDAD DE EMT: PLANIFICACIÓN A PARTIR DE FUENTES BIG DATA

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RESUMEN

El Modelo de Movilidad desarrollado por EMT es un modelo multimodal que incluye vehículo privado y transporte público. Si bien su ámbito de actuación es la ciudad de Madrid, el Modelo abarca también el entorno metropolitano.

La red es una malla completa, basada en la cartografía de HERE. La oferta de transporte público incluye todos los sistemas de transporte colectivo – METRO, Cercanías, autobuses interurbanos y autobuses de EMT- , sumando un total de 405 líneas.

El aspecto más innovador de esta herramienta es la metodología seguida para la obtención de las matrices origen-destino. Éstas se han obtenido a partir de la combinación de datos de telefonía (CDR's) y validaciones de la tarjeta de transporte público. Esta combinación de datos ha permitido obtener un amplio abanico de matrices modales para diferentes periodos del año, distintos tipos de día y diferentes intervalos horarios.

La zonificación utilizada – 1259 zonas - es la definida por el Consorcio Regional de Transportes de Madrid para la Encuesta Domiciliaria de Movilidad realizada en 2018 (EDM 18) – 605 zonas para la ciudad de Madrid y 654 para el área metropolitana.

La obtención de unas matrices origen-destino tan detalladas, combinado con el diferente grado de precisión geográfica de origen y destino del viaje de las dos fuentes de datos utilizadas (CDR's y validaciones de la tarjeta de transporte público), ha supuesto un reto importante.

1. OBJETIVOS Y ESTRUCTURA

1.1. Objetivos y aspectos principales

El Modelo de Movilidad de Madrid es una herramienta de planificación para EMT que include tanto transporte público como vehículo privado. El Proyecto de construcción de este Modelo se inició en abril de 2017, terminándose en octubre de 2019.

El Objetivo Principal de este Modelo de Movilidad es dotar a EMT, el operador de movilidad pública de la ciudad de Madrid (100% propiedad del Ayuntamiento), de una herramienta de planificación que le permita una mejor planificación, así como propuestas relacionadas con los servicios de transporte que gestiona.

El principal aspecto innovador de este Proyecto es la obtención de matrices origen-destino a partir de fuentes de datos como los CDR's obtenidos de la telefonía móvil y las tarjetas inteligentes de transporte.

1.2. Etapas del Proyecto

El Proyecto se puede estructurar en 3 fases:

- Desarrollo del Modelo de Oferta: el Modelo, si bien se centra en la ciudad de Madrid, abarca el conjunto de la región, incluyendo tanto la red viaria como la oferta de servicios de transporte público (EMT, METRO, autobuses interubanos y Cercanías). La descripción de esta red está en el capítulo 2.

- Desarrollo del Modelo de Demanda: en este caso se ha planteado un amplio abanico de matrices origen-destino tanto para vehículo privado como para transporte público, así como para diferentes periodos del año (invierno, verano y entretiempo), días de la semana (l-j, viernes, sábados y domingos&festivos) e intervalos horarios (punta AM, punta PM, punta MEDIODÍA y horas VALLE).

Para el cálculo es estas matrices, se puso en marcha una plataforma BIG DATA, basada en una Distribución HORTON HDP 2.6, Actualmente esta Plataforma se está utilizando para otros proyectos en curso en EMT, como la estimación de aforo en los autobuses.

- Validación y Calibrado de resultados.

Los resultados obtenidos al asignar dichas matrices se han contrastado con los datos de aforos de tráfico, así como subidos y bajados en transporte público. Primeramente han servicio para afinar algunos parámetros del Modelo, y posteriormente para calibrar dichas matrices.

2. LA RED DE TRANSPORTE: DESCRIPCIÓN

La red viaria se ha construido a partir de la cartografía HERE para el conjunto de la región – 2.000 km. de vías de alta capacidad, 5.500 km. de carreteras y más de 22.000 km. de red urbana.

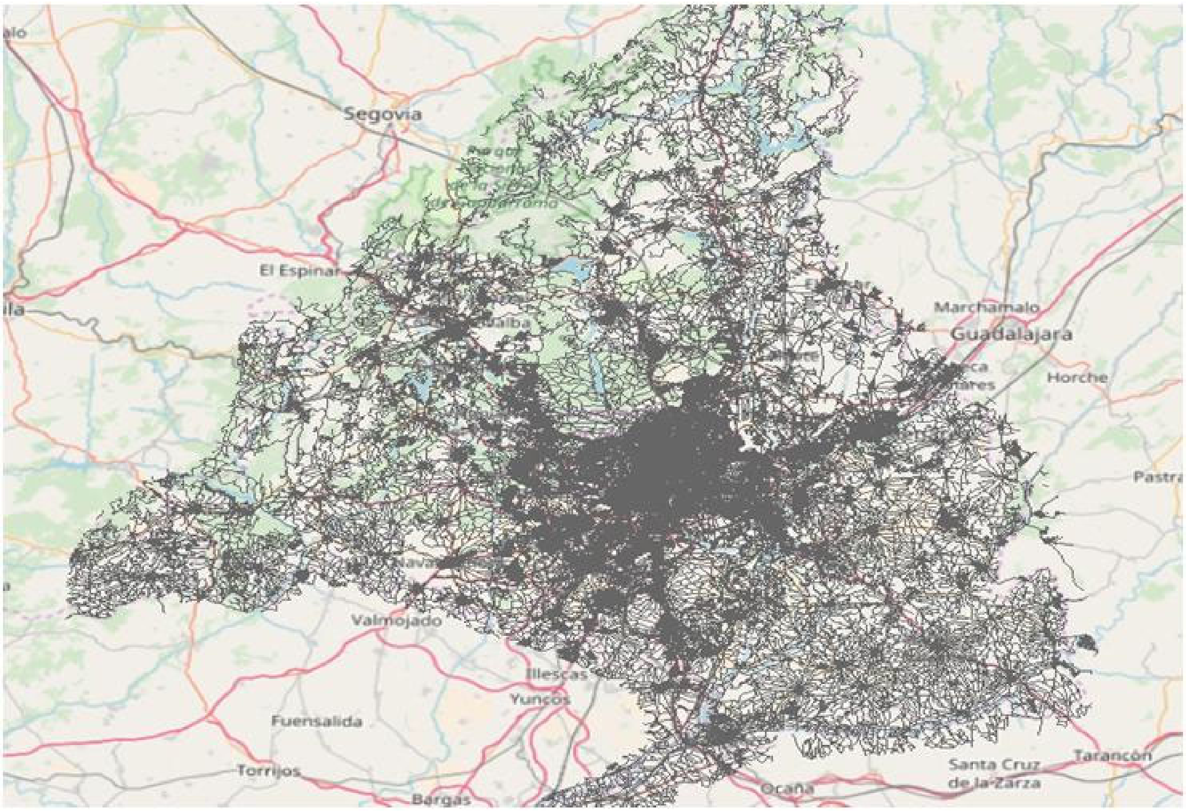

Fig. 1. Red viaria

También se han incluido las diferentes redes de (EMT, Metro, Cercanías, Metro ligero y autobuses interurbanos), junto con sus correspondientes horarios y/o frecuencias.

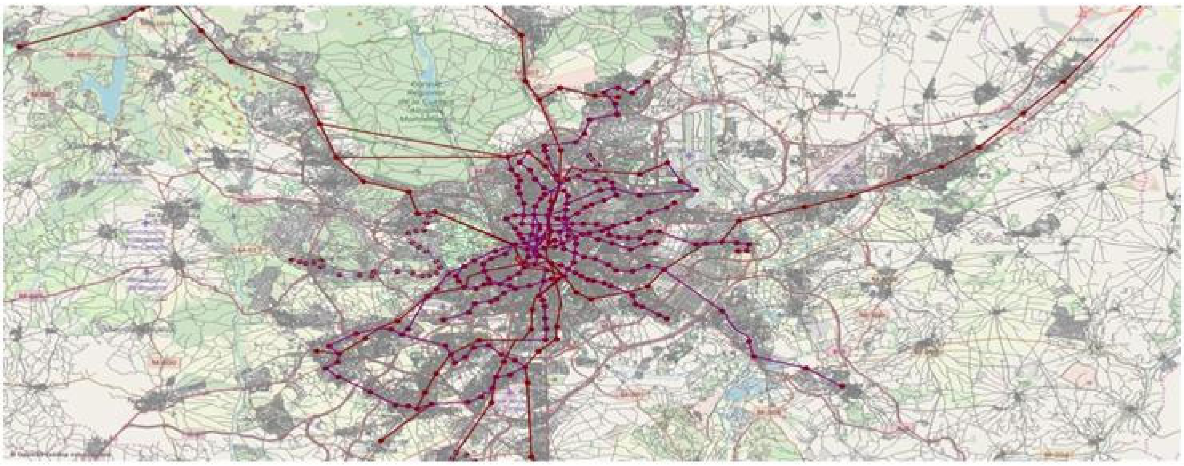

Fig. 2. Red de transporte público: CERCANÍAS Y METRO

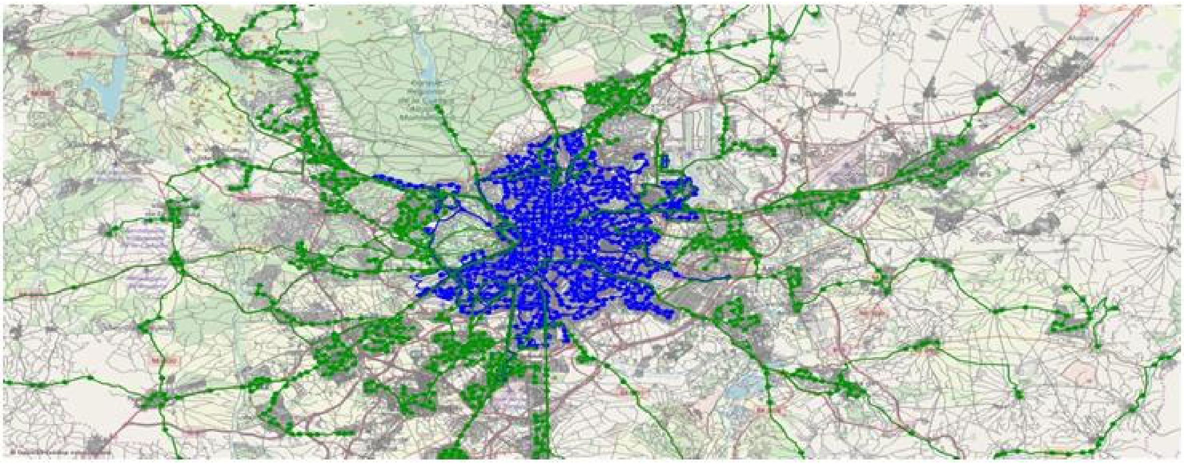

Fig. 3. Red de transporte público: Autobús urbano e interurbano

Esta oferta supone, en total, 393 líneas, más de 9.000 paradas y 62.000 servicios diarios.

La zonificación considerada es la definida por el Consorcio de Transportes de Madrid para la encuesta de movilidad llevada a cabo en 2016, 1259 zonas, de las cuales 605 zonas corresponden a la ciudad de Madrid mientras las otras 654 pertenecen a los otros 199 municipios que integran el conjunto de la región.

3. EL MODELO DE DEMANDA

3.1. Metodología para la obtención de matrices origen – destino (OD)

Los enfoques tradicionales de obtención de matrices O/D se basan en encuestas de hogares y / o recuentos de tráfico. Las encuestas origen / destino y las encuestas de hogares para obtención de orígenes y destinos implican una recopilación de datos costosa y, consecuentemente, tienen tamaños de muestra limitados y frecuencias de actualización más bajas de lo deseado, entre 5 y 10 años incluso en las ciudades más desarrolladas (Toole et al, 2015). De hecho, según Iqbal et al (2016), son propensas a sesgos de muestreo y errores de notificación.

Al mismo tiempo, solo proporcionan una instantánea del rendimiento del tráfico, ya que se realizan en un momento puntual y no de manera continua en el tiempo (White et al, 2002).

Frente a estos métodos clásicos de recopilación de matrices O-D, este trabajo se centra en la obtención de estas matrices de movilidad utilizando fuentes BIG DATA como los datos de telefonía o las tarjetas de transporte. La obtención de las matrices origen-destino mediante combinación de estas fuentes ha conllevado diferentes etapas, que se detallan a continuación.

El primer paso ha sido la obtención de matrices de movilidad general O-D para la Comunidad de Madrid a partir de telefonía móvil. Estos datos de telefonía proporcionan una información completa sobre viajes y distribución espacial con las siguientes ventajas en relación a los métodos convencionales: alto volumen de muestra, buena distribución, volumen de datos a lo largo de todo el año, lo que nos ha permitido considerar diferentes períodos del año, semana o día sin incrementar demasiado el coste. Además, permite capturar información sobre la movilidad de los no residentes en la ciudad de forma menos sesgada.

El segundo paso ha consistido en la obtención de las matrices O/D de transporte público de la ciudad de Madrid a partir de los datos recogidos en las tarjetas inteligentes de transporte público. Para ello, hemos realizado un cruce de información de los datos almacenados (con anonimización previa) con el resto de datos almacenados en la plataforma Big Data.

La información almacenada en estas tarjetas permite la estimación de los viajes realizados en diferentes modos de transporte público, teniendo en cuenta diferentes matices que se explicarán más adelante con más detalle.

Por último, una vez obtenidas ambas matrices OD (movilidad general y transporte público) el siguiente paso ha sido diseñar un procedimiento para obtener matrices de vehículos privados a partir de las anteriores, restando según diferentes zonas la matriz OD pública a la matriz de movilidad general. Este último paso, muy sencillo en apariencia, ha conllevado importantes dificultades derivadas de la diferente aproximación espacial de unos y otros datos.

3.2. Obtención de matrices O/D de movilidad general a partir de datos de telefonía

Las matrices de O / D de movilidad general para la Comunidad de Madrid se han obtenido a partir de datos de telefonía móvil, mediante registros de actividad de teléfonos móviles o CDR (Call Detail Records).

Los datos utilizados para la obtención de estas matrices han sido datos de telefonía celular (datos geolocalizados desde dispositivos móviles, Grupo Orange España), datos de población residente y datos de movimientos fronterizos (FRONTUR, INE), datos de movimientos fronterizos y datos de uso del suelo (Sistema de Información de Ocupación del Suelo).

Al mismo tiempo, se ha tenido en cuenta:

- Población de estudio: residentes en España mayores de 10 años y personas residentes en el extranjero que visiten España.
- Zonificación: las matrices origen-destino estarán referidas a la zonificación establecida por el Consorcio de Transportes de Madrid para la Encuesta de Hogares de 2018, ZT1259.
- Viajes objeto de estudio: viajes con origen y destino en la Comunidad de Madrid con una distancia superior a los 1.000 metros. Este criterio de distancia permite filtrar la mayor parte de los viajes no mecanizados, que no están cubiertos por este estudio.

- Períodos de estudio: se define como período de estudio la combinación de mes o tipo de mes (invierno, verano y temporada media), día o tipo de día (día laborable, viernes, sábado y domingos y festivos) y franja horaria (pico de la mañana, pico de mediodía, pico de tarde y horas valle). Esta combinación resultó en 32 períodos de estudio. En cada uno de ellos, el nivel de desagregación de viajes es el siguiente:
    - Segmentación por género y edad (menores de 20 años, 20-44 años, 45-64 años, 65-79 años y mayores de 70 años)
    - Segmentación por lugar de residencia (municipio de Madrid, resto de la Comunidad de Madrid, resto de España y fuera de España)

La metodología ha seguido los siguientes pasos:

- Preprocesamiento y depuración de telefonía móvil (los datos base se han extraído de los meses de junio, julio, septiembre, octubre y noviembre de 2017)
- Construcción de la muestra potencial de usuarios de telefonía móvil
- Identificación del lugar de residencia de los usuarios residentes en España y características de los no residentes
- Abstracción de la actividad y diarios de viaje
- Aumento de la muestra a la población general
- Generación de las matrices origen-destino

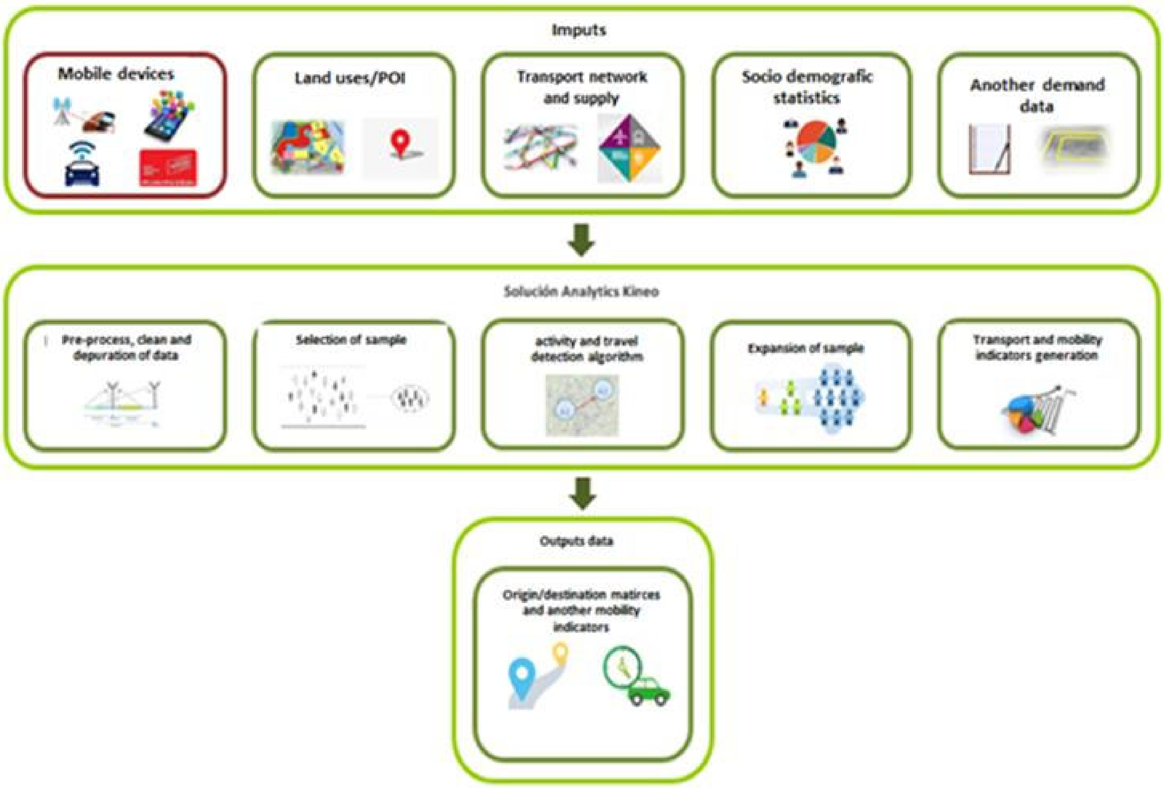

Fig. 4. Proceso de obtención de las matrices O/D generales

3.3. Obtención de matrices O/D de transporte público mediante los registros de las tarjetas inteligentes de transporte

Los datos de la red de telefonía nos dan la posibilidad de comprender mucho mejor los patrones de viaje dinámicos, lo cual tiene una gran cantidad de aplicaciones diferentes dentro de la gestión, el análisis y el apoyo a la toma de decisiones del tráfico y el transporte. Sin embargo, estas fuentes de datos tienen varias características clave que son diferentes de las fuentes de datos tradicionales y que deben manejarse con cuidado mientras se procesan los datos con fines de estimación y predicción. A diferencia de los sistemas de infraestructura fija para la recopilación de datos, los datos de señalización de teléfonos móviles no están limitados por ningún modo de transporte ni por ninguna región espacial específica. Esto no permite analizar la demanda de viajes y los tiempos de viaje según el modo de viaje (David Gundlegard et al., 2016). Esta es la razón por la que hemos utilizado la información de las tarjetas de transporte inteligent

Hoy en día, la mayoría de los sistemas AFC (recolección automática de tarifas) en todo el mundo solo registran la información de embarque de los pasajeros y se pierden los datos de bajada, como la ruta del autobús, la parada de embarque y la hora de embarque. (Daming Li, Xinliang Zhao et al. 2011). La estimación de orígenes y destinos (O/D) de trayectos en transporte público es un producto importante del procesamiento de datos de tarjetas inteligentes.

En los últimos años, varios métodos de estimación O/D que utilizan el enfoque de encadenamiento de viajes han atraído mucha atención tanto de investigadores como de profesionales.

En este caso, para estimar la cadena modal (monoetapa o multietapa) para cada usuario, hemos considerado a los usuarios de la tarjeta de transporte público de Madrid con billetes mensuales, anuales y de 10 viajes, ya que para el billete simple no es posible inferir la salida del viajero debido al uso ocasional de los servicios de transporte público.

En cuanto a la metodología para la recolección de viajes a partir de las validaciones, el proceso seguido se basó en el enfoque de encadenamiento de etapas.

Para unir las validaciones de viaje utilizamos el programa que predice la parada de salida (si no la tenemos) en función de la distancia mínima de transferencia y el tiempo de viaje por modo, que se fijará en función del tipo de día y franja horaria (estos límites se determinarán en función de los datos de otras fuentes externas, como Simplycity, CDRs, etc. .).

Paralelamente, se desarrolló un algoritmo que sirve para encontrar la parada más cercana a la siguiente validación en los casos en que no existan distancias calculadas previamente para poder saber qué parada se utilizó para el traslado, teniendo en cuenta que el operador y la línea de salida deben ser los mismos que la línea de entrada.

Los escenarios adoptados han sido los siguientes:

- Cuando la diferencia horaria entre validaciones en una misma tarjeta es inferior a 45 minutos, las hemos considerado como etapas de un mismo viaje y las hemos encadenado en un mismo viaje.
- Las tarjetas de transporte se almacenan en el punto de validación (parte superior de acceso a la red de transporte público). Para ir más allá de este punto de acceso a la red hasta la zona de disparo de origen, hemos redistribuido los viajes entre las áreas vecinas a cada parada de la red. Las zonas de influencia se generan con dos criterios diferentes en cuanto al radio de acción:
    - En las áreas de metro y ferrocarriles (es decir, en estos operadores) se necesitan 600 metros.
    - Se toman 500 metros al resto de operadores.
    - Para la redistribución se utiliza el producto cartesiano individual para cada zona de origen y destino.
    - La redistribución se realiza a nivel de viajes.

Para cada uno de los periodos de estudio, se ha tenido en cuenta la distribución espacial de viajes entre áreas de la matriz integral provenientes de la matriz de telefonía móvil.

Dado que no ha sido posible disponer de información suficiente de los viajes en transporte público con origen o destino fuera de la ciudad de Madrid, hemos optado por considerar solo aquellos viajes con origen / destino dentro de la ciudad de Madrid, excluyendo el análisis de los viajes al resto de áreas en la Comunidad. Para éstos, se ha estimado la misma distribución de viajes que había en la última Encuesta Domiciliaria.

3.4. Obtención de las matrices O/D de vehículo privado

El último paso ha consistido en la recogida de matrices de transporte privado. En este punto ya conocíamos las matrices integrales y las matrices de transporte público, por lo que procedimos de la siguiente manera:

- De las matrices de transporte público O D se han eliminado aquellos viajes cuya distancia sea inferior a 1.000 metros, ya que estos viajes no estaban incluidos en la matriz integral O/D obtenida de la telefonía móvil.
- A cada matriz de O/D integral obtenida de la telefonía móvil (considerando solo los viajes entre áreas de la ciudad de Madrid), se ha eliminado su contraparte de la matriz de transporte público, dando como resultado la matriz de viajes en vehículo privado.
- Cuando lo hacemos, en algunas combinaciones, se obtiene un resultado negativo restando información entre CDR y O/D público.

Para minimizar la densidad de valores negativos que no cubre la versión original del algoritmo, es necesario modificar el algoritmo entre la creación del “buffer” y la asociación de zonas candidatas (que se realizará a nivel desagregado).

Por último, se han calibrado estas matrices usando los datos de tráfico y de viajeros subidos por línea. Las figuras 5 y 6 muestran los resultados para el periodo punta de la mañana de un día laborable de invierno.

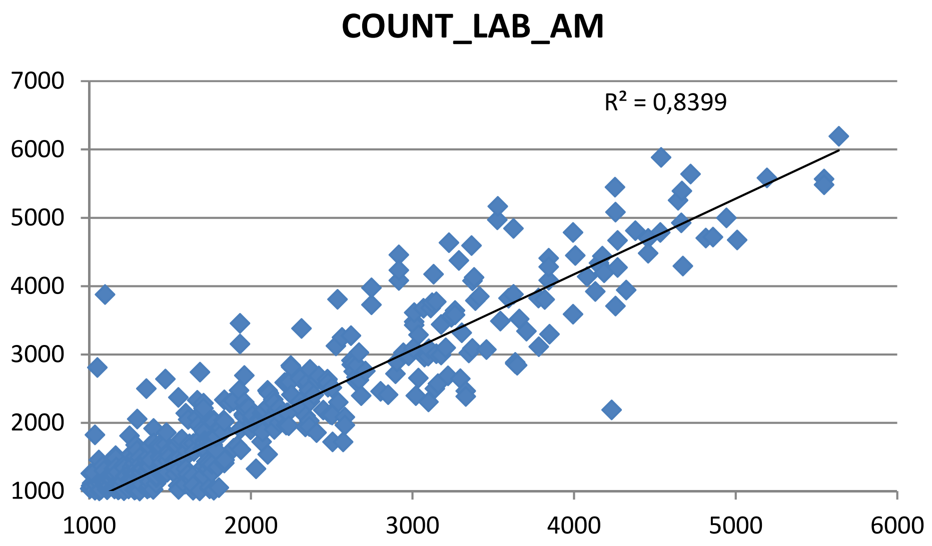

Fig. 5. Resultados calibrado matriz vehículo privado: periodo AM día laborable de invierno

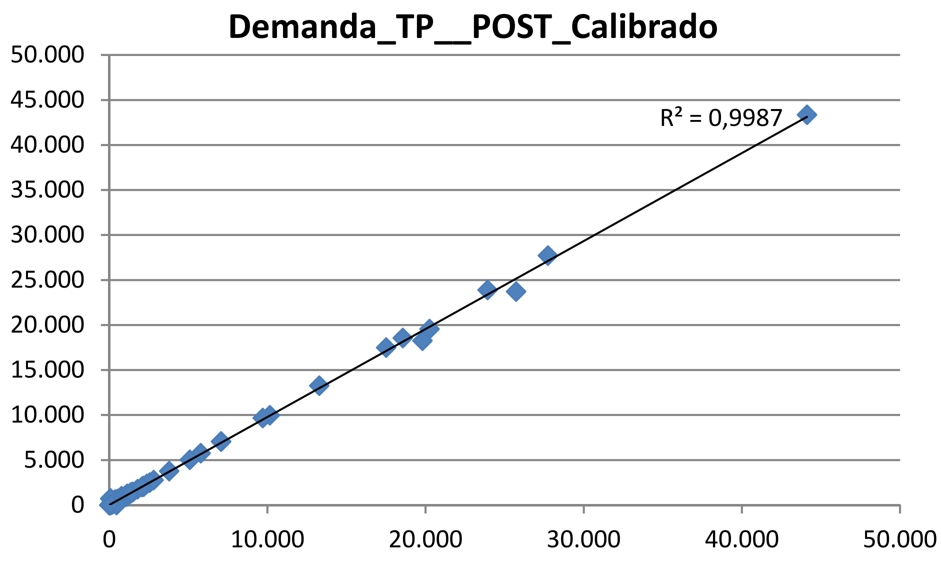

Fig. 6. Resultados calibrado matriz transporte público: periodo AM día laborable de invierno

4. UTILIDADES Y CASOS DE ESTUDIO

El Modelo de Movilidad se ha utilizado y se está utilizando actualmente para diferentes escenarios de análisis, tanto desde la necesidad operativa (1 y 2) como para la investigación (3), tales como:

1) Cierre del túnel de Recoletos de la red de Cercanías: variación de la movilidad y necesidades de refuerzo mediante servicio alternativo de EMT.

Fig. 7. Variación del tráfico con el cierre del túnel de Recoletos de Cercanías

2) Definición y selección de itinerario de las nuevas líneas de autobús 00 (cero coste, cero emisiones): 001 Atocha Renfe – Moncloa y 002 Argüelles – Puerta de Toledo

3) Proyecto europeo MOMENTUM: este Proyecto, perteneciente al Programa H2020, tiene entre sus objetivos caracterizar los cambios en las pautas de movilidad derivados de las nuevas opciones emergentes de movilidad, así como incorporar en el Modelo de Movilidad opciones para incorporar el impacto de estas nuevas opciones.

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MODELOS DE EMISIONES DE PARTÍCULAS Y NOX DE AUTOBUSES EN RECORRIDOS URBANOS

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RESUMEN

En las grandes ciudades el principal motivo de la pérdida de la calidad del aire es la emisión de los productos de combustión procedentes del tráfico de vehículos. El objetivo de este trabajo es mostrar los resultados de las predicciones realizadas para emisiones de partículas y de óxidos de nitrógeno por autobuses urbanos de ciudad de Madrid, utilizando modelos de minería de datos que consideran la influencia de variables cinemáticas, ambientales, altitud y pendiente. Para la realización de las predicciones se usó la herramienta estadística *Random Forests* de R.

Se obtuvo los perfiles de altitud y pendiente de manera teórica (usando la aplicación *GPS Visualizer)* y experimental (determinación del perfil de altitud sobre el nivel del mar). Se detectó un desfase entre las curvas de caudal de contaminantes respecto a las curvas de las variables cinemáticas, por ello se hizo corresponder el valor de la variable respuesta en el instante t con las cinemáticas en el instante t + r. Se determinó las mejores combinaciones del desfase a partir de la elaboración de modelos sencillos.

A continuación, a los mejores modelos sencillos se añadió las componentes ambientales como variables explicativas creando modelos globales, y finalmente se creó un modelo incorporando al mejor modelo global la altitud y pendiente como nuevas variables explicativas.

Se verificó que los modelos que consideran el retardo entre la variable respuesta y las cinemáticas y la incorporación de la altitud y pendiente como variables explicativas mejoran los modelos en términos de predicciones y errores. Los perfiles de altitud y pendiente determinados por el método teórico presentan mejores resultados, en ambos métodos la pendiente es la tercera variable más influyente en la emisión de los contaminantes, mientras que las variables cinemáticas son las que más contribuyen a reducir la impureza nodal y el error *MSE-OOB*.

1. INTRODUCCIÓN

La contaminación atmosférica, producida por los gases, provoca efectos negativos sobre el medioambiente y la salud de las personas. Las emisiones de partículas (PM) y los óxidos de nitrógeno (NOx) tienen en el tráfico rodado la principal fuente de emisión en grandes ciudades (Ministerio de Agricultura, 2013).

Pese a que el sector automovilístico ha incorporado importantes mejoras y novedades tecnológicas que han permitido reducir de manera notable el consumo de combustible y las emisiones de los vehículos, la calidad del aire no ha mejorado lo que se deseaba.

En el año 2018, la ciudad de Madrid, sufrió varios episodios de superación de los niveles recomendables de dióxido de nitrógeno y/o ozono troposférico que motivaron la adopción de medidas basadas en los Protocolos de Actuación para Episodios de Contaminación (Ayuntamiento de Madrid, 2018) La Dirección General de Tráfico (DGT), organismo dependiente del Ministerio del Interior, clasificó el parque automovilístico español en base a lo que cada vehículo contamina, con el objetivo de discriminar positivamente a los vehículos más respetuosos con el entorno y ser un instrumento eficaz en políticas municipales (DGT, 2016).

Jiménez et al. (2009) compararon dos alternativas de dispositivos de control de emisiones de autobuses urbanos circulando por zonas urbanas e interurbanas, haciendo uso de ensayos con equipos de medida embarcados.

Fonseca González (2012) estudió los problemas asociados a la medición de las emisiones gaseosas y los distintos factores que influyen en las emisiones y en el consumo de combustible de turismos en tráfico real y diseñó y construyó un equipo experimental, denominado MIVECO-PEMS, que permite medir las emisiones másicas instantáneas y los factores de emisión.

Carrese et al. (2013) evaluaron y cuantificaron el impacto de los patrones de conducción, la pendiente de la vía y la carga del vehículo (pasajeros) sobre el consumo de combustible y las emisiones de contaminantes atmosféricos en autobuses de Roma.

Román de Andrés (2014) propuso una metodología para la redistribución optimizada de una flota de vehículos en una red de rutas fijas urbanas con el propósito de reducir la emisión de sustancias contaminantes.

Ruiz Porro (2017) desarrolló una metodología para obtener ciclos de conducción optimizados de autobuses con los que identificar los patrones de conducción con mejor comportamiento en cuanto a emisiones contaminantes.

Cueto-Felgueroso (2018) estudió la influencia que las variables cinemáticas, ambientales, altitud y pendientes ejercen en la emisión de contaminantes y consumo de combustible en los autobuses urbanos de la ciudad de Madrid.

En el Proyecto ECOTRAM (2007) se desarrolló una metodología para calcular las emisiones de diversos contaminantes de la flota de autobuses de la Empresa Municipal de Transportes de Madrid (EMT) (López et al. 2017).

Este trabajo, enmarcado en el Proyecto CÍCLOPE (*Sistema de optimización de ciclos urbanos de conducción*) desarrollado por el INSIA, presenta los resultados de las predicciones de emisiones de PM y NOx de autobuses urbanos en la ciudad de Madrid, mediante modelos de minería de datos. Los datos de emisiones instantáneas se obtuvieron mediante equipos a bordo en una muestra de autobuses. Los modelos muestran la influencia de las variables cinemáticas, ambientales y del perfil altimétrico de los recorridos sobre los contaminantes PM y NOx.

2. BASE DE DATOS

La base de datos utilizada contiene información sobre las variables cinemáticas, posicionales, ambientales y de emisiones de un autobús MAN, de motor de encendido por compresión (MEC), con normativa europea EURO IV (Directiva 2005/55/CE) circulando en 4 líneas de la EMT (C1, 27, 63 y 145) durante distintos trayectos habituales de ida y vuelta, obtenidos de un conjunto de ensayos realizados durante los años 2007 y 2008 en el proyecto ECOTRAM (2007).

Carga	Línea / Itinerario								Total por carga
	C1		27		63		145		
	Ida	Vuelta	Ida	Vuelta	Ida	Vuelta	Ida	Vuelta	
Plena	1	2	2	2	2	2	-	-	11
Media	4	3	2	2	-	-	2	2	15
Vacío	2	2	2	2	-	-	2	2	12
Total									38

Tabla 1 – Número de ensayos realizados por nivel de carga con B100.

Se obtuvieron más de 152.000 observaciones o medidas por segundo mediante la instalación del equipo PEMS Horiba OBS-2200, en distintas condiciones de ensayo: distintas horas y días, en los itinerarios de ida y vuelta en las distintas líneas, con tres estados de carga (vacío, a media carga y a plena carga) y dos tipos de combustible, gasóleo y biodiesel 100% (B100).

A comienzos del año 2009 se sustituyó el gasóleo por un biocombustible (B100) en toda la flota de autobuses de la EMT (EMT, 2010), y en este trabajo se muestran los resultados considerando los 38 ensayos, con Biodiesel 100% (B100) de la Tabla 1.

3. METODOLOGÍA

La base de datos proporciona como variable cinemática la velocidad del autobús. Las variables aceleración y sobreaceleración, que tienen una importante influencia en la dimensión de las emisiones, se definen como un incremento entre dos valores en instantes consecutivos y fueron calculadas a partir de las velocidades instantáneas del autobús.

3.1 Determinación de los perfiles de altitud y pendiente

Los valores de altitud recogidos en la base de datos no presentan una fiabilidad suficientemente alta porque el aparato medidor no fue capaz de captar los datos adecuadamente debido a los obstáculos e interferencias, como túneles o edificios.

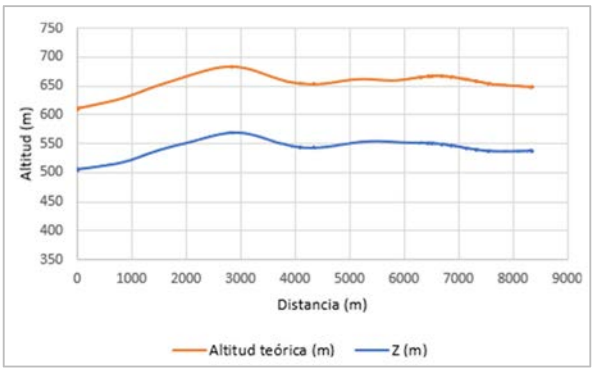


Fig. 1 – Evolución de las altitudes calculadas con *GPS Visualizer* y según el método de las presiones (Z) en un ensayo de media carga de B100 (Cueto-Felgueroso, 2018)

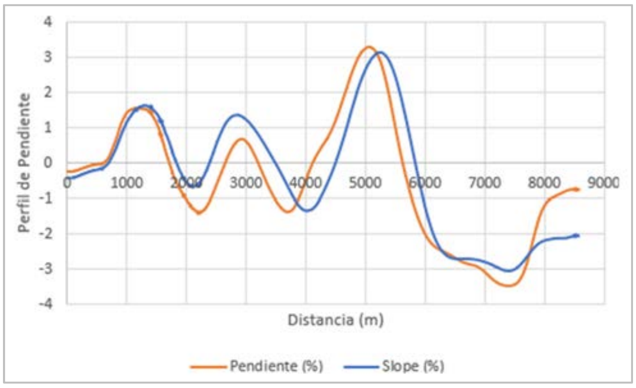


Fig. 2 – Comparación de los perfiles de pendiente obtenidos con el método teórico (Pendiente) y experimental (Slope) (Cueto-Felgueroso, 2018)

Se determinaron los valores de la altitud por dos métodos: teórico y experimental (Figura 1) (Cueto-Felgueroso, 2018). En el primero se utilizó la aplicación *GPS Visualizer* (GPS Visualizer, 2003) que utiliza valores de longitud y latitud recogidas en la base de datos. En el segundo se determina el perfil de altitud sobre el nivel del mar en base a la presión atmosférica, medida por el equipo embarcado en el autobús (Fonseca Gonzáles, 2012).

Se calcularon las pendientes como el cociente entre las variaciones de altitud y de distancia. En la Figura 2 se observa que no hay diferencias significativas entre los perfiles de pendientes calculados con los dos métodos de determinación de altitudes.

3.2 Modelado

Para elaborar los modelos de predicción se estudiaron las curvas de caudal de contaminantes respecto a las curvas de las variables cinemáticas (velocidad, aceleración y sobreaceleración) y debido al desfase entre ellas, se introdujeron retardos para la variable respuesta en el instante t con las cinemáticas en el instante t + r.

Se realizaron tres grupos de modelos de árboles aleatorios *(Random Forests):* el primer grupo, denominado *modelo sencillo* (solo con variables cinemáticas como variables de entrada), con el objeto de determinar las variables cinemáticas que presentan mejores resultados (menor MSE-OOB y mejor variabilidad explicada); el segundo grupo, *modelo global*, con la incorporación a los mejores modelos del primer grupo de las variables ambientales como variables explicativas; y finalmente el tercer grupo, *modelo global con altitud y pendiente*, con la adición al mejor modelo del segundo grupo (caracterizado por menores valores de MAPE, MSE-OOB y MSE y mejor variabilidad explicada) de la altitud y la pendiente como nuevas variables explicativas. Se compararon los resultados del modelo global sin y con incorporación de las variables altitud y pendiente, con el fin de analizar cómo se comporta el modelo ante esta nueva situación (Cueto-Felgueroso, 2018).

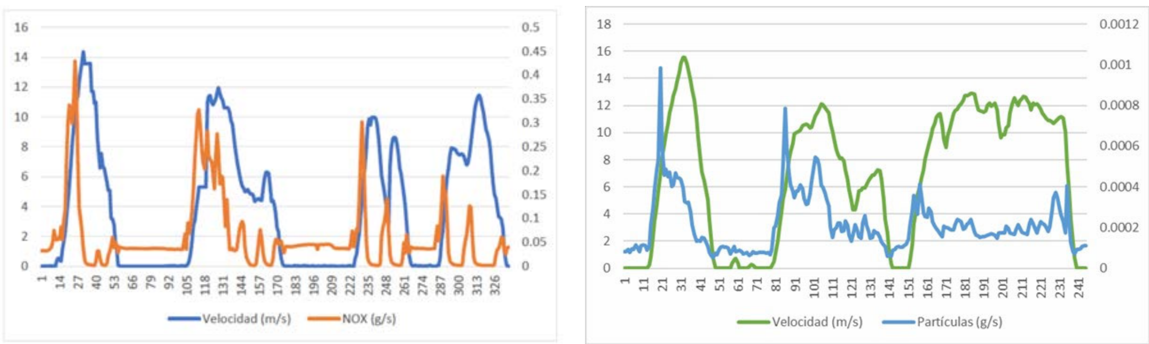
Para el modelado con *Random Forest* se definieron los parámetros *mtry*= 2 (Breiman et al. 1984), y *ntree*= 500. Al mismo tiempo, se compararon los resultados obtenidos con los dos métodos diferentes de obtención de los perfiles de altitud y pendiente.

Para la identificación de los modelos se empleó la nomenclatura: contaminanteABC, donde A es el desfase de la velocidad, B el de la aceleración y C el de la sobreaceleración, con respecto a la emisión del contaminante analizado.

4. RESULTADOS Y DISCUSIÓN

4.1 Caracterización del desfase

La Figura 3 muestra el desfase entre las curvas de velocidad y del caudal de contaminante, a) NOx y b) PM. Se estimó el tiempo de retardo para NOx entre 2 y 4 segundos, mientras que para PM se observó que el desfase es muy pequeño. Se verificó un comportamiento similar con la aceleración y el caudal másico de contaminante.



a) NOx b) PM

Fig. 3 – Curvas de velocidad y caudal másico de contaminante de un fragmento de un ensayo de B100 - vacío. a) NOx y b) PM (Cueto-Felgueroso, 2018)

4.2 Modelos

Se elaboraron los modelos sencillos para determinar la mejor combinación del desfase entre el caudal de contaminante y las variables cinemáticas (velocidad, aceleración y sobreaceleración). Para el caso de NOx, se observó que el retardo óptimo está entre 3 y 4 segundos, mientras que para PM está entre 0 y 1 segundo.

Tras determinar las mejores combinaciones de los modelos sencillos se elaboraron los modelos globales. El mejor modelo global para cada contaminante se muestra en la Tabla 2.

Modelo	Variabilidad Explicada	MSE-OOB	MAPE	MSE
NOx34	77,35	0,001162	1,66	0,001158
PM11	82,71	2,76E-09	0,206	3,00E-09

Tabla 2 – Resultados de los mejores modelos globales (Cueto-Felgueroso, 2018)

A continuación, al mejor modelo global se incorporó la altitud y la pendiente, obtenidas con los dos métodos, como variables explicativas, cuyos rangos de valores se muestra en la Tabla 3. En la nomenclatura de los modelos se incorpora una V en el caso de utilizar los perfiles de altitud y pendiente con la aplicación *GPS Visualizer*, y una E para el Método Experimental.

Variable	Unidades	Rango de valores
Altitud	m	500,13 – 729,39
Pendiente	%	-3,46 – 5,01

Tabla 3 – Unidades e intervalo de valores de las variables altitud y pendiente (Cueto-Felgueroso, 2018)

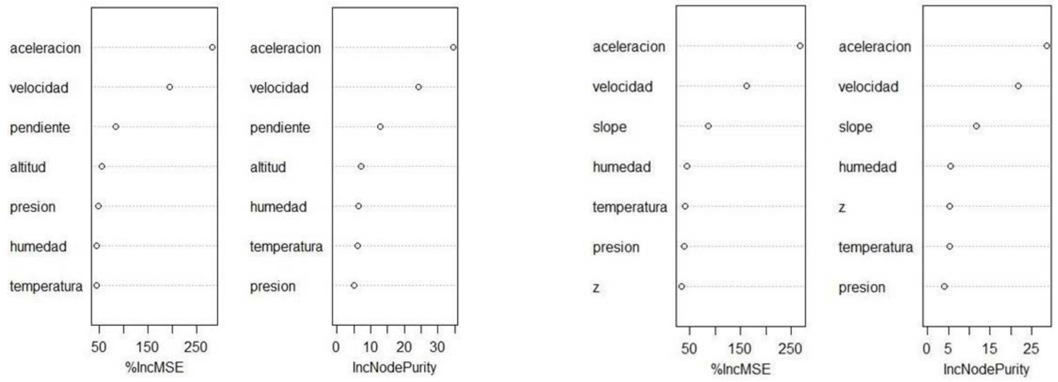
La Tabla 4 presenta los resultados de los *modelos globales con altitud y pendiente* de los dos contaminantes.

Modelo	Obtención de la altitud	Variabilidad Explicada	MSE-OOB	MAPE	MSE
		a) NOx			
NOx34V	**GPS Visualizer**	**83,14**	**0,000813**	**1,15**	**0,000816**
NOx34E	Método experimental	81,29	0,000836	1,22	0,000904
		b) PM			
PM11V	**GPS Visualizer**	**85,87**	**2,39E-09**	**0,18**	**2,62E-09**
PM11E	Método experimental	82,61	2,86E-09	0,20	4,19E-09

Tabla 4 – Resultados de los modelos globales con altitudes y pendientes. a) NOx y b) PM (Cueto-Felgueroso, 2018)

Tanto para NOx como para PM los mejores resultados se alcanzaron con los perfiles de altitud y pendiente obtenidos con la aplicación *GPS Visualizer* (modelos NOx34V y PM11V, respectivamente). No obstante, el método experimental proporciona unos valores similares, y la incorporación de estas variables explicativas mejoraron los modelos, aumentando la variabilidad explicada, un 7,48% en el caso del contaminante NOx y un 3,82% para PM.

Las Figuras 4 y 5 recogen la importancia de las variables explicativas para los dos métodos de obtención del perfil de altitud por los criterios MSE y Gini, para los contaminantes NOx y PM, respectivamente.

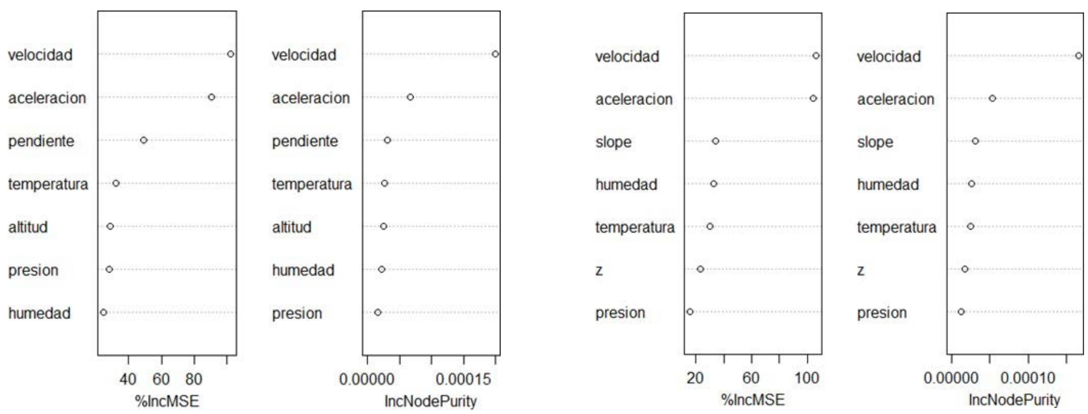


a) Método *GPS Visualizer* (NOx34V) b) Método Experimental (NOx34E)

Fig. 4 – Importancia de las variables en el modelo global de NOx con altitud y pendiente. a) Método *GPS Visualizer* y b) Método Experimental (Cueto-Felgueroso, 2018)

En la Figura 4 se observa que para el contaminante NOx en ambos métodos la variable más importante es la aceleración, seguida de la velocidad. La pendiente (*slope*) es más influyente que la altitud (*z*). Para el modelo NOx34V la altitud es la cuarta variable más influyente por los dos criterios. Mientras que para el modelo NOx34E la altitud está en la última posición por el criterio MSE y en la quinta por el criterio Gini, esto se debe a que los valores de las alturas se han obtenido a partir de la presión barométrica en cada cota, por lo que los perfiles obtenidos dependen en gran medida de las componentes ambientales.

La Figura 5 muestra que para el contaminante PM en ambos métodos la variable más importante es la velocidad, seguida de la aceleración. La diferencia entre ambas variables es muy notable según el criterio de Gini, y no ocurre lo mismo para el criterio MSE. En los dos métodos la pendiente ocupa la tercera posición siendo más influyente que la altitud.



a) Método *GPS Visualizer* (PM11V) b) Método Experimental (PM11E)

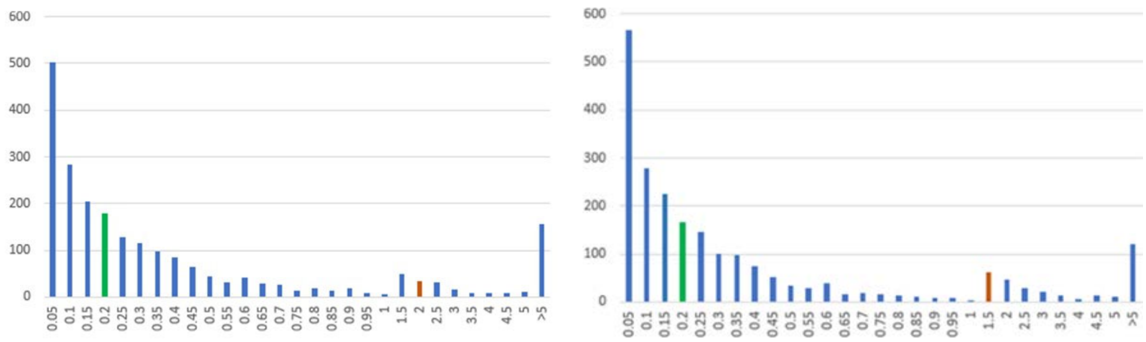
Fig. 5 – Importancia de las variables explicativas en el modelo global de PM con altitud y pendiente. a) Método *GPS Visualizer* y b) Método Experimental (Cueto-Felgueroso, 2018)

Las Figuras 6 y 7 presentan las distribuciones del error relativo de las predicciones realizadas con el conjunto de datos *test set* en el mejor modelo global para NOx y PM, respectivamente. Antes de incorporar la altitud y pendiente en (a) y después de la incorporación en (b). Se representa la mediana del error en verde y la media en marrón.

La Figura 6a presenta el histograma del error relativo del modelo NOx34**.** La mediana se sitúa en 0,18, la mitad de los datos presentan un error menor o igual al 20%. El valor medio es de 1,66. La diferencia entre la mediana y la media es muy elevada debido al número de observaciones concentradas en el final de la cola del histograma.

Aunque dicha cantidad suponga un 15% del total de datos del conjunto *test set*, al presentar valores que superan el 100% del error, contribuye a elevar significativamente la media, hasta alcanzar un valor casi diez veces más elevado que la mediana.

La Figura 6b presenta el histograma del error relativo del modelo NOx34V. El valor de la mediana es 0,16, por lo que la mitad de los datos presenta un error menor o igual a 20%, como ocurría antes de incorporar la altitud y pendiente. Sin embargo, se ha conseguido reducir su valor en un 11,11%. El valor medio es 1,15, un 30,7% menos que el *MAPE* antes de incorporar la altitud como variable explicativa. La diferencia entre la mediana y la media se ha reducido un 22,12%. Sin embargo, sigue demasiado elevada debido al número de observaciones del conjunto *test set* que se acumulan en el final de la cola del histograma, correspondiente a los valores más altos del error. Destacan la reducción en un 21,8% de la cantidad de datos que presentan un error superior a cinco y el incremento de un 11,3% de los datos que presentan el valor más bajo del error.

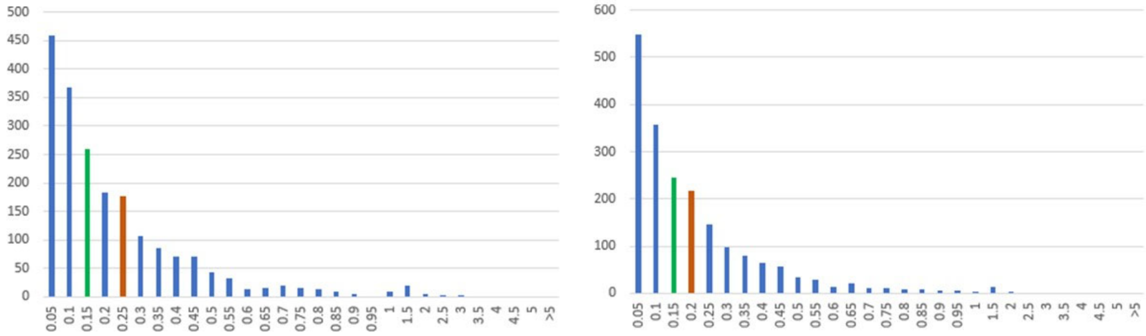


a) Sin altitud y pendiente (NOx34) b) Con altitud y pendiente (NOx34V)

Fig. 6 – Dispersión del error relativo para el conjunto de datos *test set* en el mejor modelo global para NOx. a) sin altitud y pendiente y b) con altitud y pendiente (Cueto-Felgueroso, 2018)

Se concluye que considerar la pendiente y la altitud en el estudio de las emisiones del contaminante NOx mejora el ajuste de los modelos. Se redujo de forma notable la cantidad de observaciones que se acumulan en cada uno de los intervalos del error relativo.

Sin embargo, existe un número de observaciones que, aunque no llegan a representar un cuarto del total de los datos, presentan unos valores tan elevados que incrementan de manera considerable el error relativo medio. Para esos datos, el modelo no se ajusta correctamente, a diferencia de lo que ocurre con la mayoría de las observaciones.



a) Sin altitud y pendiente (PM11) b) Con altitud y pendiente (PM11V)

Fig. 7 – Dispersión del error relativo para el conjunto de datos *test set* en el modelo global para PM. a) sin altitud y pendiente y b) con altitud y pendiente (Cueto-Felgueroso, 2018)

La Figura 7a presenta el histograma del modelo PM11. El valor de la mediana es de 0,13, indicando que la mitad de los datos presentan un error menor o igual a 15%. El valor medio es de 0,206, o sea 1,58 veces el valor de la mediana. Aunque la diferencia no es despreciable, es significativamente menor que la mostrada en el estudio del contaminante NOx. En la cola del histograma no hay observaciones con error mayor o igual a 3,5. Pese a que la cantidad de observaciones del conjunto *test set* con un error mayor o igual a 1 representa un 1,96% del total de observaciones, al presentar un error superior al 100% contribuyen a aumentar el valor medio del error relativo. La mayoría de los datos se agrupan en valores bajos del error, que son menores que los obtenidos en el análisis del contaminante NOx, demostrando que el modelado de PM se ve menos afectado por factores externos.

La Figura 7b representa el histograma del error relativo del modelo PM11V. La mediana es 0,12, por lo que la mitad de los datos presenta un error menor o igual a 15%, como ocurría antes de incorporar la altitud y la pendiente. No obstante, se redujo su valor un 8,46%. El valor medio del error es de 0,18, lo que supone una disminución de un 12,62%. Al introducir las dos nuevas variables explicativas se consiguió acortar aún más la cola del histograma, ya que ninguna observación del conjunto *test set* presenta un error superior a 2,5.

Disminuyó el número de datos con un error superior a 1 hasta un 1,26% del total. Sin embargo, la cantidad de datos con un error del 95% experimentó un ligero aumento, pasando de ser nulo a 7. Pese a ello, para el resto de los intervalos con errores elevados (0,5 a 0,75), el número de datos se ha mantenido o ha disminuido.

Se concluye que incorporar la altitud y la pendiente como variables explicativas contribuyó a mejorar el modelo de predicción de PM. La gran mayoría de las observaciones se agrupa en valores bajos del error.

Los errores son mucho menores que los obtenidos con el contaminante NOx, demostrando que cada uno de ellos se ve afectado por diferentes factores.

5. CONCLUSIONES

Los modelos que consideran el desfase entre las curvas de variables cinemáticas y de caudal de contaminante conducen a mejores predicciones. Sin embargo, los modelos obtenidos presentan unos errores significativamente elevados a raíz de las fuentes de variabilidad asociadas a las variables estudiadas, por lo que no han sido capaces de adaptarse de manera precisa a los datos.

La incorporación de la altitud y pendiente como variables explicativas contribuyó a una notable mejora de los modelos. Pese a que las predicciones son más precisas y se redujeron significativamente los errores, éstos siguen siendo no despreciables, por lo que es posible que no se esté considerando algún efecto que sea muy relevante en el modelado de las emisiones.

La utilización de los perfiles de altitud y pendiente elaborados a partir de la aplicación *GPS Vizualizer* conduce a mejores resultados en comparación con los perfiles determinados a partir de la altura sobre el nivel del mar.

Ambos métodos, teórico y experimental, coinciden a la hora de determinar que la pendiente es la variable que más influye después de las cinemáticas (velocidad y aceleración).

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NEW UNCONVENTIONAL SOURCES OF INFORMATION FOR TRANSPORT ANALYSIS. THE CASE OF A MODEL FOR PUBLIC TRANSPORT SERVICES IN MAJORCA

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ABSTRACT

Most transport modeling requires the use of data available in official sources plus complementary information that helps to fill gaps. This later information is mostly obtained with the help of private data and field data collection. But sometimes this field data collection is not possible for several reasons. On the other hand, there are more and more sources of information readily available, which may provide indirect clues about users' behavior.

Within the framework of a bidding process, a modelling of Majorca's public transport was carried out in order to ascertain elasticities of demand to several parameters of supply that were expected to change. For that purpose, there appeared a need of getting detailed information on tourist activities, which are a huge share of total mobility in summertime. Official information on population is rather detailed, but tourism data are available only on an aggregated basis.

Some indirect sources of information were analyzed. The easiest and most useful ones were *TripAdvisor* and *Booking*. The former is sort of a macro-survey of popularity and it seems logical that those nuclei with more opinions are those most visited, thus acting as an indicator of attraction. The latter provides information on location of accommodation offered, thus providing a tool for the geographical distribution of trip generation on a very detailed basis. In total, 933,934 opinions for 198 nuclei from *TripAdvisor,* and 2,114 accommodation assets for 51 Municipalities from *Booking* were used. With this information it was possible to calibrate different models for the whole Island, this opening the door to further analyses in the field of transportation and mobility.

The Transport Consortium of Majorca (CTM), entity in charge of planning and management of scheduled public transport services on that island, published in March 2019 the call for tenders for all intercity public passenger transport services by bus. It opened a scenario of important changes (CTM 2017a and 2017b) that sought to increase the total demand of the intercity bus network by 25% between 2015 and 2028, by means of a substantial variation in the supply side (travel times, timetables, connectivity between lines, etc.). For example, an increase in supply between 35.8% and 73.1% of vehicle-km was planned, with different figures for each of the three packs into which the tender was divided. In addition, a new fare system was introduced, with a very complex structure that imposed a heavy surcharge when purchasing the ticket on the bus. However, no technical study with more information on the expected demand figures was released.

Under these circumstances, any projection of the historical data was irrelevant and one of the bidding companies, which also operated a good part of the existing services, felt the need of calculating the expected demand with scientific tools.

The analysis of the problem in question faced, fundamentally, an important lack of detail of the available information:

- As for transport supply or demand, the official information was limited to total figures by line (CTM, 2017 and "Open Data" site).
- In terms of demand factors, the greatest disaggregation available in official sources (ibestat) was at municipal level.

The following sections focus on the cross-section analysis of the general services, without dealing with other issues analyzed at the time, such as the new lines to the airport and the time-series modeling.

1. THE CONTEXT

Majorca has about 3,600 km² and 868,700 inhabitants (2017). It has 53 municipalities, overshadowed by the capital, Palma, with 406,500 inhabitants (47% of the total). It is a top-level tourist destination: in 2017 Majorca received 11.6 million tourists.

The most important tourist areas are Calvià and Palma, as well as the east coast, while the municipalities in the center of the island have a much lower tourist activity. Tourism presents strong seasonality, with the maximum in the summer months and small volumes in winter.

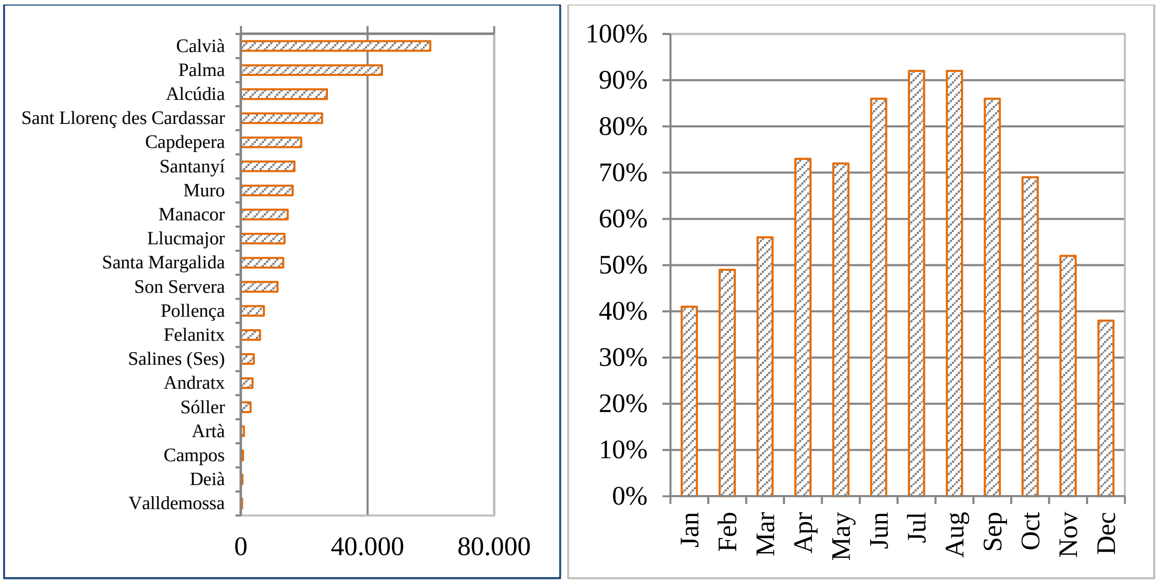

Fig. 1 - Bed capacity of the 20 municipalities with the highest volume (left) and hotel occupancy of the whole island per month (right). (2017). Source: Own elaboration with IBESTAD data

The number of vehicles is very high, due to the presence of an important rent-a-car activity. Vehicles are distributed territorially by fiscal considerations: the most extreme case is this of Escorca, where the car ownership rate is 22,000 vehicles per 1,000 inhabitants.

The island has two railway lines and one subway line, but its territorial coverage is feeble, particularly in tourist areas, with the exception of the Sóller railway, a tourist attraction in itself. The structure of the intercity bus network is essentially this of spokes directed towards Palma, with great concentration on the east coast.

The demand for the rail is not subject to the same seasonality of the intercity bus, whose demand is closely linked to tourism. The correlation between the airport demand and the bus demand is remarkable, while the huge share of the single ticket for bus users is another proof of the sporadic nature of its patronage.

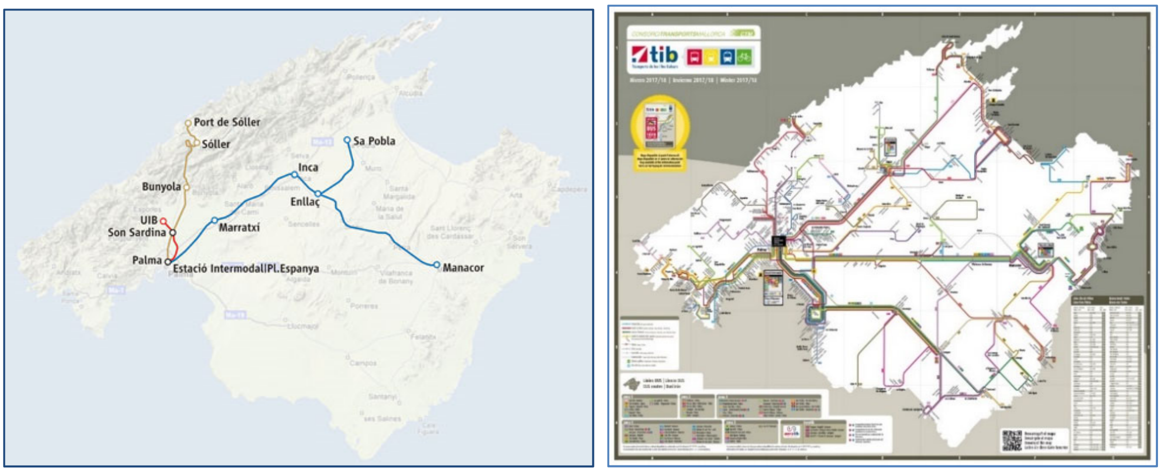

Fig.2 - Railway network (left) and intercity bus (right). 2017. Source: trenscat.com and CTM (2018)

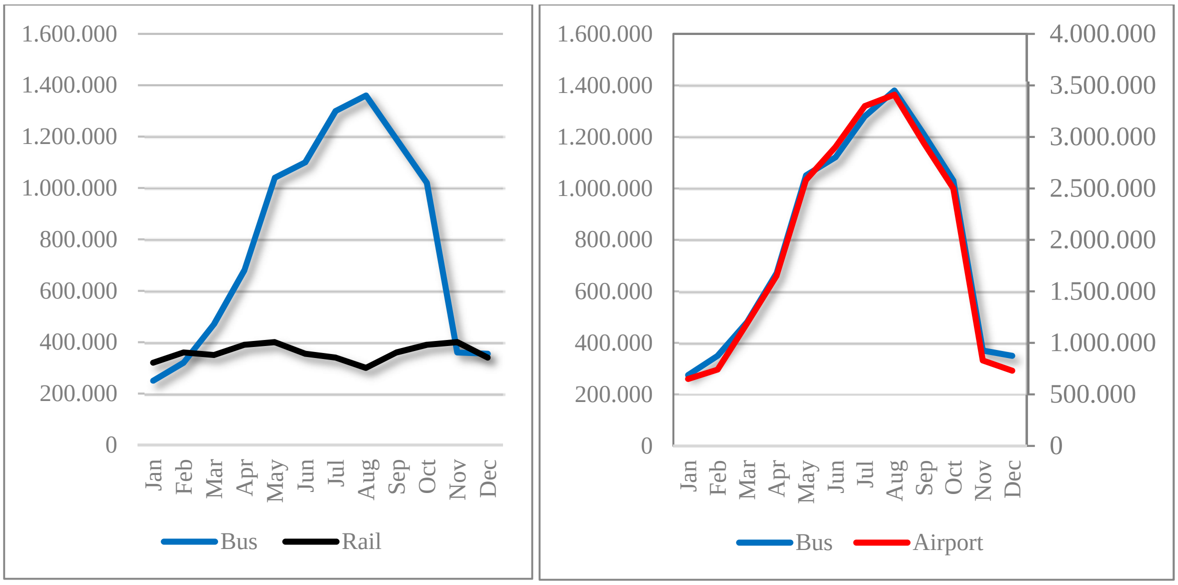

Fig. 3 - Monthly demand by transport mode: Bus and rail (left) and bus and plane (right). 2015. Source: CTM (2017 c).

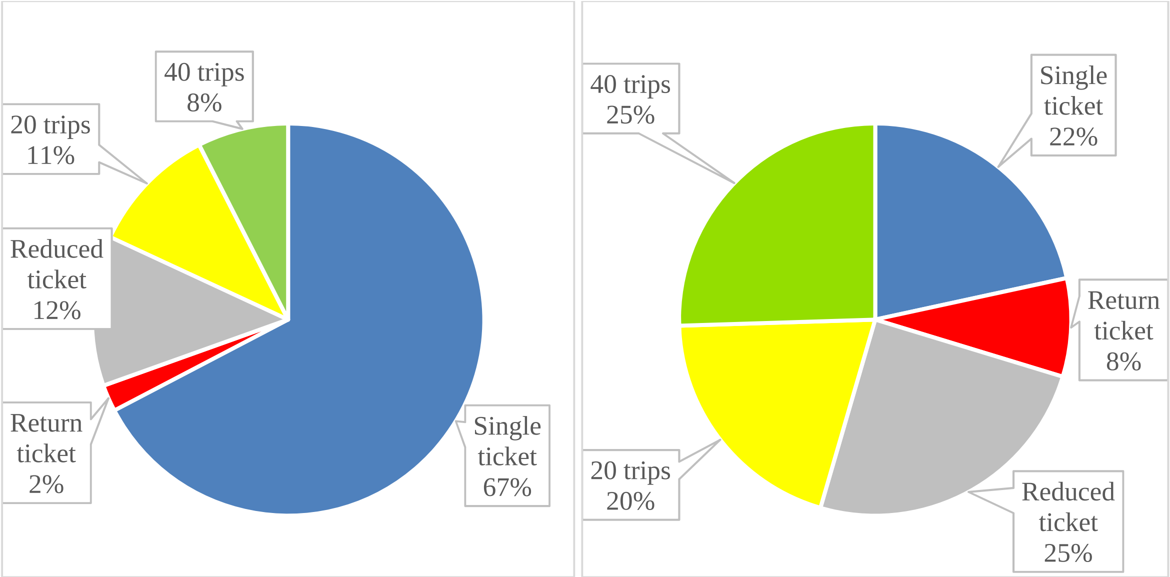

Fig.4 - Share of transport tickets: Bus (left) and Rail (right). 2016. Source: CTM (2017 c).

2 THE INPUTS

2.1Conventional sources

The information available for calibration was initially of two types:

- The one from official sources, with disaggregation, at best, at municipal levela or at line level.
- The one available by the operator itself, of a strictly internal nature, on a line basis lines (lines 100, 102, 104, 105, 106, 107, 111, 500, 501, 502, 503, 505, 507, 515, 520, 525, 530 y 811). It included demand data for 271 Origin-Destination pairs in nine tariff groups and other data (pax-Km, total revenues per line, etc.).

Given the complexity of the variation of the new tariff structure (based on number of areas crossed and accumulation of travel points), a face-to-face survey of revealed preferences was carried out among almost one thousand users, which shed enough light on that particular problem.

2.2 Possible alternatives

As the problem of lack of enough granularity to characterize the demand factors persisted, a research of alternative means was carried out. Many references to the potential of big data were found (Anda, 2017) and a large sample of analyses based on mobile phone data were of public domain (Alexander, 2015; Bonnel, 2015), besides many other related to different innovative sources of information, such as smart cards. But no solution that could identify trips on a detailed basis was available. In particular, mobile phone data could not provide transport mode information with the required reliability.

Some warnings were also found on the topic of potential problems of trying to use data not oriented to mobility analyses, mainly in terms of data volume availability and owners' willingness to allow it to be used by third parties (Milne y Watling, 2019). But something had to be done and two highly atypical sources of information showed some interest:

- *TripAdvisor* as an indicator of attraction.
- *Booking* as an indicator of tourist residence location.

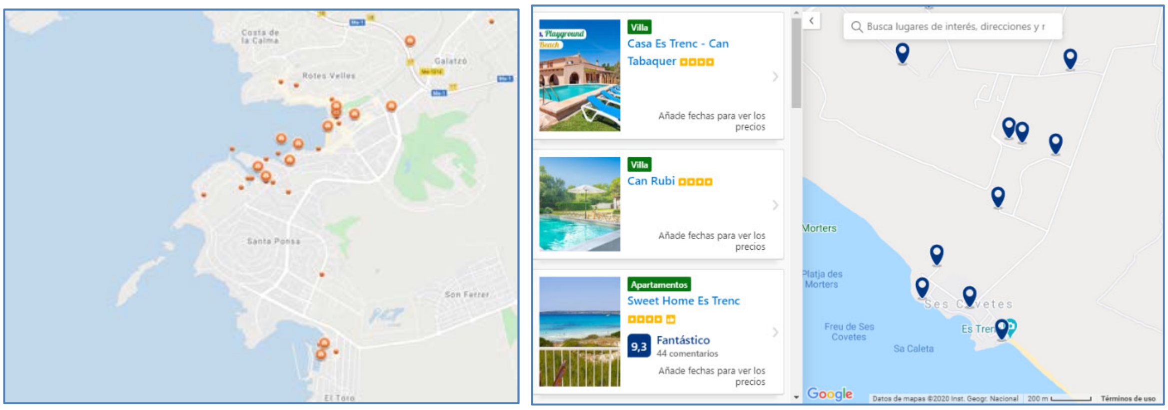

Fig. 5 - Screenshots of TripAdvisor (left) and Booking (right) websites.
Source: TripAdvisor.es and Booking.com.

2.3 TripAdvisor

TripAdvisor.com is a website owned by Tripadvisor, Inc. that provides reservations for travel-related activities, with the particularity of collecting user reviews. In that sense, *TripAdvisor* acts as a popularity survey. The basis of using this source is the hypothesis that the number of visits to a certain site of tourist interest is strongly correlated with the number of opinions recorded on *TripAdvisor*, irrespective of their attitude (positive, neutral or negative).

In total, 198 locations were analyzed manually on which 933,934 opinions were found.

The information obtained was as follows:

- Location of the tourist site.
- Type of tourist interest (general, leisure, accommodation, catering).
- Number of opinions collected.

2.4 Booking

In Majorca there is official information on the number of accommodation places per municipality, but without further disaggregation. As there is a notable dispersion and there is a great diversity of establishments of very different sizes, it was hypothesized that the territorial distribution of beds within each municipality could be significantly proportional to the location of establishments.

The source of information in this case was Booking, a virtual agency specialized in hotel reservations, owned by Booking Holdings Inc., a holding company listed on the American Nasdaq that includes other tourism-related companies such as Kayak or Momondo.

Booking offers reservations for establishments whose location can be viewed in an on line map. As in TripAdvisor, Booking has an option for user valuation, but this feature was not considered relevant and the analysis consisted of merely identifying the different locations according to a predefined zoning, related to the bus stops, simply using the “map view” available in the search engine. A total of 2,114 establishments were identified in a total of 203 different zones.

3. THE FORMULATION

In this case, the objective was to calculate the bus demand, so the analysis was focused only in this transport mode, leaving aside the railway (both because the corridors mostly do not coincide, and because of its very different seasonality) and the car (with a much larger market share).

A generalization of the classic gravity model was used, as follows:

$$T_{ij} = \alpha\ \pi(G_{rij}^{g})\ \pi(A_{sij}^{a})\ c_{ij}^{k} \qquad (1)$$

Where the notation is as follows:

- T_{ij} = volume of demand between zones “i” and “j”.
- α = parameter.
- π = multiplication operator.
- r = ordinal index of the different possible indicators of trip generation.
- s = ordinal index of the different possible indicators of trip attraction.
- G_{ij}= Generating potential of zone “i” and zone “j”.
- g = parameter of the generation factors, equal to the corresponding elasticity of demand.
- A_{ij}= Attractor potential of zone “i” and zone “j”.
- a = parameter of the attraction factors, equal to the corresponding elasticity of demand.
- c_{ij}= friction factor between both zones.
- k = parameter of the friction factor, equal to the elasticity of demand to the friction factor.

The selection of the different model formulations and the selection of the corresponding variables followed a trial and error process, through regression analysis between the 2017 demand data for the 271 origin-destination pairs and various independent variables (all of them oriented to the forecast in the following phase). The best explanatory capacity was found with the following variables:

- Sum of population of origin and destination.
- Sum of indicators of tourist attraction (*TripAdvisor*) of origin and destination.
- Sum of tourist places by zone (*Booking*) of origin and destination.
- Fare distance (km). It is the nominal distance between origin and destination used for pricing. It is almost identical to actual road distance, with minor differences.
- Fare rate (€/pax-km). It is the price per pax-km that multiplied by the fare distance gives the tariff.

The number of services per line was discarded out, although it is an excellent indicator of quality from the point of view of users. The reason was the high correlation between number of services and demand, as expected in any sensible operation: the lesser the demand volume, the less services the operator provides.

3.1 The results

The results can be synthesized as follows, expressed through the coefficients of the corresponding variables (which are the corresponding elasticity) and the regression statistics.

<table>
<tr><th colspan="2">Variable/Indicator</th><th>Tourist generation only</th><th>Tourist attraction only</th><th>Generation and tourist attraction</th></tr>
<tr><td rowspan="5">Elas-ticity</td><td>Population</td><td>0,72</td><td>0,64</td><td>0,56</td></tr>
<tr><td>Tourist attraction</td><td>-</td><td>0,70</td><td>0,51</td></tr>
<tr><td>Tourist generation</td><td>0,65</td><td>-</td><td>0,37</td></tr>
<tr><td>Fare distance</td><td>-2,27</td><td>-2,37</td><td>-2,41</td></tr>
<tr><td>Fare rate</td><td>-2,51</td><td>-2,53</td><td>-2,62</td></tr>
<tr><td rowspan="2">Statistic s</td><td>Multiple correlation coefficient</td><td>0,66</td><td>0,67</td><td>0,68</td></tr>
<tr><td>R2 adjusted</td><td>0,42</td><td>0,44</td><td>0,45</td></tr>
</table>

Table 1 - Elasticities and indicators obtained. Source: Own elaboration.

Although the quality of the adjustment is not high, the values of the exponents are very reasonable. From the point of view of forecasting, the similarity of exponents of the fare distance and the fare rate were interesting, corroborating the fact that the trip friction is given, simply, by the trip price.

4. CONCLUSIONS AND FINAL REFLECTIONS

An adequate understanding of mobility in a specific area requires data of according quality, which usually official sources do not provide, for lack of detail. Sometimes these data can be obtained through surveys or other measurements, but often there are important restrictions due, for example, to seasonality.

Many studies have a strict completion period, especially if they are related to tendering processes, and then it is not reasonable to waste any effort that is expected to be fruitless.

In today's world there are numerous sources of information that can act as explanatory variables of demand or as *proxies.* In the study described above, even with a very simple approach, it was possible to find some clues about the trip attraction and generation, in particular thanks to two portals with a purely commercial objective: *TripAdvisor* and *Booking*.

The results obtained, have not only been useful for the study, but also point in the direction of the potential value of the huge amounts of information currently available, which are usually a mere by-product of commercial businesses.

The data obtained in the study were manually obtained, but this did not entail excessive consumption of resources.

Although it is conceivable to obtain that information massively, thanks to some automation, the data is not designed for that purpose and the automation would foreseeably face strong protections.

But it is not unlikely that the companies that own this type of data can sell them to third parties, as some mobile phone operators are already doing, provided privacy and other legal issues are respected. For such companies, this is not their core business and it will never be a source of large-scale revenue.

But it seems that there is a certain market and the companies in question have experience in diversifying very intelligently. Everybody would benefit from it, not least transport planners and transport economists.

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OBTENCIÓN DE MATRICES ORIGEN DESTINO PARA MODELOS MESOSCÓPICOS A PARTIR DE DATOS GPS

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RESUMEN

El objetivo del presente artículo es exponer la metodología seguida para obtener matrices Origen/Destino a partir de datos masivos geolocalizados (trazas GPS). Se trata de una metodología que actúa de manera complementaria con los procedimientos tradicionales de aforo. Las principales ventajas derivadas de esta metodología radican en una reducción de tiempos y de costes en los proyectos, además de aportar mayor fiabilidad en los resultados de los modelos al tratarse de matrices muestra obtenidas a partir de valores reales.

Existen distintas variaciones de la metodología, pudiendo ésta adaptarse a proyectos tanto de micromodelación como de macromodelación, convirtiéndola en una metodología muy flexible.

Esta metodología ya ha sido probada en distintos proyectos, obteniendo resultados satisfactorios, aunque también es cierto, que se encontraron ciertas debilidades en los procesos. Estas debilidades se han subsanado mediante la aplicación de algoritmos de Inteligencia Artificial (IA).

El presente artículo detalla los diferentes procedimientos de obtención de matrices, así como un análisis de sus debilidades y mejoras desarrolladas. Finalmente, una comparativa con los modelos tradicionales de obtención de matrices y los resultados obtenidos en los proyectos en los que se implantó esta metodología.

1. PROCEDIMIENTOS

Como se ha mencionado previamente, existen ciertas diferencias a la hora de aplicar la metodología a un proyecto de macrosimulación o a uno de microsimulación. A continuación, se exponen mabas metodologías, así como sus diferencias y las debilidades.

1.1 Macromodelización

El proceso de macromodelización responde al siguiente esquema:

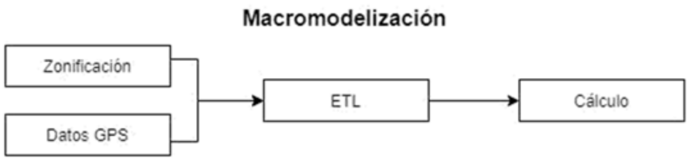

Figura 1. Esquema del proceso aplicado a macromodelización. Fuente: Elaboración propia

A continuación, se detalla cada uno de los componentes del proceso:

- Zonificación
  Se definen cada una de las áreas que servirán para establecer los posibles orígenes y destinos de los viajes. Aquellos viajes que comiencen o acaben fuera de las áreas establecidas, son agrupados en un área ficticia, denominada “Zona exterior”
- Datos GPS
  Cada registro representa la posición de un vehículo en un instante determinado.
- ETL (Extraxt Transform Load)
  En este proceso se transforman los datos existentes, se generan nuevas variables y se eliminan aquellos registros que no son necesarios para el proceso “Cálculo”. Con este proceso se reduce el tiempo de cálculo.
- Cálculo
  Una vez que se han realizado los pasos anteriores, se extraen los orígenes y destinos de cada uno de los trayectos. El resultado final es un archivo formato csv con la matriz OD deseada.

1.2 Micromodelización

El proceso de microsilulación responde al siguiente esquema:

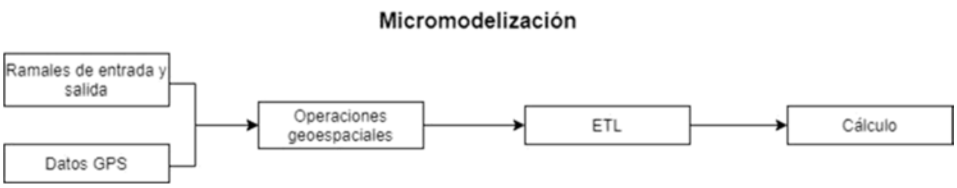

Figura 2. Esquema del proceso aplicado a microsimulación. Fuente: Elaboración propia.

Se observa cómo, las principales diferencias entre metodologías radican en los datos de entrada y en las operaciones geoespaciales.

A continuación, se detalla cada uno de los componentes del proceso:

- Ramales de entrada y salida
  Se definen cada uno de los ramales que intersectan con el contorno del área de estudio.
- Datos GPS
  Cada registro representa la posición de un vehículo en un instante determinado.
- Operaciones geoespaciales
  El objetivo de este paso es doble: disminuir la cantidad de registros que no se encuentran en nuestra área de estudio y eliminar posibles *outliers* o registros fuera de rango.
- ETL
  En este proceso se transforman los datos existentes y se generan nuevas variables necesarias para procesos posteriores. Este proceso es fundamental para reducir tiempo de cálculo.
- Cálculo
  Una vez que se han realizado los pasos anteriores, queda un conjunto de datos tratados de los cuales se extrae el ramal de entrada y salida de la zona de estudio de cada uno de los viajes. El resultado final es un archivo csv con la matriz deseada.

1.3 Debilidades encontradas

Como cualquier metodología, presenta una serie de ventajas, pero al mismo tiempo una serie de debilidades. Es importante realizar un análisis de estas a fin de conocer las flaquezas del proceso y poder implementar poco a poco medidas que permitan corregirlas.

A continuación, se enumeran las debilidades encontradas principalmente en la metodología de micromodelización. Cuando se aplica la metodología en los casos de micromodelización, existen una serie de inconvenientes que no ocurren en los casos de macromodelización. Esto se debe a que el detalle que se busca en este tipo de proyectos es mucho mayor.

Los dos principales inconvenientes son:

- Tiempo elevado a la hora de preparar los datos de entrada.
  La preparación de los datos de entrada es una tarea de carácter manual. Además, al tratarse de una tarea de esta naturaleza, hay que tener en cuenta la posibilidad de introducir errores de carácter humano.
- Tiempo elevado en el proceso “Cálculo”
  Se trata del proceso que más tiempo y recursos de la máquina consume.

1.4 Mejoras implementadas

A continuación, se describe una herramienta desarrollada que emplea una metodología mejorada que subsana los principales inconvenientes mencionados anteriormente.

Esta nueva metodología emplea algoritmos que provienen de distintos campos de la Inteligencia Artificial (IA), como son algoritmos de *machine learning* y algoritmos de búsqueda.

El esquema de esta nueva metodología es el siguiente:

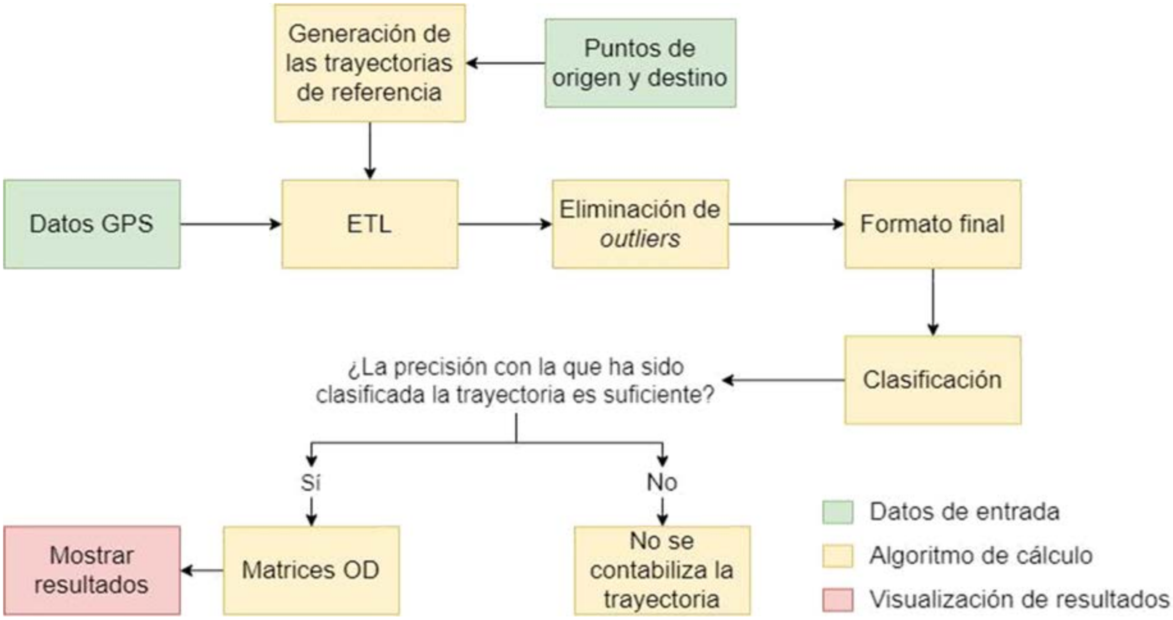

Figura 3. Metodología de mejoras implementadas. Fuente: Elaboración propia.

Los procesos de la metodología actualizada son los siguientes:

- Datos de entrada.
  - Datos GPS.
    Igual que en los casos anteriores, cada registro representa la posición de un vehículo en un instante determinado.
  - Puntos de origen y destino.
    Puntos en las calles que representan los orígenes y destinos de la matriz OD.
- Generación de las trayectorias de referencia.
  A partir de los puntos de origen y destino se generan todas las posibles rutas entre el cada origen y destino, que servirán para clasificar los viajes.
- ETL.
  Se transforman al formato deseado las variables existentes y se generan nuevas variables para hacer posible la clasificación de las trayectorias.

- Eliminación de *outliers*.
  Se eliminan las trayectorias que no cumplan con una serie de condiciones mínimas que, en el caso de tenerlas en cuenta, generarían ruido en la clasificación e, incluso, llegar a generar una clasificación errónea.
- Formato final.
  Una vez realizado los pasos anteriores, se preparan los datos para que puedan ser ingeridos por parte de los algoritmos de *machine learning.*
- Clasificación.
  Mediante algoritmos de *machine learning* se identifican las carreteras por las que entra y sale cada vehículo de la zona de estudio.
- Matrices OD.
  Se genera la matriz OD deseada.

Gracias a esta nueva metodología, no solo las debilidades de la metodología anterior son subsanadas, sino que además se obtienen nuevas mejoras:

- Los tiempos de preparación de los datos de entrada y de cálculo se han reducido.
  La preparación de los datos es sumamente menor empleando la nueva herramienta, siendo 15 veces menor en las pruebas realizadas. A su vez, el tiempo de cálculo se han reducido de manera destacable, siendo ahora aproximadamente 60 veces más rápido que la metodología anterior.
- Se convierte en un proceso automático.
  Se han automatizado todos los pasos que antes eran manuales (la única tarea manual es generar los puntos de origen y destino).
- Se ha creado una interfaz de usuario.

Ahora existe una interfaz gráfica que le permite al usuario no solo explotar los datos de manera sencilla, sino que además puede realizar un análisis exploratorio de los resultados obtenidos.

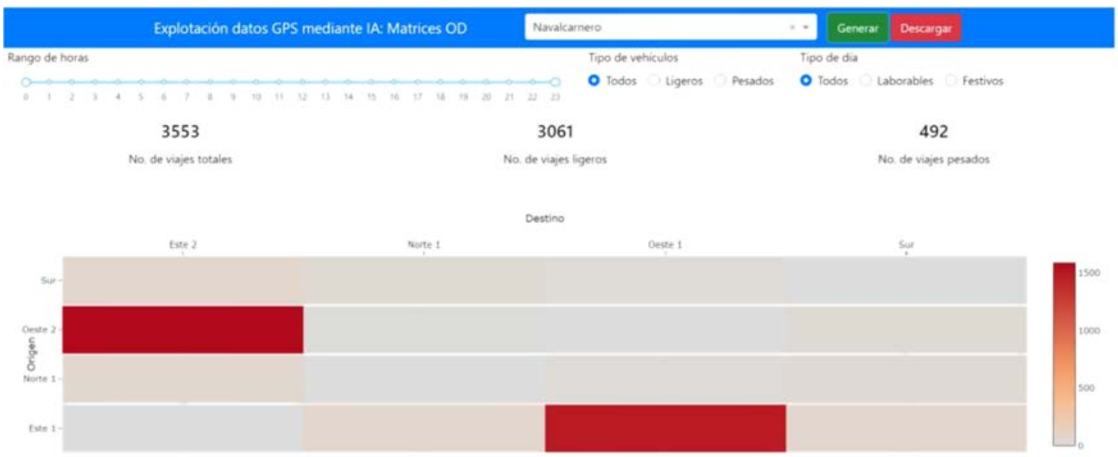

Figura 4. Interfaz de usuario desarrollada. Fuente: Elaboración propia.

Finalmente, la distribución de los vehículos obtenida mediante la nueva herramienta, como ocurría con la herramienta anterior, es similar a la distribución obtenida mediante aforamientos físicos (porcentaje de vehículos totales capturados por movimiento).

2. VENTAJAS Y DESVENTAJAS DE LA METODOLOGÍA CON RESPECTO A LAS METODOLOGÍAS TRADICIONALES

Actualmente se dispone de una amplia gama de metodologías para la detección de tráfico, desde la más tradicional, como es el caso del aforo manual, hasta las más actuales, como es el de lectores de matrículas o sistemas de detección por bluetooth.

La nueva metodología puede considerarse que comparte el mismo principio que los sistemas de detección por bluetooth, dando por hecho que hoy en día todo el mundo viaja con un móvil encima y que de la información que este generase puede obtener un beneficio, concretamente la información es el posicionamiento del aparato.

La diferencia es que los sistemas de bluetooth usan la detección de móviles que pasan por una sección en la que se colocan los detectores y esta nueva metodología es mucho más flexible y fiable.

Esta nueva metodología permite solventar los principales problemas de los métodos tradicionales disponibles, al ser una metodología basada puramente en la compra de datos de posicionamiento y su procesamiento. A continuación, se detallan las ventajas de la metodología:

- No son necesarios trabajos de instalación ni mantenimiento in situ en la zona de estudio, eliminando todos los problemas relacionados con: corte de vías por obras para su instalación o reparación, dependencia de las inclemencias meteorológicas o la no detección de vehículos a baja velocidad.
- Los resultados no se ven afectados por condiciones meteorológicas adversas.
- Proceso muy económico, puesto que no existen instalaciones al uso para la obtención de los datos, sino que el coste dependerá del volumen de datos que se quieran comprar y del ingeniero de datos que los procese bajo esta metodología.
- Reducción de tiempos, esta metodología permite obtener información de una zonificación mucho más amplia de la que permitirían el procesamiento por separado de cada una de las zonas como se realizaría de forma tradicional.
- Flexibilidad, al disponer de los datos en bruto el procesamiento de los datos se pueden orientar de diferentes enfoques de un mismo proyecto, permitiendo obtener matrices distintas si se desean cambiar la zonificación cambiando el proceso de tratamiento de los datos. Con las metodologías tradicionales requeriría la realización de nuevos aforos con el incremento del coste con cargo a proyecto que supondría.

- Mayor alcance temporal, permite tratar datos en bruto de varios días por lo que permite realizar por lo que permite un análisis del comportamiento del tráfico en la zona de estudio que no se encuentre limitada a horas como ocurre con las metodologías tradicionales.

Por contraposición se pueden mencionar las siguientes desventajas detectadas:

- Limitación de precisión en el posicionamiento, para casos microscópicos algunos datos pueden presentar desviaciones de posicionamiento. Esta desviación no depende tanto del dato sino del móvil que se encuentra emitiendo la señal.
- Como consecuencia del punto anterior, no es posible llevar a cabo una segregación de tráfico por carriles.
- Ratios de ocupación de vehículos, el proceso tiene en cuenta el posicionamiento de los móviles y GPS, pero no es capaz de detectar si esos móviles o GPS van en el mismo vehículo y por lo tanto el viaje sería solo uno.
- Representatividad de la muestra, al estar tratando con los datos de posicionamiento la representatividad dependerá en mayor o menor medida de las compañías que hayan cedido esos datos. En un supuesto idílico, si solo existiera una compañía la muestra obtenida con esta metodología sería prácticamente toda la población. Este es el principal motivo por el que estas matrices se usan como apoyo en los estudios de tráfico, pero no son, ni se pretende que sean, la matriz de origen y destino definitiva. Siendo necesario complementar esta metodología con otras tradicionales.
- Preprocesamiento, es necesaria una tarea de limpieza de los datos en bruto para incrementar la fiabilidad que se realiza de forma manual, por lo tanto, se encuentra sujeta a un porcentaje de error en el tratamiento de los datos.

3. APLICACIONES

3.1 Calibración de matrices

El principal objetivo de eso de la metodología es una mejora de la calidad de resultados en los trabajos de calibración de los modelos de tráfico. Llegado este punto es necesaria la diferenciación de la metodología a nivel macroscópico y microscópico.

- Nivel Macroscópico

Tradicionalmente la obtención se matrices obtenían a partir de métodos tradicionales de recogida de datos como las encuestas domiciliarias o de intercepción, y en función de la población se podía obtener una primera matriz para iniciar el proceso de calibrado manual.

- Nivel Microscópico

  Tradicionalmente la obtención de matrices se realiza a través de un ajuste (dinámico o estático) entre una matriz de ceros y unos y un plan de aforos de la red del modelo. La matriz resultante del ajuste es el punto de partida para el inicio de la calibración manual.

En ambos casos el proceso de calibración manual es muy sensible a los datos de entrada, resultados de encuestas para macro y de los aforos para micro. La calidad de estos condiciona en gran medida el tiempo que posteriormente se invierte en la calibración manual del modelo para el cumplimiento de los estándares de calidad del modelo.

El uso de las matrices estimadas a partir del posicionamiento GPS añade un grado de robustez a todos estos procesos.

A nivel macroscópico permite corregir los sesgos que derivan de las encuestas. Puesto que el posicionamiento es un dato real que queda registrado, y no depende del sesgo generado por el comportamiento real del usuario versus comportamiento que el usuario afirma tener.

A nivel microscópico permite obtener una matriz resultante del ajuste más cercana al comportamiento real en la red, eliminando los errores derivados de un uso de matriz ficticia de ceros y unos que requiere un amplio conocimiento de la red y puede generar grandes inconsistencias que dan lugar a procesos de calibración manual muy tediosos.

En cualquier caso, es importante remarcar que no se trata de emplear directamente la matriz de posicionamiento GPS como la matriz a partir de la cual iniciar el proceso de calibrado manual. Si no como un elemento complementario a las metodologías tradicionales repercutiendo en un incremento de la fiabilidad de los resultados y una reducción de tiempos de calibrado manual.

3.2 Comprobación del tamaño de la muestra

Una vez estimada, calibrada y validada la matriz a partir de la matriz de datos de posicionamiento GPS y las metodologías tradicionales, se realiza una última comprobación que consiste en estimar si la muestra es estadísticamente válida sobre el universo.

Esta comprobación se realiza debido a que la matriz que se usa como complemento a los procedimientos tradicionales en el proceso de calibración es una matriz que representa una muestra de la población, dado que los datos derivan de las compañías y usuarios que hayan compartido esa información.

Para ello, se utiliza lo indicado en la Nota de Servicio 5/2014, obre la obtención del tamaño de la muestra, por medio de la siguiente expresión:

$$T_{ij} = \alpha \, \pi(G_{rij}^{g}) \, \pi(A_{sij}^{a}) \, c_{ij}^{k} \qquad (1)$$

$$m = \frac{k^2\, N\, p\, (1-p)}{e^2\, (N-1) + k^2\, p\, (1-p)} \qquad (1)$$

Donde:

m: Tamaño estimado para la muestra lauestra.
n: N: Tamaño del universo
e: Error muestral deseado, en tanto por uno. El error muestral es la diferencia que puede haber entre el resultado que obtenemos preguntando a una muestra de la población y el que obtendríamos si preguntáramos al total de la población.
p: Proporción de individuos que poseen en la población la característica de estudio. Este dato es generalmente desconocido y se suele suponer que p=0,5 que es la opción más segura.
k: Constante que depende del nivel de confianza que asignemos.

Valor de k	1.15	1.28	1.44	1.65	1.96	2.24	2.58
Nivel de confianza (%)	75	80	85	90	95	97.5	99

Tabla 1. Valor de k en función del nivel de confianza. Fuente: Nota de Servicio 5/2014.

El procedimiento se basa en obtener el error muestral y el nivel de confianza, en función del universo y la muestra de partida, para cada tipología de vehículo (ligeros y pesados). Siendo la muestra representativa si la suma de los vehículos es superior a la obtenida teóricamente a partir de esta fórmula.

3.3. Costes

3.3.1. Tiempos

Los tiempos de espera en un proyecto para poder llevar a cabo los aforos y el pretratamiento y limpieza de los datos depende de muchos factores: del periodo de contratación de los trabajos, del número de puntos a aforar, la complejidad de los enlaces a aforar, el número de días aforados, etc. Y en ocasiones, tras la realización de los trabajos, en el caso de que se detecten errores de medida por fallos en los equipos de medida o que el día seleccionado a priori no sea representativo y por condicionantes del proyecto finalmente se decida que debe realizarse otro día, requiere iniciar todos los trabajos desde cero.

Toda esta problemática queda reducida a los tiempos de contratación de los datos en bruto y su tratamiento a partir de esta nueva metodología.

Si bien es cierto, dependiendo de la zonificación del modelo los tiempos pueden variar en la fase de tratamiento de los datos, una vez tratados los tiempos de cálculo son prácticamente independientes de la zonificación seleccionada.

Añadiendo la ventaja de que esta metodología permite tener a disposición del modelizador valores de comportamiento del tráfico para días medio de un mes en cualquier punto de la zonificación del proyecto. Esto resultaría imposible de llevar a cabo con las metodologías tradicionales, por ejemplo, tener controlados cada uno de los accesos y salidas d la vía de análisis de un proyecto concreto durante 24 horas, durante 1 mes o más tiempo.

Incluso proporcionando la flexibilidad de poder seleccionar otros días para el análisis del tráfico, en el caso de que se detecte cualquier anomalía en los datos del día seleccionado a priori. Esto supone que no sería necesario tener que repetir los trabajos, solo se repetiría el proceso de cálculo modificando las condiciones de salida de los datos.

3.3.2 Económicos

El coste derivado de un plan de aforos va a depender en gran medida del número de aforos, la complejidad de estos, la tecnología de los medios materiales y el número de horas/días que se decidan aforar.

Mientras que, para esta nueva metodología el coste deriva principalmente de la zonificación y de la cantidad de días.

Es importante tener en cuenta, como ya se ha mencionado, que la metodología no es sustitutiva de los aforos. Por lo que, el ahorro económico deriva de la posibilidad de reducir el número de aforos realizados a través de metodologías tradicionales, realizando solo en aquellos puntos que sean de mayor interés.

4. CASOS DE USO

4.1. Anteproyecto de Adecuación, Reforma y Conservación del Corredor Oeste de la autovía A-5

El presente apartado desarrolla los trabajos realizados en el Anteproyecto de adecuación, reforma y conservación del corredor oeste de la autovía A-5 comenzando en el p.k. 10 y finalizando en el p.k. 74, correspondiendo con el ámbito territorial de las provincias de Madrid y Toledo.

En el ámbito de este proyecto se llevaron a cabo de forma complementaria tres modelos de microsimulación para analizar el comportamiento del viario de estudio mediante la representación explícita e individual de los vehículos en la simulación, contemplándose todos los efectos dinámicos derivados de los mismos (aceleraciones, pendientes, velocidades, etc.).
El software de microsimulación permite el análisis detallado de todos los vehículos del modelo y sus interacciones en cualquier elemento existente en la zona de estudio, así como su influjo en los elementos existentes en el entorno, tales como rotondas, intersecciones, ramales, etc. correspondientes a los siguientes tramos:

- Tramo 1: Discurre desde la M-40 hasta la M-143, pk 0+000 – 25+500. En dicho modelo se incluye enlaces como: el acceso al centro comercial Tres Aguas y Alcorcón, el enlace que da acceso a Móstoles por el sur, zona de Parque Coimbra y los accesos al centro comercial Xanadú.
- Tramo 2: Zona de Navalcarnero, discurre desde el pk 27+000 hasta el pk 35+000. En el se incluyen los distintos accesos a Navalcarnero.
- Tramo 3: Discurre integramente por la provincia de Toledo, empezando en el pk 35+000 y finalizando en el 75+900. En él se incluyen los enlaces restantes hasta Toledo.

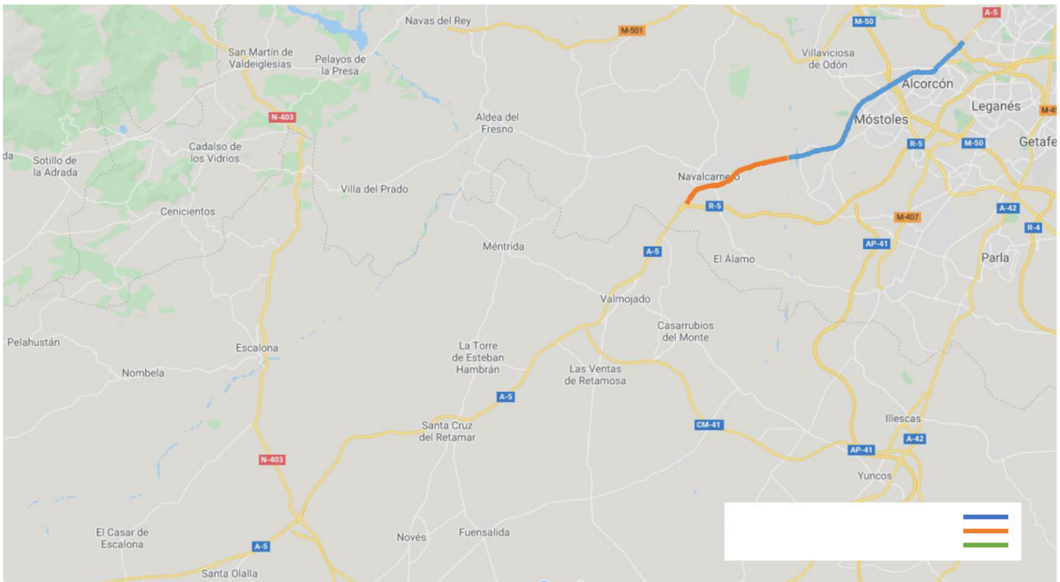

Figura 5. Ámbito de aplicación del estudio. Fuente: Elaboración propia.

A fin de comprobar la idoneidad del tamaño de la muestra de los datos de la matriz obtenida de posicionamientos GPS, se calculó el tamaño de la muestra con la fórmula que se indica en la Nota de Servicio 5/2014.

Para su aplicación se tomó como tamaño del universo el número total vehículos ligeros y pesados de la matriz final calibrada del modelo, de esta forma se puede obtener un valor del tamaño de muestra hipotético para un nivel de confianza del 99% y una porción de individuos que poseen en el universo la característica de estudio del 0.5.

Las ecuaciones de estimación de tamaño muestral tienen unos valores mínimos recomendado por la Nota de Servicio 5/2014, el error muestral debe de estar por debajo del 10%. Las pruebas realizadas con este valor proporcionan tamaños muestrales muy inferiores al tamaño de las matrices de los datos GPS.

Por lo tanto, el análisis se centra en la estimación del error muestral que se comete al usar esas matrices GPS. Para ello se llevó a cabo un proceso iterativo del error muestral que finaliza una vez que el tamaño estimado de la muestra es mayor que el tamaño de la muestra de partida (las matrices de los datos GPS).

A continuación, se muestran los resultados del análisis llevado a cabo para cada tramo y la estimación del error de muestreo que se alcanzado por el uso de esta metodología.

TRAMO 1

		LIG	PES
m	tamaño estimado de la muestra	22.623	210
N	tamaño del universo	47.387	2.359
e	error muestral deseado	< 0,01	0,09
p	proporción de individuos que poseen en el universo la característica de estudio	0,50	0,50
k	constante que depende del nivel de confianza que asignemos (99%)	2,58	2,58
m	tamaño de la muestra de partida	22.135	204

TRAMO 2

		LIG	PES
m	tamaño estimado de la muestra	3.274	57
N	tamaño del universo	7.589	365
e	error muestral deseado	0,017	0,10
p	proporción de individuos que poseen en el universo la característica de estudio	0,50	0,50
k	constante que depende del nivel de confianza que asignemos (99%)	2,58	1,65
m	tamaño de la muestra de partida	3.205	41

TRAMO 3

		LIG	PES
m	tamaño estimado de la muestra	3.398	153
N	tamaño del universo	6.286	455
e	error muestral deseado	0,02	0,09
p	proporción de individuos que poseen en el universo la característica de estudio	0,50	0,50
k	constante que depende del nivel de confianza que asignemos (99%)	2,58	2,58
m	tamaño de la muestra de partida	3.367	148

Tabla 2. Análisis del error muestral alcanzado con la implantación de las metodologías de matrices a partir de datos GPS. Fuente: Elaboración propia.

Se observa cómo, en cualquiera de los tres tramos analizados el error muestral se encuentra por debajo del 10% tanto para ligeros como para pesados, siendo esta diferencia mucho mayor para el caso de los vehículos ligeros con errores inferiores al 2%. Para los vehículos pesados se observa como el ajuste del error es menor, pero en todo caso permite el cumplimiento de las especificaciones de la Nota de Servicio 5/2014.

4.2 Proyecto de Trazado en la Autovía A-68

El presente apartado desarrolla los trabajos realizados en el Proyecto de Trazado. Autovía A-68. Tramo: Enlace Autovía A-68 / Autopista AP-15 - Calahorra. El estudio comprende el tramo de la N-232 localizado en la parte más oriental de La Rioja, desde pasado el enlace con la AP-15 (límite con la Comunidad Foral de Navarra), hasta la entrada del núcleo de Calahorra. Concretamente, entre el p.K 331,7 y el p.K 356.

Para este proyecto se realizó una microsimulación de todo el tramo, un total de 25 kilómetros de autovía con 24 centroides tal y como muestra la siguiente imagen.

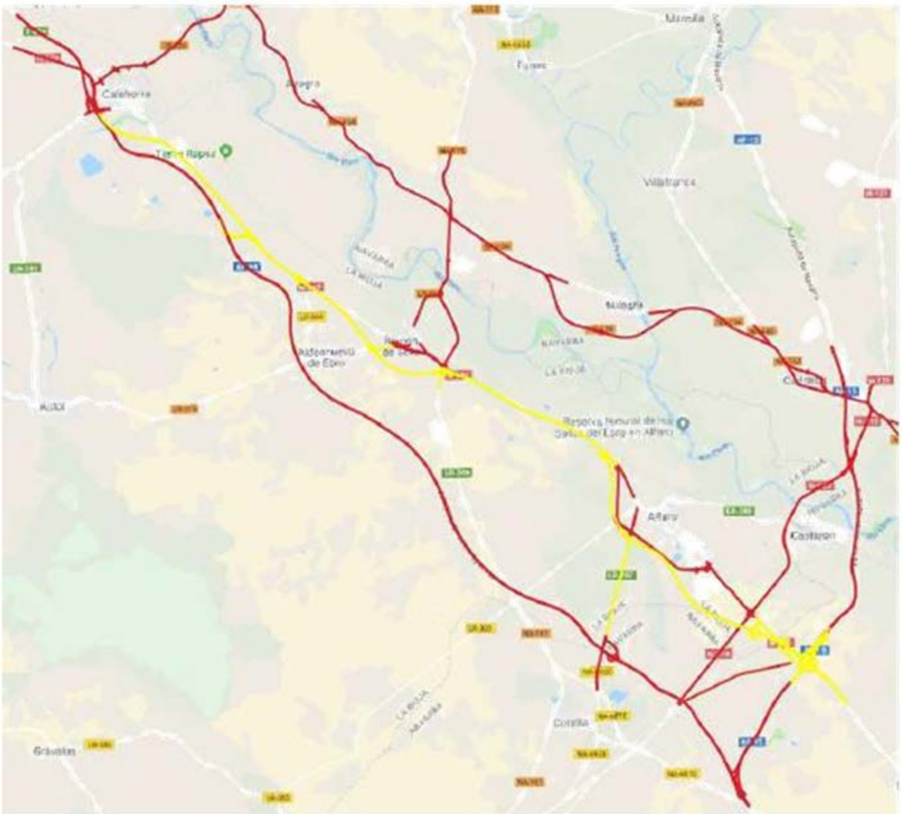

Figura 6. Ámbito de aplicación del estudio. Fuente: Elaboración propia

Para la calibración del modelo se emplearon datos del Mapa de Tráfico de 5 estaciones de aforo y los datos obtenidos de la aplicación de la metodología de posicionamiento GPS.

A fin de comprobar la idoneidad del tamaño de la muestra de los datos de la matriz obtenida de posicionamiento GPS, se calculó el tamaño de la muestra con la fórmula que se indica en la Nota de Servicio 5/2014.

Para su aplicación se tomó como tamaño del universo el número total vehículos ligeros y pesados de la matriz final calibrada del modelo, de esta forma se puede obtener un valor del tamaño de muestra hipotético para un nivel de confianza del 99% y una porción de individuos que poseen en el universo la característica de estudio del 0.5.

Las ecuaciones de estimación de tamaño muestral tienen unos valores mínimos recomendados por la Nota de Servicio 5/2014, el error muestral debe de estar por debajo del 10%. Las pruebas realizadas con este valor proporcionan tamaños muestrales muy inferiores al tamaño de las matrices de los datos GPS.

Por lo tanto, el análisis se centra en la estimación del error muestral que se comete al usar esas matrices GPS.

Para ello se llevó a cabo un proceso iterativo del error muestral que finaliza una vez que el tamaño estimado de la muestra es mayor que el tamaño de la muestra de partida (las matrices de los datos GPS).

A continuación, se muestran los resultados del análisis llevado a cabo para cada tramo y la estimación del error de muestreo que se alcanzado por el uso de esta metodología.

		LIG	PES
m	tamaño estimado de la muestra	2.911	538
N	tamaño del universo	4.132	1.114
e	error muestral deseado	0,013	0,04
p	proporción de individuos que poseen en el universo la característica de estudio	0,50	0,50
k	constante que depende del nivel de confianza que asignemos (99%)	2,58	2,58
m	tamaño de la muestra de partida	2.871	463

Tabla 3. Análisis del error muestral alcanzado con la implantación de las metodologías de matrices a partir de datos GPS

Se observa cómo, tanto para vehículos ligeros como para pesados el error muestral queda por debajo del 10% y siendo mucho menor el error en el caso de los vehículos ligeros con un 1,3% y un 4% para el caso de vehículos pesados.

5. CONCLUSIONES

Esta metodología permite alcanzar unos niveles de calidad en los proyectos de modelización superiores a los obtenidos en proyectos en los que solo se usan las metodologías tradicionales de aforo.

Además de alcanzar unos niveles de error muestral inferiores a los recomendados por la Nota de Servicio 5/2014 empleando el máximo nivel de confianza muestral (99%). Siendo este error menor en el caso de los vehículos ligeros con valores del 1% - 2%

Para vehículos pesados se alcanzan valores superiores, pero siempre inferiores a la recomendación de la Nota de Servicio 5/2014.

La mayor calidad de los datos de partida se traduce en unos mejores resultados del modelo y por lo tanto una mayor fiabilidad de estos, así como una reducción del tiempo necesario para una calibración adecuada del modelo.

En cuanto a los costes del proyecto, esta metodología permite una reducción directa de los mismos. Por un lado, con la reducción del tiempo de calibración del modelo como se ha mencionado anteriormente, y por otro, permite disminuir la contratación de campañas de campo.

En base a los dos proyectos expuestos queda demostrado que la muestra de los datos obtenidos a partir de la matriz de posicionamientos GPS es lo suficientemente representativa para usarla como elemento de apoyo y complementario a las metodologías tradicionales. Aumentando la fiabilidad del modelo, reduciendo los tiempo y costes en campañas de campo y calibrado del modelo.

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OPTIMIZACIÓN DE LA REGULACIÓN SEMAFÓRICA EN LA ZONA DEL 22@ DE BARCELONA

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ABSTRACT

Barcelona SUMP (Sustainable Urban Mobility Plan) for the 2013-2018 period included a set of measures to stimulate the change to more sustainable transportation modes, among which traffic signal configuration based on bus frequencies can be found. This document describes the pilot case implemented in the 22@ area of the city.

The approach consists of the development of a mobility simulation model including different transportation modes, relying on the commercial software Aimsun and integrating *ad-hoc* components, having a tool supporting decision-making as a result.

During the first stage of the project, a microscopic simulation model was built, including all details of the infrastructure concerning the road network (lane configuration, traffic signaling, driving constraints…), traffic light configuration and interface with input data from the City Council, public transport surface network and private vehicle demand.

Together with the model, an optimizer component implementing specific constraints to ensure a safety, efficient, sustainable mobility was developed. In this way, the resulting tool generates an optimal configuration for traffic lights that can be used for traffic management purposes, giving priority to the bus network with no relevant penalties for the private vehicle and, of course, guaranteeing safety for pedestrians.

A relevant improvement of the bus service has been obtained for the three considered scenarios, achieving an increase of the speed between 13% and 25% (average for all lines).

As expected, both travel time and the number of stops have been reduced, which results on a better level of service as the users directly perceive these two factors.

1. BACKGROUND

The Barcelona City Council continuously performs adjustments in the traffic lights configuration at local level, either because modifications of the civil infrastructure or for adapting them to new traffic conditions.

However, measures that may have an impact beyond a specific location or on more than one transportation mode require certain mechanisms for a previous assessment from the mobility point of view.

Barcelona SUMP (Sustainable Urban Mobility Plan) for the 2013-2018 period fosters the use of advanced tools in order to improve the implementation of proposed measures, from the inception and design to the deployment and maintenance, if necessary.

In that context, local authorities identified the necessity of having a flexible enough software allowing both assessment about the real impact in the whole city but also having means to test innovative mobility measures such as the ones this paper focuses on, increase of the bus network performance while preserving safety for the people in the pedestrian’s crosses.

Optimizing traffic lights settings is a well-known problem in traffic engineering and minimizing the sum of delays the most common objective. For example, for the particular case of a two-stage traffic signal, the first analytical solution can be found in Webster (1958) but many other approaches appeared from these years on, addressing both fixed-time and adaptive control.

Adaptive models are based on dynamic phase changing defined by traffic flow fluctuations detected by means of real-time sensors, forecasted from historical data or combining both as shown in Mirchandani (2001).

These models can also add stochastic parameters in terms of uncertainty for inflow or outflow at intersections as described in Tong (2015).

On the other hand, fixed-time systems are based on deterministic values for the cycle and green times that have been previously calculated for specific time intervals and day types, which is the operating mode in the case of the city of Barcelona since regular patterns exist.

In these situations, dealing with signal coordination (offsets) is a key factor to provide required performance for a certain transportation mode, such as buses.

How the concept of the offset can provide support to coordinate and synchronize a network can be found in Gartner (1975) and later evolved by Möhring (2006) where non-uniform cycle lengths are also introduced.

Next sections describe the mathematical approach to tackle the problem of prioritizing public transport against private vehicle in the study area, where the bus network is composed of horizontal and vertical lines creating a grid with shared intersections which add a degree of complexity.

2. MATHEMATICAL APPROACH

2.1 Delay at signalized intersections

Over the last decades, several models have been developed to estimate vehicle delay at signalized intersections. One of the first expressions was made by Wardrop (1952) assuming that the arrival flow rate was uniform, leading to a very simple formula (1):

$$d = \frac{\left(r-\frac{1}{2s}\right)^2}{2c(1-f)} \tag{1}$$

Where,

d = average delay per vehicle
r = effective red time
s = saturation flow
c = cycle length
f = traffic flow

Afterwards, a few models appeared by Newell (1956), Webster (1958) or Miller (1968), who developed new expressions where the uniform arrival hypothesis were no longer used.

The model proposed by Webster assumes that arrivals are random but with a uniform departure flow. It offers a better approach on the delay calculation for low traffic intersections (intersections with high intensity usually tend to an exponential behavior when it comes to arrivals). Webster expression (2) is as follows:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda X)} + \frac{X^2}{2f(1-X)} - 0.65\left(\frac{c}{f^2}\right)^{1/3} X^{2+5X} \tag{2}$$

Where,

d = average delay per vehicle
λ = green ratio

X = degree of saturation
c = cycle length
f = traffic flow

The first term corresponds to the delay due to uniform arrival flow, which is equivalent to Wardrop expression (1). The second term is the delay caused by the random arrival assumption. Finally, Webster added a third empirical term as a tuning to the formulation.

Miller solved the delay calculation with a different approach; in this case, he focused on the overflow delay. In most cases, the excessive delay at intersections are due to a peak in the arrival flow. Miller took into account the average number of vehicles missing a traffic light cycle. The first term of the expression (3) is the delay due to a uniform flow rate. The second term express the average delay when there are vehicles left in the queue when red phase starts.

$$d = \frac{c(1-\lambda)}{2(1-\lambda X)}\left(c(1-\lambda) + \frac{(2X-1)I}{q(1-X)} + \frac{I+\lambda-1}{s}\right) \quad (3)$$

Where,

d = average delay per vehicle
λ = green ratio
X = degree of saturation
c = cycle length
f = traffic flow
I = variance to mean ratio of flow per cycle

Newell, on the other hand, focused on the distribution arrival at the intersection. He studied general arrival and departure distributions for delay models at signalized intersections. He expressed (4) that the average delay experienced by a vehicles is as follows:

$$d = \frac{c(1-\lambda)^2}{2(1-y)} + \frac{IH(y)X}{2f(1-x)} \quad (4a)$$

$$y = \frac{sg-qc^{0.5}}{Isg} \quad (4b)$$

Where,

d = average delay per vehicle
λ = green ratio
X = degree of saturation
c = cycle length

f = traffic flow
I = variance to mean ratio of flow per cycle
y = flow ratio

Due to the difficulty obtaining some of the variables that define the arrival flow variance, various institutions started to develop simpler expressions based on empirical experimentation. One of the best known is the High Capacity Manual, which proposed a first equation in 1985 that was improved later by Reilly (1994) with this expression (5):

$$d = 0.38 \frac{C(1-\lambda)^2}{1-\lambda[Min(X,1)]} + 173x^2 \left[(X-1) + \sqrt{(X-1) + \frac{mX}{C}}\right] \quad (5)$$

Where,

d = average delay per vehicle
λ = green ratio
X = degree of saturation
c = cycle length
C = capacity
m = calibration term representing the effect of arrivals type

The utilization of a minimum term is due the fact that it is considered that oversaturated intersections have infinite delay (no estimation when X > 1).

2.2 Offset coordination

The formulation proposed regarding offsets is based on the paper written by Estrada (2009). There, authors proposed a reduction of travel time for several bus lines by means of offset modifications. To do so, they stablishes an expression (6) in function of the offset to be minimized, including the sum of the following three terms concerning buses:

- *Travel time in links*: average time to travel from one signalized intersection to another without taking into account the time a bus spends at stops.
- *Time lost at stops*: time spent at stops due to the passengers entering or leaving. It also includes the time lost due to acceleration and deceleration during maneuver.
- *Time lost at intersections*: time spent during red phase. Same as before, the acceleration and deceleration times are included.

Since travel time and time lost at intersections will be obtained by means of a simulation model, they will not be further developed from the theoretical point of view. On the other hand, the formulation developed by Estrada will be used further as a starting point to estimate the delay in links.

The evaluation of the total amount of time that a bus is stopped at intersections is a function (6) of the cycle time, green time and signal offset. To evaluate the intersection time, it requires determining the number of signal cycles that had passed since a bus arrives, by referencing the arrival to the signal cycle.

$$n_s = [\frac{t_{av} - theta}{T_c}] \quad (6a)$$

$$s = t_{av} - n_s T_c - theta \quad (6b)$$

Where,

s = arrival time referred to signal cycle
t_{av} = arrival time
$theta$ = offset referred to previous intersection
T_c = cycle length
n_s = number of cycles

Once the arrival times is referenced, it can be then determined if the bus will pass (green phase) or stop (red phase). Therefore, the expected delay in the link will be as detailed in expression (7):

$$t_{in} = \begin{cases} T_c - s & if \quad s > g \\ -s & if \quad s < 0 \\ 0 & if \quad 0 \leq s \leq g \end{cases} \quad (7)$$

Where,

t_{in} = time stop at the intersection
s = arrival time refereed to signal cycle
g = start of the green signal

3. METHODOLOGY

Proposed methodology envisages an underlying traffic simulation model since even unable to generate a solution by themselves, simulation models are useful as a tool for the analysis of a system and its behavior under certain conditions. Aimsun is used as the simulation environment.

For each simulation, inputs can be changed manually after analyzing the outputs of the previous one. Nevertheless, as the number of parameters or size of the model grow, this process becomes as inefficient as it is inappropriate. Then, the need for a custom component giving support to the optimization process raises.

This component must implement an import and export interface with the model together with analysis capabilities through an *ad-hoc* algorithm that runs in the context of a loop process until a suitable solution is found.

As shown in Figure 1, the initial step of the iterative process is the model simulation and the corresponding export of information about the behavior of private vehicles and tracking of buses to a custom database.

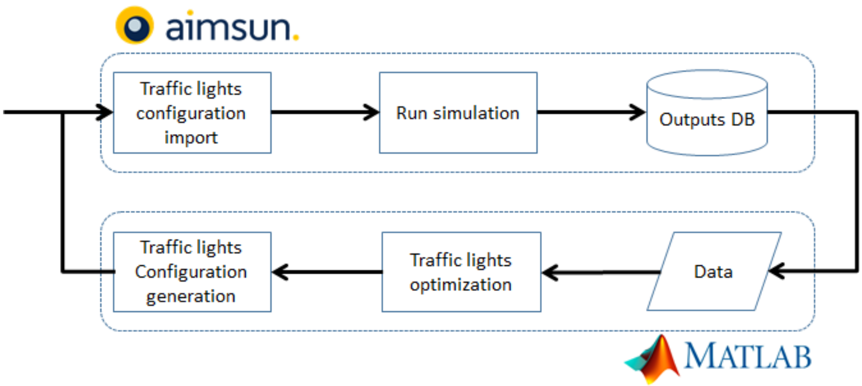

Fig. 1 – Optimization loop process

Then, simulation outputs are read by a component developed in Matlab, where optimization takes place in two sequential stages, deeply explained in next section:

- *Phases*: calculation of the available green time for each of the different existing phases in such a way that vehicles have the least delay possible while satisfying safety constraints for both vehicles and pedestrians as requested by the City Council.
- *Offsets:* calculation of optimal offsets between consecutive traffic lights to improve the performance of the bus network by means of generation of green waves considering stop and travel times.

4. OPTIMIZATION

4.1 Phases

This stage has two objectives: the extension of green windows for buses and the reduction of delay time for private vehicles at the rest of intersections. The following steps are taken to achieve the objectives this stage aims at:

1. A mathematical formulation gets the optimal starting time and duration of green phases for each signal group at every intersection in such a way that safety structure of the junction is preserved.

2. Definition of the optimization variable (e.g. delay time) respect to decision variables, in this case the phases. That way, it is possible to find a combination of phases that minimizes the optimized variables for each intersection.
3. Definition of the boundary conditions of the problem which are obtained from the constraints: crossing time for pedestrians, minimum duration of phases and intersection saturation.

4.1.1 Structure of traffic lights

In traffic lights, start and end of the green time for each signal is defined by its structure in addition to the existing phases and the definition of programs and control plans.

- *Phases*: As they are the time intervals that compose a cycle, the sum of their durations must be equal to the cycle to preserve the structure. Each phase is composed of sub phases that may have variable length (susceptible to be optimized) or fixed (for example, there are phases that, for safety reasons, are red for all signal groups, lasting 3 s or 6 s.).

Fig. 2 – Example of phases for each signal group of an intersection

Figure 2 shows an example in terms of a bar chart. The intersection has 3 signals (G1V, G2V and G3V) and 3 phases (A, D and H). Each phase is also divided in sub phases; for example, phase D also includes sub phases e, f and g.

- *Programs*: they define combinations of duration for each phase and the corresponding offset, which is used for synchronization with other intersection. Table 1 defines 4 programs, from P1 to P4 (values in bold face are used in Expression (8)).

Programs			A	b	c	D	e	f	g	H	i	j
			#	**3.0**	**3.0**	#	**3.0**	**3.0**	**3.0**	#	**3.0**	**3.0**
Plan	Cycle	Offset										
P1	96	94	**40.0**			**30.0**				**26.0**		
P2	96	53	41.0			27.0				28.0		
P3	96	56	47.0			27.0				22.0		
P4	72	12	32.0			27.0				18.0		

Table 1 – Example of signal programs of an intersection

- *Control plan*: hourly and daily distribution of the programs, which is used to synchronize groups of intersections into specific areas. Table 2 shows an example where P1 is the active program during the morning, P4 is reserved for some nights and both P2 and P3 are used during the rest of the time.

Time	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
2:30						P4	P4
6:30	P1	P1	P1	P1	P1		
10:30	P2	P2	P2	P2	P2		
17:00	P3	P3	P3	P3	P3	P3	
21:30	P2	P2	P2	P2	P2	P2	
23:00				P4	P4		P4

Table 2 – Example of a control plan (some time intervals are omitted)

Since the optimization works by changing the duration of the phases from the green perspective, it is necessary to define the existing relationship.

In expression 8, matrix A contains information about states (green or red) for each phase (columns) and, for each turn (rows). The vector $\vec{p}$ contains the total phase duration and the vector $\vec{f}$ contains the fixed part of the phase. The difference between vectors is the variable duration of the phase, which multiplied with the matrix A gives the variable green duration as a result, for each turn $\vec{g}_{var}$.

$$A \cdot (\vec{p} - \vec{f}) = \vec{g}_{var} \qquad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \cdot \left(\begin{bmatrix} 40 \\ 30 \\ 26 \end{bmatrix} - \begin{bmatrix} 6 \\ 9 \\ 6 \end{bmatrix} \right) = \begin{bmatrix} 34 \\ 21 \\ 41 \end{bmatrix} \qquad (8)$$

The next step is to process the fixed sub phases, which are sub divided into small intervals supporting transition and coordination between phases. To get the green time it is necessary to add the existing green length in these intervals, $\vec{g}_{ctt}$, to the variable green duration as shown in Expression (9):

$$\vec{g} = \vec{g}_{var} + \vec{g}_{ctt} \quad \begin{bmatrix} 34 \\ 21 \\ 41 \end{bmatrix} + \begin{bmatrix} 0 \\ 6 \\ 9 \end{bmatrix} = \begin{bmatrix} 34 \\ 27 \\ 50 \end{bmatrix} \tag{9}$$

4.1.2 Formulation

There are three different formulations depending on the degree of saturation of the intersection. For example, since it is assumed that the delay is infinite when the intersection is saturated, the formulation aims at reducing queues in those cases.

Figure 3 shows depicts diagram showing the decisions taken during the optimization process in terms of which is the specific objective in function of the degree of saturation.

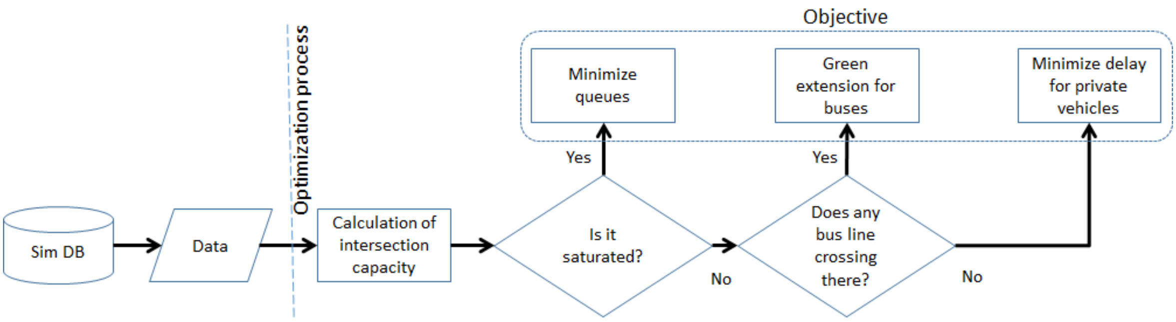

Fig. 3 – Decision diagram during the optimization process

- *Degree of saturation:* indicates the state of an intersection based on the capacity of the turns and the incoming flow. Given a turn, if traffic flow exceeds its specific threshold, then the intersection is not able to process all vehicles, resulting on the generation of queues. In those cases, there are two consequences: vehicles miss, at least, a cycle and queues being generated can eventually stuck adjacent intersections.

  The degree of saturation, as expressed in (10), is the ratio between number of vehicles arriving to the interaction and maximum number of vehicles that can be processed during one cycle. If the value is greater than one the intersection is oversaturated.

$$X = \frac{f \cdot c}{s \cdot g} \tag{10}$$

Where,

X = degree of saturation
f = traffic flow
c = cycle length
s = saturation flow
g = effective green time

- *Delay time of non-saturated intersections:* In these cases, the High Capacity Manual formulation, as expressed in (11), is used:

$$d = \frac{f \cdot 0.5 \cdot c^2 \cdot \left(1 - \frac{g}{c}\right)^2}{1 - \left(X \cdot \frac{g}{c}\right)} \tag{11}$$

Where,

d = delay time
X = degree of saturation
f = traffic flow
c = cycle length
g = effective green time

- *Over-saturated intersections:* The objective here is not to minimize the delay time but to optimize the queue distribution to reduce the impact on adjacent intersections. First, queue growth rate per cycle is obtained by calculating vehicles that miss a cycle divided by the cycle duration, as detailed in (12).

$$Q = \frac{q \cdot c - s \cdot g}{c} \tag{12}$$

Where,

Q = queue growth rate
q = traffic flow
c = cycle length
s = saturation flow
g = effective green time

Since an intersection can have multiple turns, the growth rate is calculated in a per turn basis. The first turn that collapses determines the so-called obstruction time. The algorithm optimizes the obstruction time using the expression (13).

$$U_i = \frac{C_i}{Q_i} \rightarrow U_{min}(\vec{g}) = \min(U_1, \dots, U_i) \tag{13}$$

Where,

U = lane obstruction time
Q = queue growth rate
C = capacity

- *Green extension:* For cases where a bus line circulates, an adjustment of the green phase is used to prioritize public transport. To be more specific, the duration is increased just for signals the buses cross along (degree of saturation calculated for each signal group) using expression (14). A safety factor is added to take into account potential fluctuations in the arrival flow. Finally, the green extension is configured considering the minimum green times already calculated.

$$G = \lambda \cdot \frac{f \cdot c}{s} \tag{14}$$

Where,

G = minimum green duration
λ = safety factor
q = traffic flow
c = cycle length
s = saturation flow

4.2 Offsets
The main objective when optimizing offsets is the improvement of the bus network service. This network layout was designed as a grid where users can easily transfer from vertical to horizontal lines as needed. This ease of use, however, becomes a drawback from a whole perspective because the vertical lines limit improvements in horizontal lines (and vice versa) since there are shared intersections.

In this case, the objective function does not come out of a formulation, but from the simulation model results. Input variables are the offsets of the intersections and the commercial speed is the decision variable. Therefore, the process consists of varying these variables to maximize the commercial speed.

4.2.1 The problem
First, what must be taken into account is the size of the problem to solve. In the study area, there are more than 150 intersections (with their dependencies), which is a relevant number of variables. At the same time, travel times depend on the offsets, establishing an additional dependency.

Given these characteristics, the application of conventional optimization methods such as Newton's method is not feasible. Computationally speaking, the calculation time for a matrix of 150 variables is not a handicap. However, as it has so many variables, it is very likely that Newton's method ends up after finding a local optimum of the problem, which may be very far from the global optimum.

4.2.2 Heuristic method

As a consequence of the abovementioned, a heuristic method (a genetic algorithm, to be more specific) is used, which does not ensure finding an optimal solution but very close to and being a global optimum, which better fits with such a complex problem. An additional advantage is that heuristic methods require lower computational time, which is a very interesting feature for iterative algorithms.

4.2.3 Hybrid modelling

Since a large number of generations are needed for a genetic algorithm to work properly, and for each generation, to simulate many times (one per individual) a drawback arises because each simulation lasts about 40 minutes.

To tackle with that, the methodology includes a simplified mathematical model where the genetic algorithm is applied, which results on a slight loss of accuracy but also on a significant reduction of computing time.

Thus, a hybrid approach is finally used. Every time a solution is found in the mathematical model, it is simulated to get certain parameters (time at stops and speed), which will feedback again the mathematical model. This iterative process stops when a kind of convergence is reached.

4.2.4 Mathematical model

It models the trajectory of a bus taking into account the travel time between nodes and the time a bus is stopped (stops or traffic lights). The latter will depend on the offsets while the other parameters are static during the optimization process and only change after each iteration.

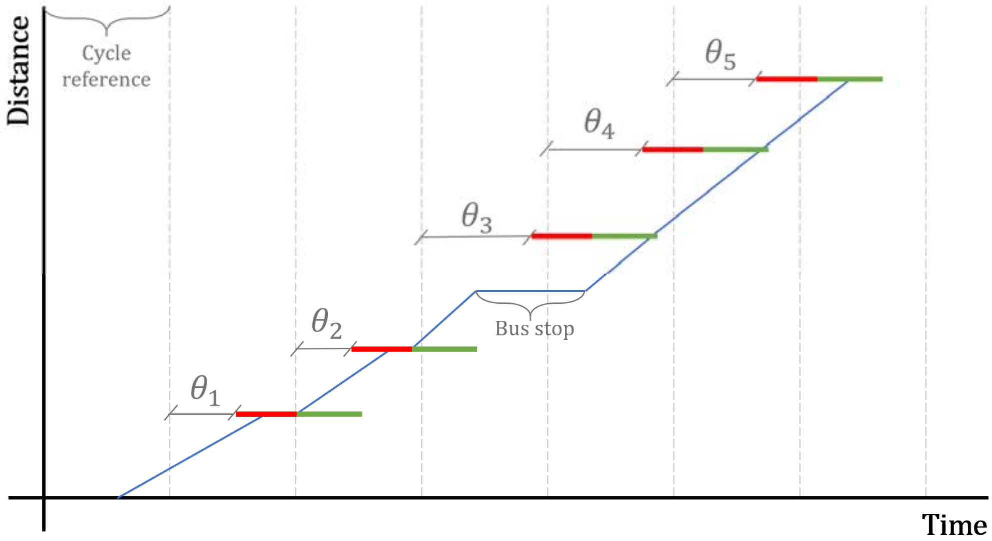

Fig. 4 – Graphical representation of the mathematical model bus trajectory

The model calculates the time that the bus stops (see Figure 4) for all traffic lights based on the offset configured and parameters coming from the simulation. The mathematical model could be understood again as a function to be optimized, where the input variables are the offsets and the output is the travel time as shown in expression (15):

$$t_1 = f_1(\theta_1, \dots, \theta_n) \tag{15}$$

As previously mentioned, the bus network is composed of m corridors that must optimized as a whole. As a consequence, the function to be optimized will not only minimize the travel time of a corridor but the sum of all of them as detailed in (16) where some variables are shared between components of the sum, representing the dependencies.

$$T = t_1 + \dots + t_m = f_1(\theta_1, \theta_2, \dots, \theta_n) + f_2(\theta_2, \theta_3, \dots, \theta_n) + \dots + f_m(\theta_3, \theta_4 \dots, \theta_n) \tag{16}$$

5. CASE STUDY

Figure 5 highlights the area of the city of Barcelona where the study is located. There are many reasons why this area was selected, remarking the following as the most relevant:

- It represents a logical extension of an existing model to which is geographically adjacent and therefore, focusing to a future model of the whole city.
- Includes a comprehensive representation of surface transportation network, where traffic lights have an impact.
- Testing new methodologies and algorithms in a reduced scope before their application to a wide are is always a best practice.

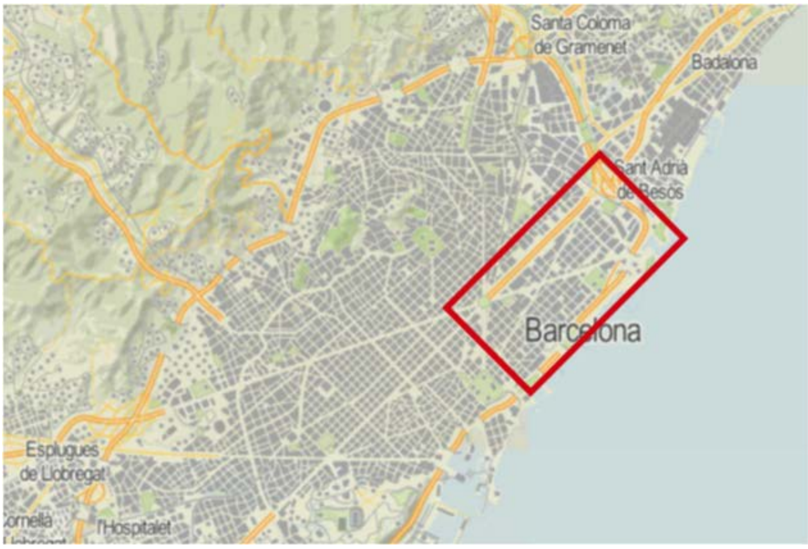

Fig. 5 – Selected area for the case study

5.1 GTFS import

Bus service is configured in the simulation model by means of real schedules included in the official GTFS-compliant files coming from the operators. *General Transit Feed Specification* defines a common format for public transportation schedules and their associated geographic information.

Aimsun has a built-in feature to import GTFS files, which unfortunately, is not totally free from some errors.

To speed up this process and to ease the detection of bugs, some mechanisms developed in python language for both pre-processing (selection of relevant services) and post-processing (completion of missing data).

5.1 Origin-Destination matrix calibration

Private traffic demand is configured by means of an OD matrix provided by the City Council.

To be more specific, the matrix was processed to get hourly matrices for the case study area since it was a daily matrix for all the Metropolitan Area.

Afterwards, a calibration step is needed to enhance quality by adjusting resulting trips:

- *Calibration tool:* Used together with traffic loop sensors, the software performs traffic assignments based on the OD matrix trying to match simulated flow with detected flow for each detector location (macro level).
- *Route definition:* Since traffic loops do not cover the entire study area, it is necessary to check whether the routes generated by the simulator are coherent or not in order to avoid traffic jams where they really do not exist.
- *Model parameters:* Some additional parameters need to be calibrated to ensure a valid behavior from the microscopic level perspective: aggressiveness, lane changes, the reaction time, etc.

5.2 Time intervals

As in most of big cities, traffic behavior in Barcelona depends on the time of day. Therefore, it is important to set the configuration for traffic lights according to the situations identified after analyzing traffic loops in the area. These time intervals define the simulation scenarios: morning and afternoon peaks, off-peak between the two previous and nightly which was finally discarded because of the low traffic and since the bus network changes a lot respect the others.

5.3 Other constraints and limitations

The study area and the City Council guidelines impose additional constraints that must be taken into account:

- *Pedestrians*: For each signal group, a minimum green time based on the crossing's length and the average speed of elderly population must be ensured.
- *High traffic and TRAM roads*: Roads with higher flows and included in the path of TRAM lines are already optimized and therefore, they are not included in the optimization process. However, their offsets are taken into account.

6. RESULTS

This section shows the main results obtained for three scenarios based on the time intervals for a typical working day. All charts have the same style: two series with values for a total of 30 iterations with bus speed (red color, left axis) and delay for private vehicles (blue color, right axis).

A relevant improvement of the bus service has been obtained for the three scenarios, achieving an increase of the speed between 13% and 25% (average for all lines). As expected, travel time is reduced as well as the number of stops, which means that green light is often found when arriving to traffic lights since commercial stops don not change between iterations.

It is important to remark that the objective was to improve the bus network as a whole not just individually lines. For that reason, although there is a global improvement, several lines can have worst indicators. There is not a fixed pattern for this behavior since it depends on some time dependent parameters resulting on having lines that improve given a scenario while they get worst in other.

6.1 Morning peak

In this time interval, modifications in the parameters lead to a significant change in the behavior of private vehicle as shown in Figure 6. Potential traffic jams do not have an impact on the bus because of most of the optimized lines are circulating through reserved lanes.

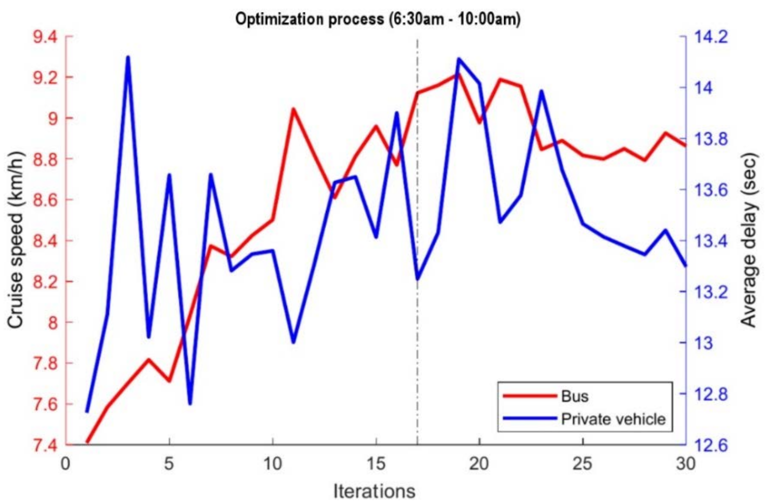

Fig. 6 – Results obtained: morning peak

Even private vehicle does not reach to a convergence, bus lines do until iteration 20 approximately. From this point on, bus speed is not improved anymore, thus going further in the optimization process has no sense.

Vertical dotted line remarks the iteration providing the best global performance.

Table 3 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 25,5 %, reducing both travel time and number of stops by 12,9 % and 6,4 % respectively.

Line	First iteration			Best iteration			Improvement		
	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (%)	Travel time (%)	Num. Stops (%)
H14-0	7,4	17,7	18,4	8,3	15,8	15,9	12,2	-10,4	-13,5
H14-1	6,8	19,5	19,2	11,1	13,4	17,2	62,2	-31,1	-10,3
H16-0	6,2	22,8	23,7	7,1	19,8	22,5	15,0	-12,8	-5,2
H16-1	6,9	19,3	20,4	7,3	18,2	19,8	6,2	-5,5	-2,8
V21-0	7,3	15,6	15,1	9,8	12,8	16,5	33,4	-17,7	8,7
V21-1	8,1	14,1	14,25	8	14,2	13,6	-1,3	1,1	-4,4
V27-0	7	18,7	19,2	8,2	16	17,3	17,2	-14,3	-9,8
V27-1	5,6	20,4	19,5	10,1	13,5	15,8	79,7	-33,8	-18,9
V29-0	9,7	10,1	11,8	14,3	7,8	8,5	47,3	-22,2	-27,8
V29-1	10,3	11,6	11,2	9,2	12,2	13	-11,3	4,8	16,2
H31-0	7,7	16,6	17,92	8	16,1	17,4	2,9	-3,1	-2,5
H31-1	5,3	16,6	16,58	7,5	14,9	15,4	42,4	-10,2	-6,6
Mean	7,41	16,9	17,3	9,1	14,6	16,1	**25,5**	**-12,9**	**-6,4**

Table 3 – Results obtained: morning peak

6.2 Off peak

Despite its name, traffic flows are relevant for this time interval and are just slightly lower than the peaks before and after. For this scenario, both series reach a stable state simultaneously being iteration number 11 the one that offers the best configuration.

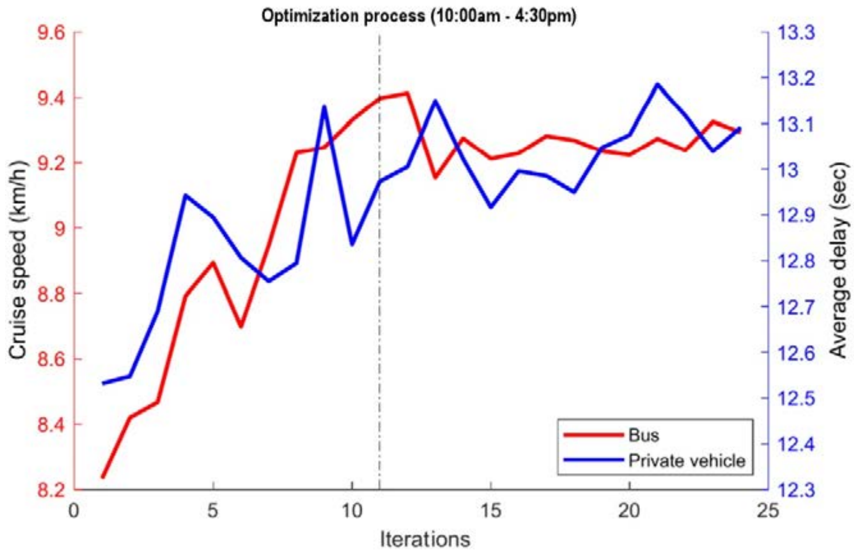

Fig. 7 – Results obtained: off-peak peak

Table 4 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 21,2 %, reducing both travel time and number of stops by 14,2 % and 10,8 % respectively.

Line	First iteration			Best iteration			Improvement		
	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (%)	Travel time (%)	Num. Stops (%)
H14-0	9,7	21,9	23,6	10,6	20,1	19,3	9,1%	-8,4	-18,1
H14-1	7,1	18,9	20,5	7,9	17	18,3	11,7%	-10,1	-10,6
H16-0	6,9	20,6	22,1	7,5	19	21,9	8,7%	-8,0	-0,7
H16-1	6,2	21,6	22	7	19,1	18,5	14,3%	-11,7	-15,9
V21-0	8,2	14,1	14,1	9	12,9	12,7	9,1%	-8,4	-10,0
V21-1	8,6	13,2	14	8,4	13,5	12,1	-2,1%	2,2	-13,7
V27-0	9,7	21,7	22,4	11,4	18,5	20,8	17,1%	-14,6	-7,1
V27-1	5,8	20,1	20,6	10,9	12,4	16,7	88,4%	-38,5	-19,0
V29-0	10,1	9,8	11,7	14,6	6,8	7,1	44,7%	-30,0	-39,3
V29-1	11,2	15,9	16,7	13	13,7	15,2	16,4%	-13,7	-9,0
H31-0	8,3	15,6	15,8	8,9	14,5	15,5	7,2%	-7,1	-2,1
H31-1	5,9	15	16,9	7,6	11,7	19,7	29,3%	-22,0	16,3
Mean	8,1	17,4	18,4	9,7	14,9	16,5	**21,2%**	**-14,2**	**-10,8**

Table 4 – Results obtained: off-peak

6.3 Afternoon peak

Behavior is similar to the peak in the morning but variation of delay for private vehicle along the iterations is not as severe. While buses reach an asymptote, private vehicle has a decreasing trend. The best configuration for traffic lights is found in iteration number 27.

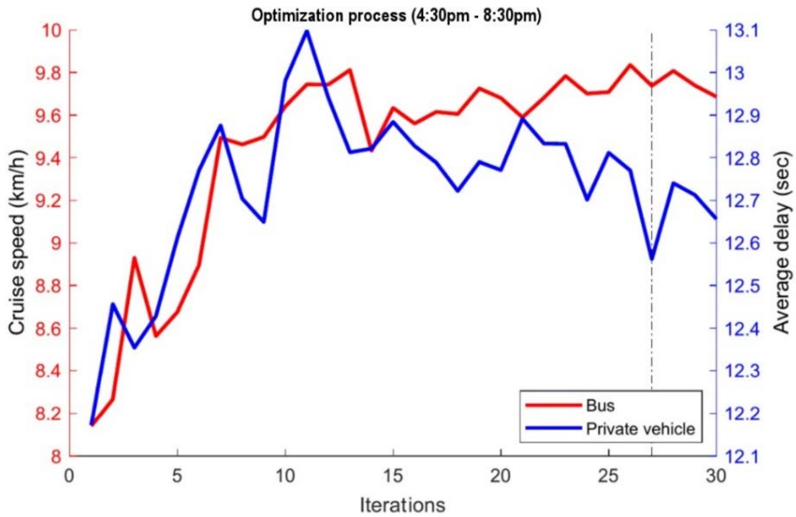

Fig. 8 – Results obtained: afternoon peak

Table 5 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 12,9 %, reducing both travel time and number of stops by 9,3 % and 11,3 % respectively.

Line	First iteration			Best iteration			Improvement		
	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (km/h)	Travel time (min)	Num. Stops (#)	Cruise speed (%)	Travel time (%)	Num. Stops (%)
H14-0	10,2	20,7	22	11,6	18,2	17,8	13,9	-12,0	-19,0
H14-1	7,7	17,3	18,3	8	16,7	17,8	3,3	-3,4	-2,7
H16-0	6,7	21,2	21,8	7,7	18,4	21,1	15,6	-13,0	-3,1
H16-1	6,9	19,3	21	9,3	15,1	17,7	34,4	-21,7	-15,5
V21-0	8,2	14	16	8	14,4	15	-3,0	2,7	-6,2
V21-1	7,7	14,6	14,6	8,4	13,4	12,1	9,0	-8,1	-17,0
V27-0	6,9	18,9	19,7	9,7	14,5	13,3	41,1	-23,0	-32,6
V27-1	8,9	20,9	21	10,2	18,3	18,6	14,6	-12,3	-11,2
V29-0	9,2	10,7	13	11,8	8,3	8,7	27,6	-22,1	-33,1
V29-1	10,4	11,6	12,1	10,3	11,7	12,6	-0,8	1,0	4,1
H31-0	7,6	16,9	17,7	8	16,1	17,3	4,1	-4,6	-2,3
H31-1	8	17,8	20	7,6	18,6	20,6	-4,3	4,5	2,9
Mean	8,2	17	18,1	9,2	15,3	16,1	**12,9**	**-9,3**	**-11,3**

Table 5 – Results obtained: afternoon peak

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CARACTERIZACIÓN DE LA MOVILIDAD DE CORREDORES EN MARATONES

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RESUMEN

En la última década se ha producido un incremento significativo de las personas que practican el "running" como deporte principal para mejorar su calidad de vida. Este hecho ha producido un aumento de la celebración de carreras populares, entre las que cabe destacar la maratón por el volumen de personas que concentra. Para evitar aglomeraciones y que la carrera se celebre bajo condiciones de flujo libre, las organizaciones separan a los corredores en olas y cajones de manera que los corredores son lanzados con un desfase de tiempo determinado. Sin embargo, el número de estudios sobre el comportamiento de los corredores a lo largo de la carrera es escaso.

Así, el objetivo principal de esta investigación fue caracterizar la movilidad de los corredores desde el punto de vista de su operación, analizando el ritmo de cada uno de ellos de manera individual y grupal. Para ello, se realizó un análisis macroscópico y microscópico de los corredores que participaron en las maratones de Valencia entre 2016 y 2019.

Todo ello permitió caracterizar el comportamiento de los corredores que pertenecían a la misma ola. Como resultado, la variación del ritmo a lo largo de la carrera es mayor a medida que el ritmo promedio de la carrera aumenta. Además, mientras que la descarga de corredores en la primera ola presentaba intensidades muy elevadas durante los primeros minutos, en el resto de las olas se observó una descarga más homogénea y tendida.

Finalmente, se identificó que tanto la intensidad, expresada en número de corredores por unidad de tiempo, como la densidad, expresada en número de corredores por unidad de longitud, alcanzaban sus valores máximos en la primera parte de la carrera, indicando que la zona con mayor interacción entre corredores se produce en los primeros 5-10 kilómetros de la carrera.

Estos resultados pueden sentar la base para la definición de modelos de simulación para una organización más eficiente y segura de este tipo de eventos, principalmente cuando existan medidas excepcionales como las establecidas por la pandemia de la COVID-19.

1. INTRODUCCIÓN

A pesar de que a partir del año 2016 se observa un decaimento de la participación global en carreras, los maratones siguen aglutinando un mayor número de corredores con el paso de los años registrando una tasa de crecimiento anual ligeramente menor al 2% (RunRepeat y IAU, 2019). Los motivos para participar en este tipo de carreras están cambiando y son muy diversos. A principios de siglo, la mayoría de los corredores buscaban batir sus propios registros, mientras que hoy en día predominan los motivos relacionados con la fisiología, la salud y la sociedad. Este hecho ha producido una mayor movilidad por parte de las personas que se desplazan para correr, un incremento de los tiempos de finalización de la carrera y una menor proporción de participantes con edades comprendidas entre los 30 y los 50 años (RunRepeat y IAU, 2019).

El aumento de la participación en este tipo de carreteras ha generado que la salida se estructure en lo que comúnmente se conoce como *olas* y, a su vez, estas en *cajones* (Treiber, 2014). Cada *ola* y *cajón* tiene asociado un tiempo objetivo, es decir, el tiempo en que un corredor considera que finalizará la carrera. Con el fin de minimizar las interacciones entre corredores y garantizar que la carrera se produzca en flujo libre – ningún corredor ve afectado su ritmo por la afección de otro –, algunos organizadores solicitan a los participantes, en el momento de inscribirse en la carrera, prueba de que puede lograr ese tiempo objetivo – habitualmente a partir de resultados de carreras anteriores –. Sin embargo, la influencia de la estructura de la salida no ha sido todavía estudiada, principalmente porque cada organizador lo hace de manera particular para el evento que organiza y la comparación de los resultados obtenidos es compleja al depender de otros factores clave como, por ejemplo, el ancho de la sección. En este sentido, cuanto mayor es el ancho, mayor puede ser la intensidad de descarga de corredores por unidad de tiempo.

En los últimos años se han desarrollado varias investigaciones con el fin de modelizar la evolución del ritmo de los corredores a lo largo de la carrera (Rodriguez et al., 2014; Kwong y Nadarajah, 2019; Lin y Meng, 2018). Estas se desarrollaron en base a los resultados de los maratones de Nueva York, Chicago, Berlín, Londres y Boston, en distintas ediciones. Las distribuciones globales de velocidad – considerando todos los corredores en cada carrera – siguen, en general, una distribución log-normal (Lin y Meng, 2018). En este sentido, se identificó que las distribuciones de velocidad de los grupos de edad más rápido tenían la misma forma – distribución log-normal – que el resto de los finalistas. Mientras que Kwong y Nadarajah (2019) observaron mayores variaciones del ritmo cuanto más lento era un corredor y con el avance de la carrera, Lin y Meng (2018) identificaron mayores variaciones de ritmo individual en los primeros 5 kilómetros de la carrera y a partir del kilómetro 30. En el resto de longitud – desde 5k hasta 30k – el ritmo se mantenía relativamente constante (Lin y Meng, 2018).

Por su parte, Rodriguez et al. (2014) modelizó la dinámica del pelotón del maratón a través de una ecuación diferencial parcial de convección-difusión con velocidad media dependiente de la posición y coeficiente de difusión. De esta forma, se concluyó que la velocidad media del pelotón disminuye mientras que el coeficiente de difusión aumenta con la distancia. Esto significa que la intensidad y densidad de corredores se diluye a lo largo del recorrido.

Adicionalmente, Treiber (2014) analizó las distribuciones de tiempos finales por categorías – edad y sexo – en medias maratones. En este caso, se observó que, en ausencia de perturbaciones importantes, la distribución de la velocidad dentro de cada grupo es casi gaussiana. Particularmente, solo se observaron desviaciones significativas en: (i) grupos de élite pequeños por efecto pelotón; y (ii) colas de baja velocidad, que producían distribuciones más amplias.

Como conclusión, el estado actual del conocimiento en cuanto a los patrones de comportamiento de los distintos grupos o categorías que conforman un maratón es escaso, pues las investigaciones presentadas anteriormente se centran principalmente en el análisis del ritmo global de la carrera o para categorías muy específicas. Además, todavía cobra mayor importancia la caracterización de los factores más importantes en el desarrollo de maratones a partir de las medidas de seguridad establecidas por la pandemia de la COVID-19, puesto que la distancia social supone una restricción a tener en cuenta a la hora de diseñar el trazado de la carrera.

2. OBJETIVOS E HIPÓTESIS

El objetivo principal de esta investigación es el análisis descriptivo y cuantitativo de aquellos factores que permiten caracterizar el comportamiento de maratones.

Concretamente, las principales variables exploradas en este estudio están estrechamente ligadas al ritmo de los corredores, el cual ha sido analizado tanto de manera agregada como desagregada, la intensidad de corredores, entendida como la cantidad de corredores que atraviesan una sección por unidad de tiempo, y la densidad de corredores, expresada en términos de número de corredores por unidad de longitud. Todas estas variables se examinan teniendo en cuenta la configuración inicial o de salida de este tipo de pruebas, habitualmente estructurada en olas.

Las hipótesis más importantes del estudio son: (i) la distribución general de ritmos presenta una asimetría positiva debido a la baja proporción de corredores con condiciones de mantener ritmos de carrera muy bajos y una cola situada en la zona de ritmos altos debido a la dispersión existente de las condiciones físicas de corredores amateur; (ii) la intensidad de descarga de corredores en la salida disminuye a lo largo del tiempo y, además, también lo hace de una a otra ola; (iii) la variación del ritmo a lo largo de la carrera incrementa conforme lo hace el ritmo medio de la carrera, es decir, los corredores más rápidos tienen mayor facilidad para mantener un ritmo constante a lo largo de la carrera; y (iv) las intensidades y densidades más elevadas se producen en la parte inicial de la carrera debido a la mayor interacción entre corredores.

3. MÉTODO Y MATERIALES

Para llevar a cabo el presente trabajo se procedió según el diagrama de flujo de la Figura 1.

En primer lugar, se realizó una descarga masiva de los resultados de los maratones celebrados en la ciudad de Valencia desde 2016 hasta 2019, ambos inclusive. Los resultados de estas carreras están disponibles de manera gratuita a través de la página web del maratón (https://www.valenciaciudaddelrunning.com/maraton/maraton/). No obstante, no existe la posibilidad de descargar los datos de manera directa – p.ej., en formato csv – a través de dicho repositorio web. Por ello, se programó un script de *web scraping* mediante lenguaje de programación Python. Este proceso trata usar *bots* para extraer contenido y datos de un sitio web mediante el acceso a su código *HTML* y, a partir de este, obtener los datos almacenados en la base de datos.

Adicionalmente, también se descargaron los datos de los resultados de la página web que aloja los vídeos de la carrera (https://corriendovoy.com) con el fin de obtener información extra de los corredores como, por ejemplo, el tiempo de desfase en la salida con respecto al origen de tiempos general. Este tiempo, como se verá posteriormente en el análisis, es clave para determinar en que *Ola* salió cada uno de los participantes.

Fig. 1 – Diagrama de flujo de la investigación

La Tabla 1 indica los datos obtenidos de cada uno de los participantes de los maratones de Valencia celebrados de 2016 a 2019. Estos han sida agrupados en tres categorías de datos: (i) general; (ii) salida; (iii) puntos de paso. Los datos que se integran en la categoría "general" han sido empleados principalmente para caracterizar de manera global las carreras celebradas.

En este sentido, posteriormente se analiza la distribución de corredores según el ritmo promedio de estos y se evalúa la evolución de la participación de hombres y mujeres de manera desagregada – por categoría – y agregada – total por sexos –.

Los datos de la categoría "Salida" hacen referencia al *desfase*, que se define como la diferencia entre el tiempo oficial de la prueba – comenzando a contar desde que se da la salida de la primera ola – y el tiempo real del corredor – desde que cruza la salida hasta que llega a meta –. Principalmente, este tiempo permitió identificar a qué *ola* pertenece cada corredor y analizar la descarga de corredores en la salida.

Finalmente, los datos correspondientes a la categoría "puntos de paso" proporcionaron información sobre el tiempo de paso real de cada corredor en los puntos de control de la carrera. Estos datos fueron empleados para analizar la evolución del ritmo de cada corredor y cuantificar la intensidad de corredores en cada uno de estos pasos y la densidad de corredores entre los mismos.

Categoría de datos	Variable
General	Posición
	Dorsal
	Categoría
	Nombre y apellidos
	Tiempo oficial
	Tiempo real
Salida	Desfase
Puntos de paso	Tiempo en: • 5k • 10k • 15k • 21,097 (media maratón) • 25k • 30k • 35k • 40k • 42,195 (meta)

Tabla 1 – Resumen de datos obtenidos por corredor

Cabe destacar que una vez descargados los datos se realizó una reducción de los mismos con el fin de eliminar cualquier dato anómalo o incompleto. Para ello, al disponer de diferentes fuentes de datos – clasificación general y datos individuales –, se cruzaron los tiempos reales de cada corredor haciendo una búsqueda por su nombre. Se decidió utilizar el nombre del corredor para este proceso debido a las inconsistencias detectadas en las variables *dorsal* y *posición*.

4. ANÁLISIS Y RESULTADOS

El análisis que se presenta a continuación se ha dividido en cuatro bloques principales, yendo desde aspectos más generales a más particulares: (i) caracterización general; (ii) análisis de la salida; (iii) análisis de ritmo; y (iv) análisis espacio-temporal. Mientras que el primero de los bloques presenta datos de todos los maratones disponibles (2016-2019), los bloques siguientes se centran exclusivamente en los datos del maratón del año 2019. En este sentido, las tendencias que muestran los años anteriores (2016-2018) son similares al año que se presenta.

4.1 Caracterización general

Esta sección se centra en el análisis de los participantes por categoría, la evolución de la participación de hombres y mujeres a lo largo de los años y la distribución de corredores según su ritmo medio.

La Figura 2 muestra el tanto por ciento de hombres y mujeres que participaron en las ediciones del maratón de Valencia entre 2016 y 2019. A pesar de la baja participación de las mujeres en este tipo de pruebas (< 20%), se puede apreciar que año tras año su presencia es mayor.

Este mismo fenómeno se puede observar si analizamos los tantos por ciento de cada una de las categorías en las que se divide el maratón (Figura 3). Concretamente, la mayor reducción de corredores masculinos (categorías *M*) se produce en tres categorías de las que mayor presencia tienen en el maratón – *Senior Masc*, *M35* y *M40* –. Sin embargo, la proporción de hombres para el resto de categoría – hombres menores que 23 años y mayores de 40 años – se ha mantenido e incluso ha crecido a lo largo de los años. Por su parte, la participación de mujeres ha aumentado en prácticamente todas las categorías.

A grandes rasgos, el grueso de la carrera se concentra en la franja de edad comprendida entre los 23 años – incluso superior, aunque no se puede verificar con los datos disponibles – y los 45 años.

La presencia de cada una de las categorías restantes se va diluyendo con la edad. También es llamativa la poca participación de jóvenes menores de 23 años, confirmándose que la práctica del *running* se desarrolla en edades más avanzadas, muchas veces cuando las personas dejan de realizar otro deporte considerado como principal (p.ej., fútbol o baloncesto).

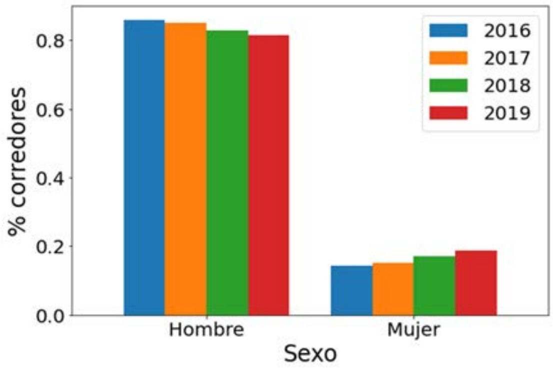


Fig. 2 – Proporción de hombres y mujeres entre 2016 y 2019

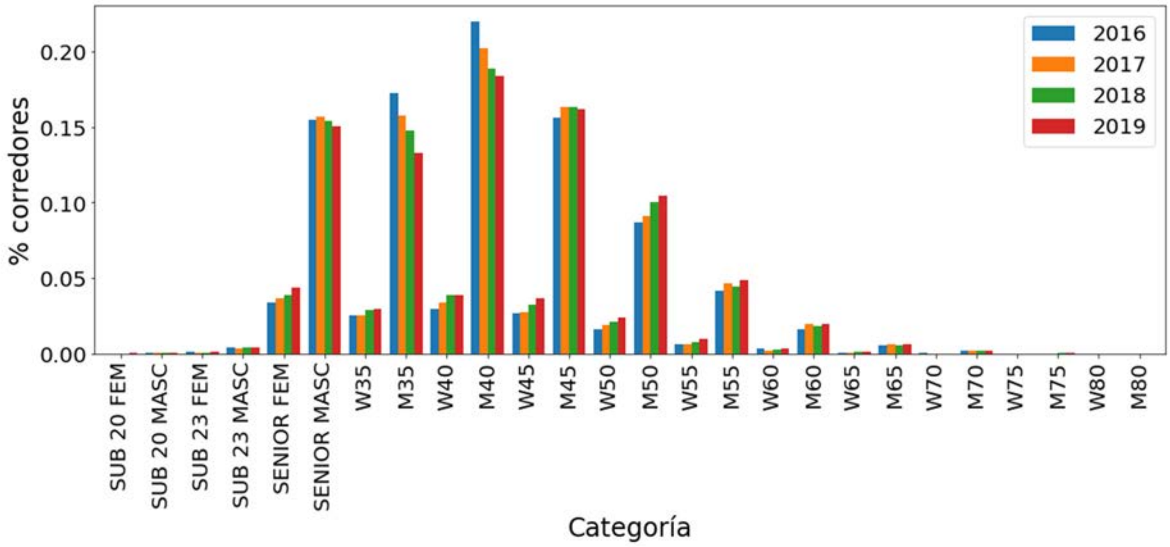


Fig. 3 – Proporción de hombres y mujeres por categorías entre 2016 y 2019

La Figura 4 presenta la distribución de corredores según el ritmo promedio para los distintos maratones evaluados. Como se puede apreciar, la distribución de ritmos es prácticamente similar. Este hecho confirma que existe un patrón o comportamiento común en este tipo de pruebas y, por tanto, los resultados de los análisis que se presentan más adelante para el maratón de 2019 pueden ser extrapolables a las carreras desarrolladas con anterioridad a pesar de que el número de corredores ha crecido desde 2016 a una tasa anual aproximadamente del 10% (Tabla 2).

Particularmente, la distribución presenta una asimetría ligeramente positiva, con un ritmo promedio de alrededor de 5:25 min/km (Tabla 2). El crecimiento repentino de la distribución desde ritmos bajos indica que existen pocos corredores rápidos o de élite, mientras que la cola que se observa para los ritmos más altos es sinónimo de una mayor proporción de corredores lentos (Figura 4). Asimismo, el 50% de los corredores presentan ritmos medios entre 4:50 min/km y 6 min/km (Tabla 2).

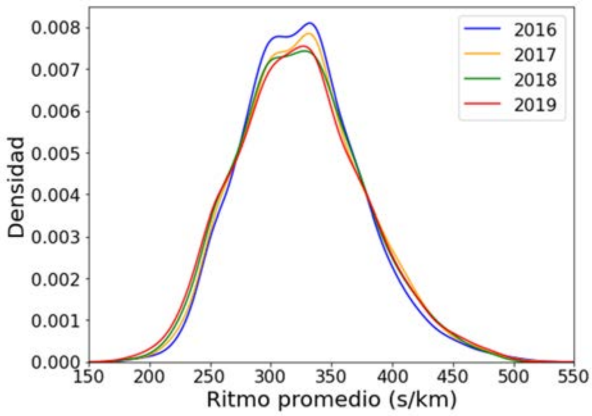


Fig. 4 – Distribución de corredores por ritmo medio entre 2016 y 2019

	2016	2017	2018	2019
Número de participantes	15858	16187	19243	21196
Ritmo promedio (s/km)	326.00	326.98	325.14	324.68
Desviación estándar del ritmo (s/km)	49.23	51.36	51.64	53.33
Ritmo mínimo (s/km)	181.44	178.1	177.01	176.09
Percentil 25 (s/km)	291.84	291.27	288.85	287.62
Percentil 50 (s/km)	323.51	324.73	322.67	322.36
Percentil 75 (s/km)	356.32	358.88	359.41	358.29
Ritmo máximo (s/km)	526.51	522.95	494.94	520.49

Tabla 2 – Resumen estadístico del ritmo

4.2 Análisis de la salida

El análisis de la salida se ha realizado exclusivamente para el maratón del año 2019. En este caso, la salida se organizó en 4 olas (Tabla 3). Adicionalmente, la *Ola 1* se distribuyó en 5 cajones, la *Ola 2* y *3* en 2 cajones y la *Ola 4* en un único cajón. Aunque sí se ha podido identificar la ola a la que pertenece cada corredor gracias a los datos relativos al desfase de la salida para cada corredor, la asignación en cajones no se pudo llevar a cabo.

Ola	Desfase (min)	Tiempo objetivo (hh:mm:ss)
Ola 1	0	< 03:31:00
Ola 2	10	< 03:46:00
Ola 3	20	< 04:01:00
Ola 4	30	≥ 04:01:00

Tabla 2 – Distribución de olas en el maratón de 2019

La Figura 4 muestra la intensidad de descarga de corredores por segundo junto al número de corredores acumulado a lo largo del tiempo. Como se puede apreciar, entre cada una de las olas existe un cierto intervalo de tiempo que se emplea para el posicionamiento en la salida de los corredores de la siguiente ola.

Focalizando la atención en la descarga de corredores de las olas, se puede intuir una reducción de las intensidades de descarga de cada una de ellas con el paso del tiempo.

Además, comparando las intensidades de unas olas con otras, se observan mayores valores de la intensidad en la *Ola 1* que en la *Ola 2* y, a su vez, mayores en la *Ola 2* que en la *Ola 3* y *4*. Este fenómeno también se puede apreciar por la pendiente de la recta tangente a la curva que muestra el número de corredores acumulado por segundo (línea negra a puntos en Figura 5). En este sentido, la pendiente ligada a la *Ola 1* es mayor que la de la *Ola 2*, siendo la pendiente de esta última ola mayor que las observadas en la *Ola 3* y *4*.

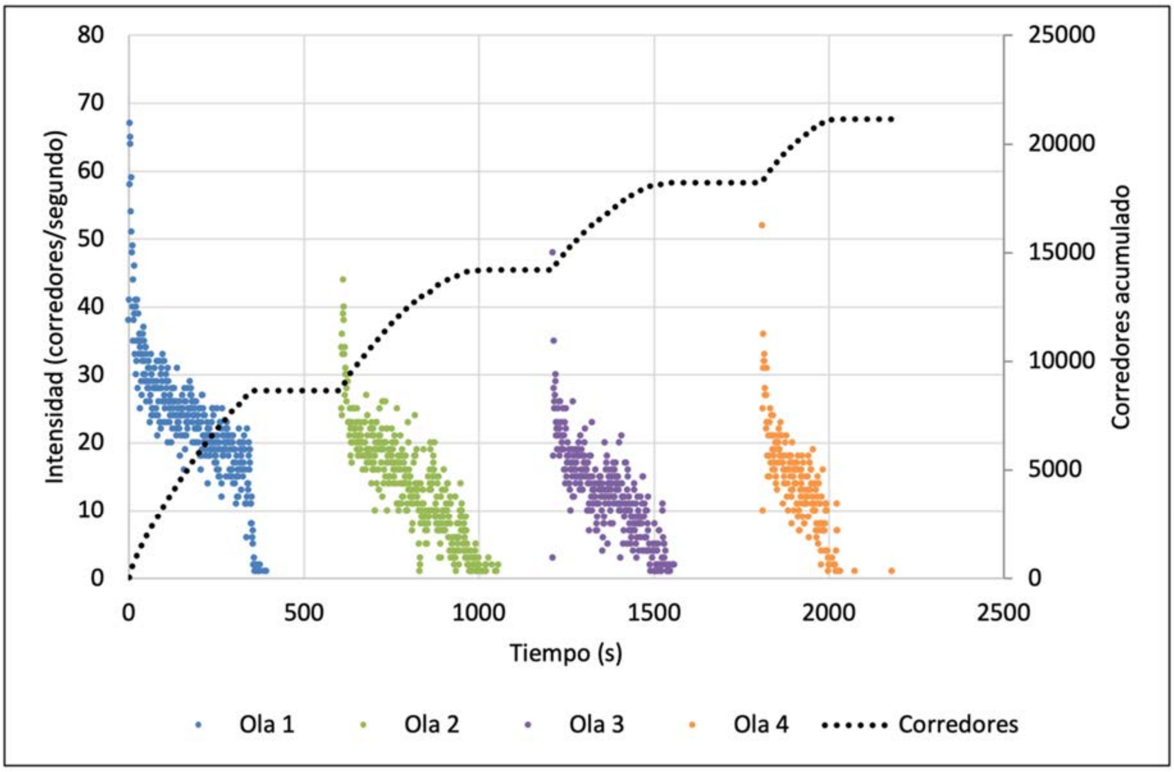


Fig. 5 – Descarga de corredores

Para analizar con mayor detalle la descarga de corredores en cada una de las olas, se ha establecido un origen de tiempos similar para todas ellas (Figura 6) y se ha calibrado un modelo para cada una de ellas según la forma funcional de la Ecuación (1), que responde al comportamiento asintótico, tanto horizontal como vertical, que presenta la intensidad a lo largo del tiempo.

$$y(t) = \frac{\beta_1}{t^{\beta_2}} + \beta_3 \qquad (1)$$

donde *y(t)* es la intensidad de descarga de corredores medida en corredores por segundo; *t* es el tiempo transcurrido en segundos; y β_i son los coeficientes del modelo.

La Tabla 3 presenta un resumen de la calibración de los modelos, mientras que la Figura 6 muestra cada modelo junto a los datos observados de la intensidad de descarga de corredores.

En primer lugar, cabe destacar que los modelos calibrados presentan una precisión adecuada – coeficiente de correlación entre 0.60 y 0.71 – para el fenómeno estudiado. Además, ponen de manifiesto todas las observaciones indicadas anteriormente para la Figura 5. A este respecto, los modelos estiman mayores intensidades de descarga para la *Ola 1*, intensidades bastante menores para la *Ola 2* y, a su vez, intensidades bajas tanto para la *Ola 3* y *4*, que prácticamente presentan resultados similares.

	Ola 1	**Ola 2**	**Ola 3**	**Ola 4**
$\boldsymbol{\beta_1}$	1621.48	1585.48	1660.00	1741.83
$\boldsymbol{\beta_2}$	0.00479	0.00396	0.00315	0.00315
$\boldsymbol{\beta_3}$	-1560.48	-1540.67	-1622.90	-1704.06
$\mathbf{R^2}$	0.71	0.66	0.60	0.66

Tabla 3 – Modelos de descarga de corredores en salida

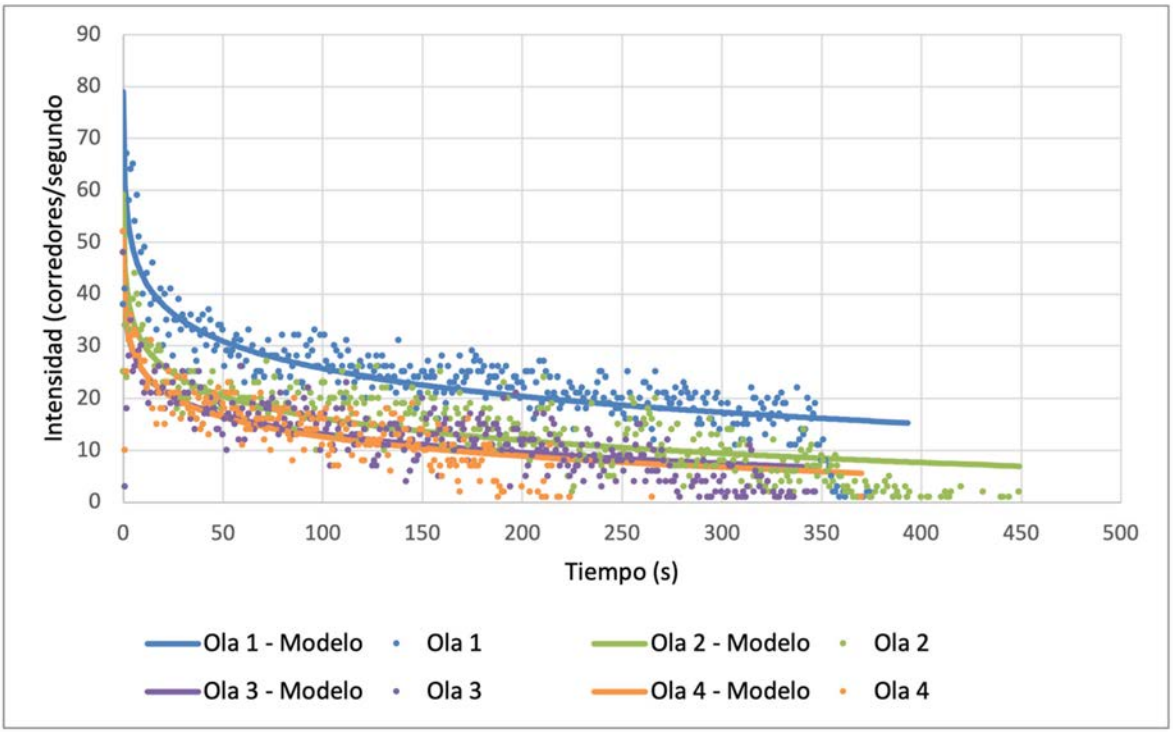


Fig. 6 – Modelos de intensidad de descarga de corredores en la salida según ola

Los resultados obtenidos en cuanto a la intensidad de descarga están estrechamente asociado a los ritmos de los corredores de cada una de las olas. En principio, los ritmos son más rápidos en las primeras olas, lo que se traduce en mayores intensidades de descarga. Por el contrario, los ritmos lentos asociados a la *Ola* 3 y *4* producen intensidades de descarga mucho más reducidas.

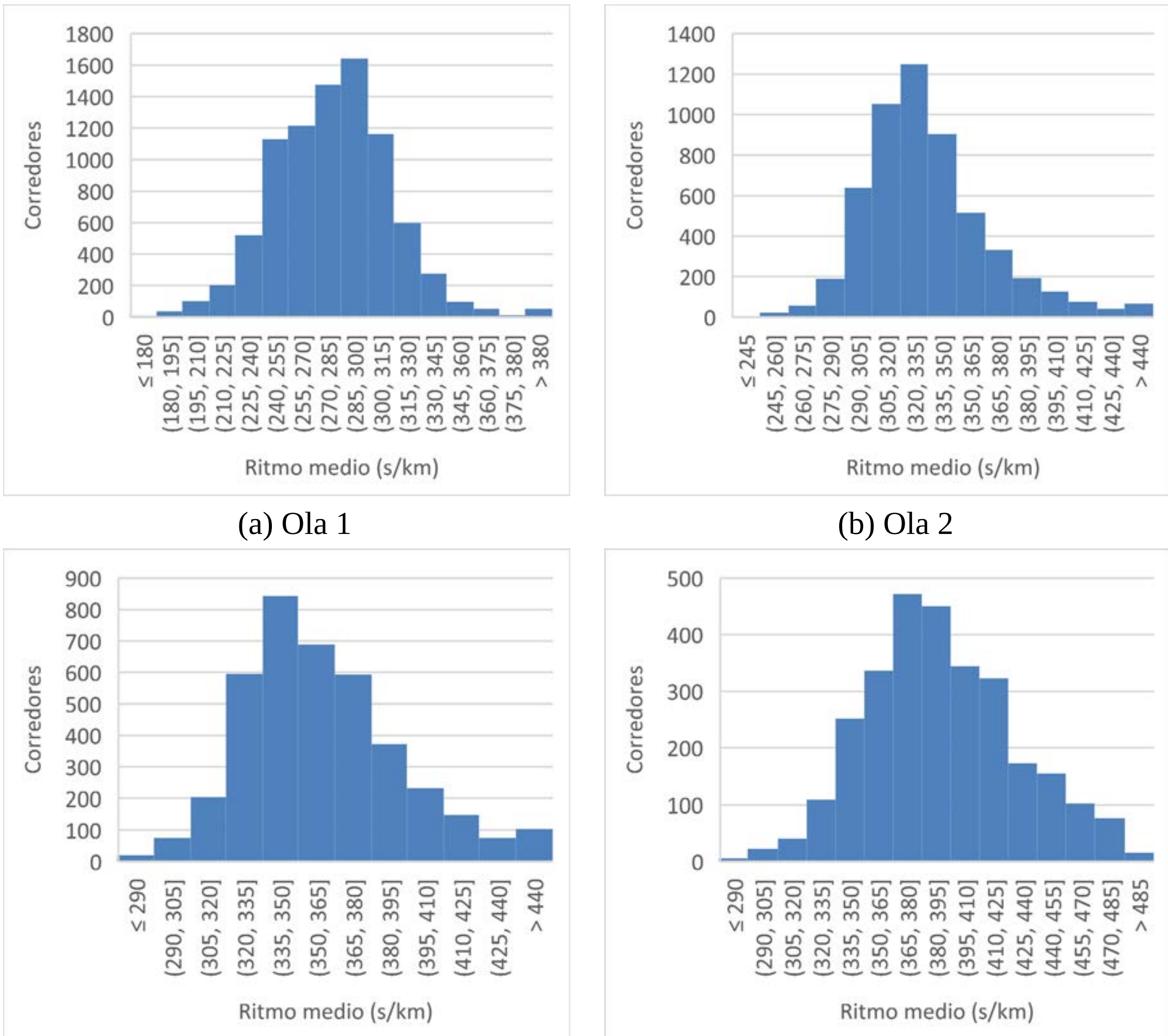
4.3 Análisis de ritmo

En las secciones anteriores se ha analizado el ritmo promedio de la carrera y la distribución de corredores en función de su ritmo medio.

Ahora se estudio con mayor nivel de detalle la evolución del ritmo de cada corredor a lo largo de la carrera, es decir, si aumenta de manera progresiva su ritmo o si el propio desgaste de la carrera le lleva a reducir el ritmo en los kilómetros finales.

Para ello, se cuenta con los tiempos de paso por el kilómetro 5k, 10k, 15k, 21.097k – media maratón –, 25k, 30k, 35k, 40k, 42,195k – meta –. A partir de estos tiempos se ha estimado, para cada corredor, el ritmo promedio de cada uno de los intervalos de distancia producidos por los puntos de paso.

En primer lugar, la Figura 7 muestra la distribución de ritmos de los corredores de cada una de las olas. Por tanto, la forma de la distribución general (Figura 4) es el resultado de la suma de otras distribuciones. Mientras que las distribuciones asociadas a la *Ola 2* y *3* presentan claramente una asimetría positiva, en aquellas ligadas a la *Ola 1* y *4* la asimetría no es tan evidente. El ritmo medio de cada una de la *Ola 1*, *2*, *3* y *4* es 4:40, 5:34, 6:00 y 6:30 min/km, respectivamente.



(a) Ola 1 (b) Ola 2

(c) Ola 3 (d) Ola 4

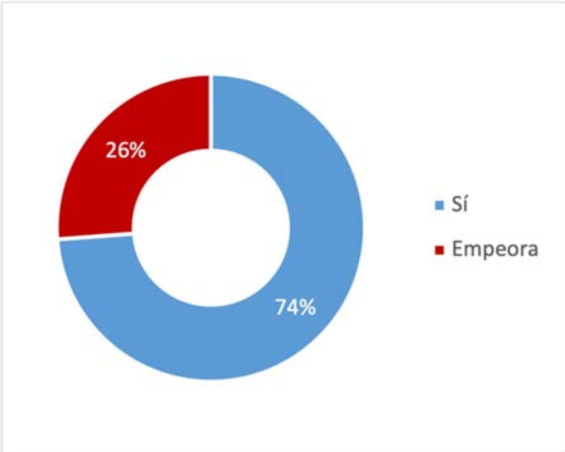
Fig. 7 – Distribución de ritmos por ola

A la hora de participar en el maratón, cada participante debe proporcionar un tiempo estimado de finalización de la carrera que la organización utiliza para la distribución de corredores en olas y cajones. En algunos maratones se suele pedir alguna prueba de ello – basado en carreras previas –, pero en otros no.

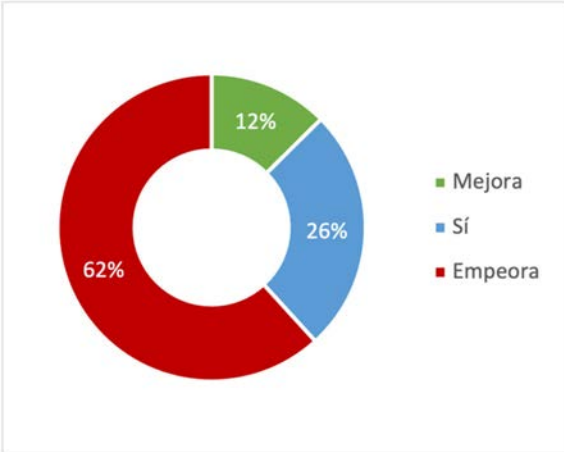
Para determinar el grado en que los corredores cumplieron su objetivo en el maratón de 2019, se ha comparado el tiempo asociado a cada ola (Tabla 2) con el tiempo real de la prueba (Figura 8).

De este modo, se ha identificado que el tanto por ciento de corredores que empeoran el tiempo previsto aumenta conforme mayor es el tiempo previsto para finalizar la carrera, desde el 26% de corredores de la *Ola 1* al 65% de la *Ola 3*. Por otro lado, se observa una pequeña parte de corredores – alrededor del 10% en cada ola – que mejoran su tiempo previsto.

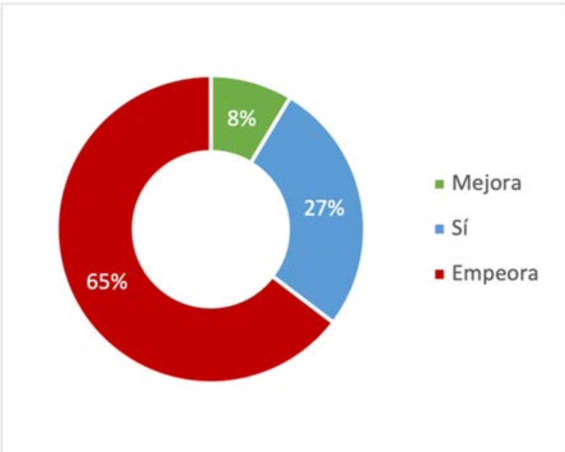
Además, destacar que en las olas centrales – *Ola 2* y *3* – únicamente un cuarto de los corredores cumple – *"Sí"* – con el tiempo esperado (Figura 8). Finalmente, es necesario resaltar que sería necesario estudiar, dentro de la *Ola 1*, el cumplimiento de los tiempos previstos asociados a cada uno de los cajones que la integran.



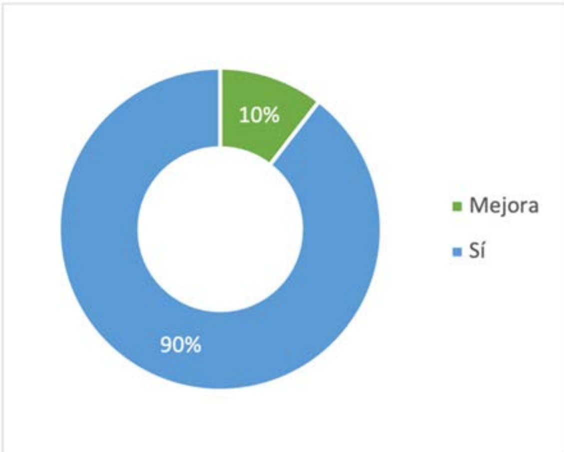
(a) Ola 1



(b) Ola 2



(c) Ola 3



(d) Ola 4

Fig. 8 – Cumplimiento de tiempo estimado de finalización

Una vez estudiadas las distribuciones de ritmos de cada ola e identificada la poca proporción de corredores que cumplen con los tiempos previstos, a continuación se compara el ritmo medio de cada corredor con la variación del ritmo a lo largo de la carrera (Figura 9. Para ello, la variación del ritmo ha sido estimada como la desviación típica de los ritmos promedios estimados en cada punto de control.

Estos ritmos promedios son estimados como el ritmo medio entre dos puntos de control consecutivos. De esta manera, para cada corredor se dispone de un total de ocho ritmos promedios, asignados a cada punto de control (ver Tabla 1). Por ejemplo, el ritmo promedio en el punto de control 5k será el ritmo medio, en s/km, desde la salida hasta el kilómetro 5.

Por su parte, el ritmo promedio en el punto de control 30k será el ritmo medio entre el kilómetro 25 y 30.

En primer lugar, se ha observado un aumento de la variación del ritmo conforme el ritmo promedio de los corredores incrementa. Este fenómeno se debe al hecho de que cuanto más rápido es un corredor, teóricamente, en mejor forma física se encuentra para desarrollar la carrera, lo que conduce a experimentar menores cambios de ritmo a lo largo de la carrera.

Además, para un mismo ritmo medio de carrera, aquellos corredores que mejoran el tiempo previsto presentan variaciones del ritmo significativamente menores a aquellos que empeoran su tiempo esperado de carrera.

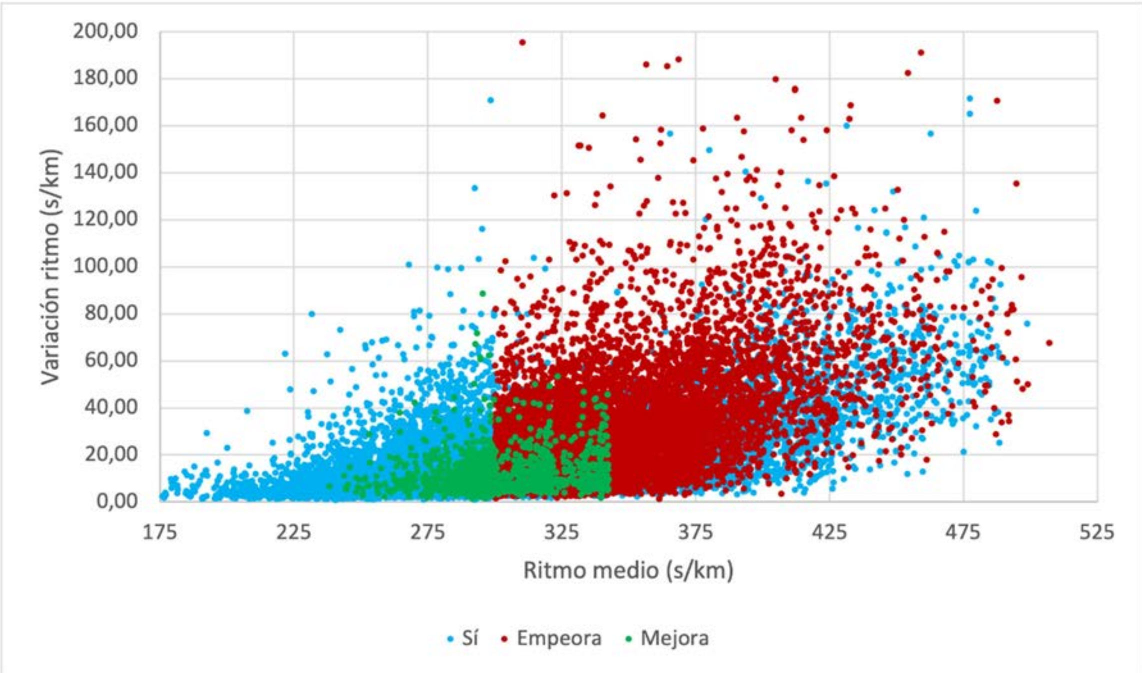


Fig. 9 – Cumplimiento de tiempo estimado de finalización

Una vez identificadas las diferencias generales entre los grupos analizados – corredores que cumplen tiempo previsto, lo mejoran o lo empeoran –, ahora se compara el ritmo medio de la carrera con el ritmo promedio estimado en cada punto de control. En la Figura 10 se representa el ritmo medio de la carrera frente a la ratio entre dicho ritmo y el ritmo en un determinado punto de control.

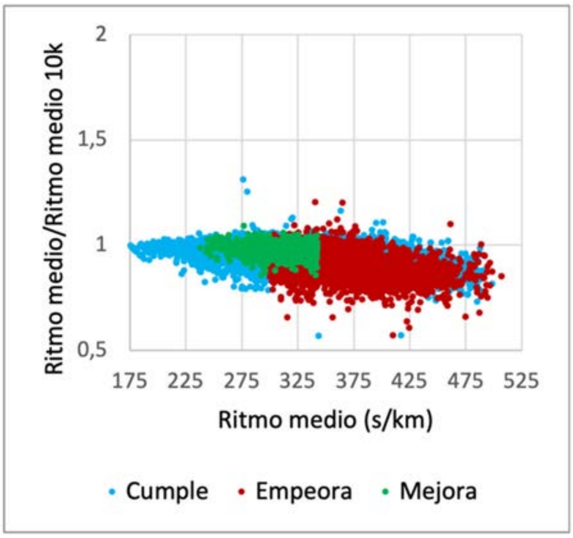
De esta forma, una ratio mayor que 1 significa que el ritmo del corredor asociado a ese punto de control es superior al medio de la carrera, es decir, va más lento. Por el contrario, un valor menor que 1 indica que el corredor ha recorrido a un ritmo más rápido que el ritmo promedio de la carrera la longitud que separa ese punto de control y el anterior.

De manera general, cuanto mayor es el ritmo medio de la carrera, más se aleja la tasa evaluada del valor 1.

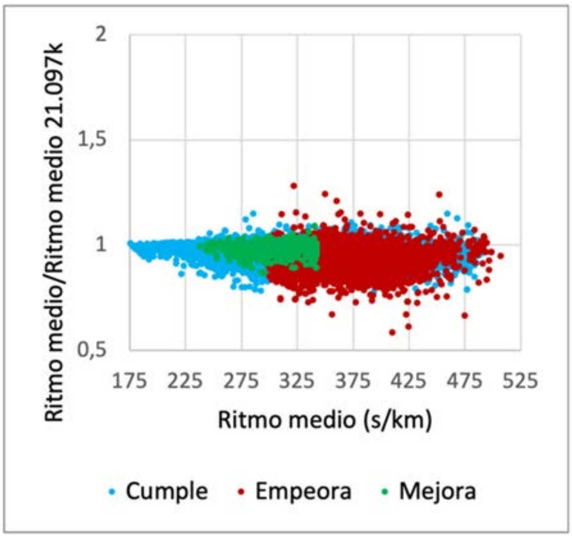
Aquellos corredores que cumplen o empeoran el tiempo previsto experimentan una reducción del ritmo conforme avanza la carrera.

En este sentido, se observan ritmos más rápidos – ratio menor que 1 – en la primera mitad de la carrera (Figura 10a y 10b) y ritmos lentos – ratio mayor que 1 – en la segunda parte de la misma (Figura 10c y 10b).

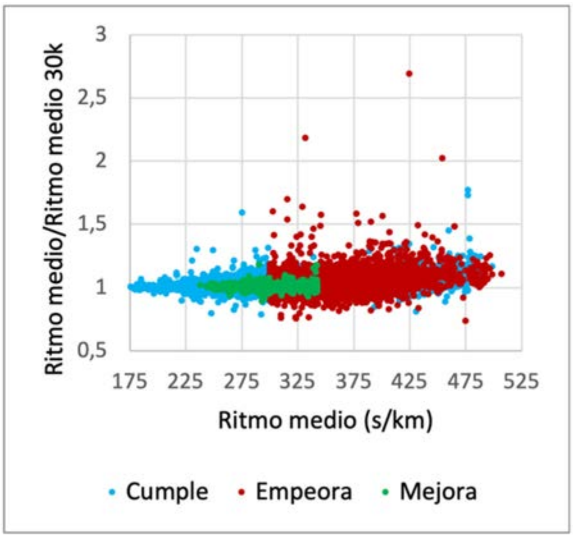
Por otra parte, los corredores que mejoran su tiempo esperado parecen ser más conservadores al inicio de la carrera – ratios ligeramente menores a 1 –, lo que les permite mantener un ritmo muy similar al promedio de la misma – ratio igual a 1 – en la parte final (Figura 10c y 10d).



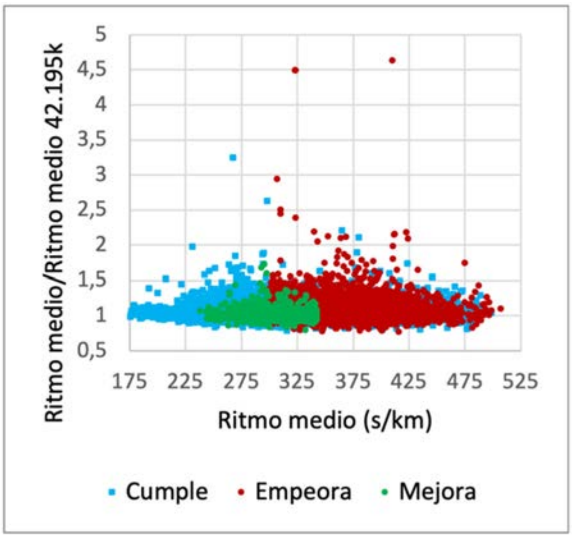
(a) 10k



(b) 21.097k



(c) 30k



(d) 42.195k

Fig. 10 – Evolución del ritmo a lo largo de la carrera

Concluyendo, la variación del ritmo de los corredores aumenta a medida que lo hace el ritmo medio de la carrera. Mientras que los corredores élite – asociados a ritmos muy bajos – y los corredores que mejoran su tiempo previsto son capaces de mantener un ritmo aproximadamente constante a lo largo de la carrera, el resto de los corredores tienden a ir más rápido en la primera parte de la carrera, lo que les conduce – principalmente por fatiga muscular – a ritmos significativamente mayores al ritmo promedio de la carrera en la parte final de la misma.

4.4 Análisis espacio-temporal

Esta última sección del análisis se centra en el estudio de la intensidad y la densidad de corredores a lo largo de la carrera, considerando un intervalo espacial de un kilómetro. Para ello, se ha asumido que cada participante corre cada kilómetro de carrera al ritmo promedio asociado al siguiente punto de control – ritmo calculado a partir de los tiempos de paso entre ese punto de control y el anterior –. Por ejemplo, en el kilómetro 26 se asume que el corredor lleva el ritmo asociado al punto de control 30k, ya que dicho ritmo se ha estimado a partir de la diferencia de tiempos entre los puntos de control 25k y 30k, dividido entre cinco kilómetros (30-25).

La Figura 11 presenta la intensidad de corredores por minuto, en cada punto de control de la carrera (representados por colores), a lo largo del tiempo. La intensidad de corredores en la salida presenta ciertos saltos bruscos que están asociados, como ya se ha comentado anteriormente, a la salida de cada una de las olas. Estos saltos se van laminando conforme la carrera avanza, es decir, en los puntos de control sucesivos, de manera que las intensidades más altas se observan en los primeros puntos de control. En este sentido, la Figura 12 muestra las intensidades máximas en cada kilómetro de la carrera.

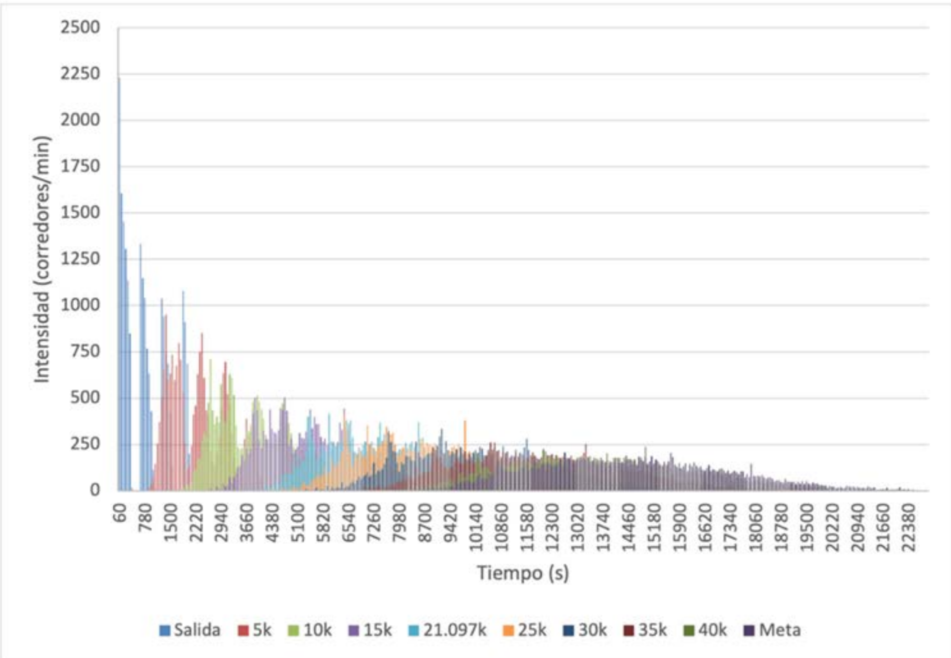


Fig. 11 – Intensidad de corredores por minuto en puntos de control

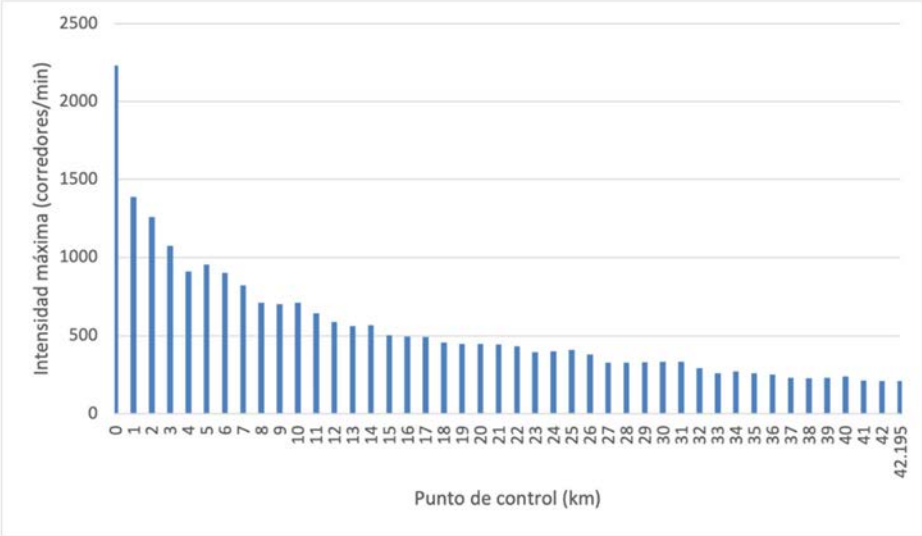


Fig. 12 – Intensidad máxima de corredores en puntos de control

Paralelamente, también se ha estudiado la evolución de la densidad de corredores, estimada como la cantidad de corredores por kilómetro (Figura 13). Para ello, se ha identificado el número de corredores que se encuentran entre dos puntos de control a lo largo del tiempo.

Al igual que ocurre para la intensidad, las mayores densidades de corredores se producen en los primeros kilómetros de la carrera. A medida que la carrera avanza las densidades van disminuyendo, lo que conduce a que la llegada de corredores a meta se realice paulatinamente.

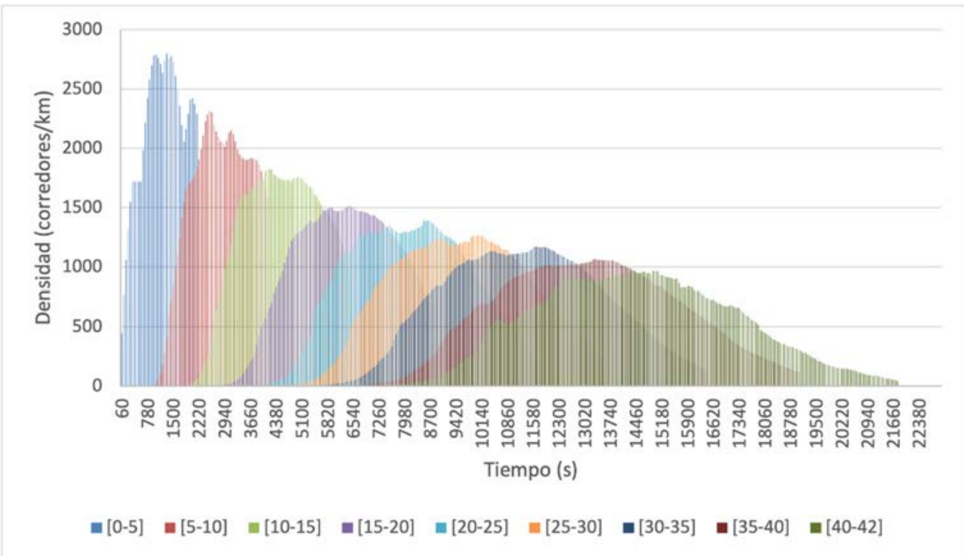


Fig. 13 – Densidad de corredores por kilómetro en intervalos de longitud entre puntos de control

Finalmente, la Figura 14 presenta la densidad de corredores máxima en cada kilómetro de la carrera.

En este sentido, la densidad máxima en cada valor del eje de abscisas está asociada a la cantidad de corredores entre ese valor y el siguiente. Por ejemplo, la densidad máxima para el valor 5 expresa la densidad entre los kilómetros 5 y 6. De acuerdo con lo observado anteriormente, la máxima concentración de corredores se produce en los primeros kilómetros de carrera mientras que a partir del kilómetro 10 la densidad experimenta una reducción muy pausada.

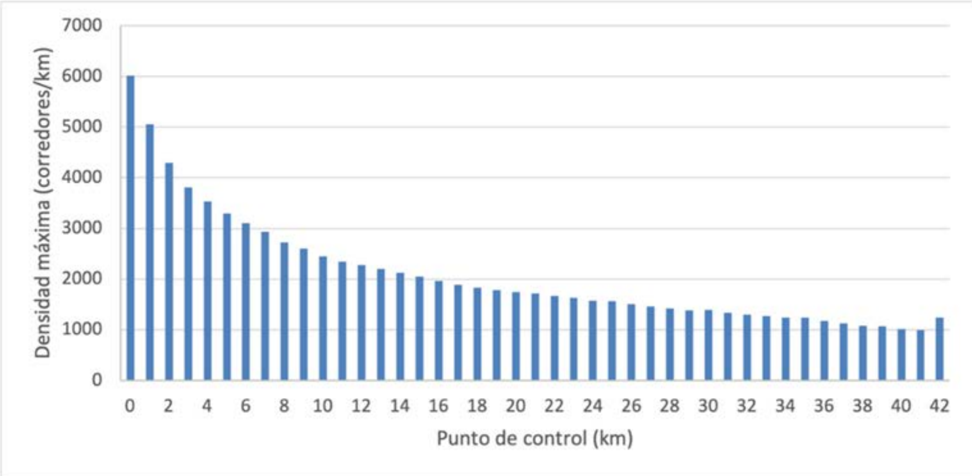


Fig. 14 – Densidad máxima de corredores por kilómetro

Resumiendo, las secciones más críticas durante la carrera se encuentran al inicio de la misma, cuando la intensidad de corredores, expresada en número de corredores por minuto, y la densidad de corredores, expresado en número de corredores por kilómetro, alcanzan sus valores más elevados. Conforme avanza la carrera, ambas variables se reducen considerablemente fomentando una llegada a meta con un flujo de corredores constante y pausado.

5. DISCUSIÓN

Conocer la distribución de corredores a lo largo del tiempo en carreras populares con gran participación puede permitir una gestión más eficiente de la carrera, desde aspectos relacionados con la configuración de la salida en olas y cajones, hasta la disposición de avituallamientos y los anchos mínimos requeridos por unidad de longitud.

Particularmente este último aspecto – ancho mínimo por sección – cobra especial importancia debido a la pandemia de la COVID-19. Conociendo la intensidad de corredores en cada sección, la densidad de corredores por kilómetro y el ritmo medio de los corredores en cada instante y sección se puede estimar el ancho mínimo para garantizar una distancia de seguridad entre participantes.

Para ello, se puede partir del modelo teórico ideal representando en la Figura 15 en el que todos los corredores están equiespaciados a una distancia de seguridad *d*. Bajo esta premisa, en un área específica de la carrera – ancho (a) de sección por longitud (L) de sección – se pueden concentrar un total de N corredores resultado del producto del número de corredores n situados a lo largo de a y el número de corredores m dispuesto a lo largo de L. Las variables de este modelo se relacionan a través de la Ecuación (3), (4) y (5).

$$a = d \cdot (n - 1) \quad (2)$$

$$L = d \cdot (m - 1) \quad (3)$$

$$N = n \cdot m \quad (4)$$

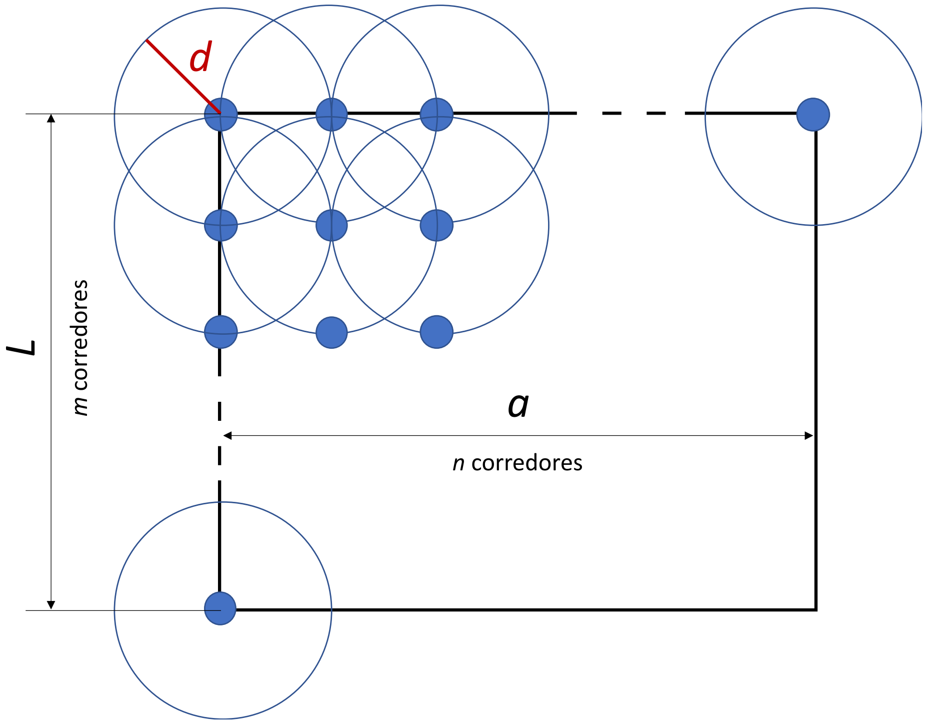


Fig. 15 – Modelo teórico ideal de distribución de corredores

Partiendo de la relación fundamental del tráfico (Ecuación 5) aplicado a este fenómeno concreto, la relación entre la velocidad (V) y el ritmo (R) (Ecuación 6) y la relación que existente entre la densidad de corredores longitudinal (D_l) y transversal (D_t) (Ecuación 7), se obtiene la expresión de la Ecuación 8, que relaciona la densidad transversal (D_t) con la intensidad (I), el ritmo (R) y el ancho de la sección (a).

$$I = D_l \cdot V \quad (5)$$

$$V = 1/R \quad (6)$$

$$D_t = \frac{D_l}{a};\ D_l = D_t \cdot a \quad (7)$$

$$D_t \cdot a = \frac{I}{V} = I \cdot R;\ D_t = \frac{I \cdot R}{a} \tag{8}$$

Por otro lado, la densidad transversal también se puede estimar como el cociente entre el número de corredores *n* que puede atravesar una sección – limitado por la distancia de seguridad (Ecuación 2) – y su anchura (Ecuación 9).

$$D_t = \frac{n}{a} = \frac{\frac{a}{d}+1}{a} \tag{9}$$

Combinando la Ecuación 8 y 9 se obtiene la expresión que permite estimar el ancho requerido en una sección dada una intensidad de corredores, con un ritmo específico y asumiendo una determinada distancia de seguridad (Ecuación 10).

$$\frac{I \cdot R}{a} = \frac{\frac{a}{d}+1}{a} \tag{10}$$

$$a = (I \cdot R - 1) \cdot d \tag{10a}$$

donde a es el ancho requerido (m); I la intensidad máxima de la sección (corredores/s); R el ritmo promedio de los corredores asociado a la intensidad máxima (s/m); y d la distancia de seguridad (m).

La Figura 16 muestra el ancho mínimo requerido al paso por cada kilómetro de la carrera asumiendo diferentes distancias de seguridad. Como se esperaba, los anchos más restrictivos se encuentran en las secciones iniciales de la carrera, cuando la intensidad de corredores es más elevada. Concretamente, la sección que requiere de un mayor ancho se encuentra en el kilómetro 2, con un valor de casi 16 m para una distancia de seguridad de 2 m.

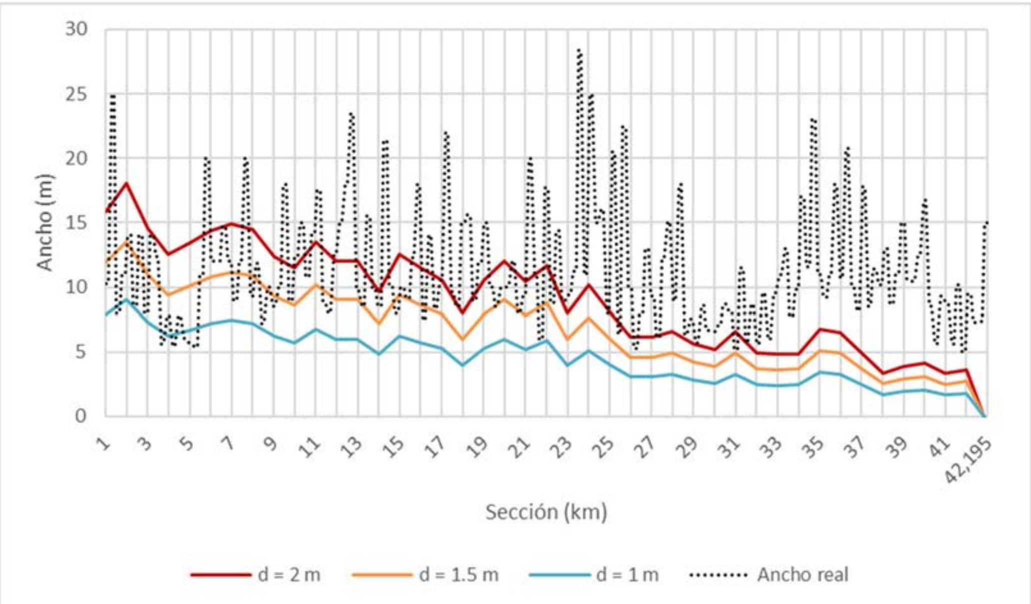


Fig. 16 – Ancho mínimo por sección según intensidad máxima

Comparando los anchos reales de la carrera con los obtenidos se puede afirmar que la carrera no puede desarrollarse en condiciones de seguridad en escenarios de pandemia que requieran asegurar un distanciamiento social como es el caso de la pandemia provocada por la COVID-19 durante el último año, puesto que el ancho real es inferior a los anchos mínimos requeridos para una distancia de seguridad de 2 m en los primeros 6 kilómetros de carrera.

Asimismo, a lo largo de la primera mitad de la carrera se suceden, para la distancia citada, multitud de secciones críticas. No obstante, considerando distancias menores – 1.5 y 1 m – el número de secciones con anchos menores a los requeridos disminuye considerablemente.

Particularmente, para una distancia de seguridad de 1.5 m se observan secciones críticas hasta el kilómetro 10, mientras que considerando 1 m solo se identifican problemas de ancho de sección en los primeros 5 kilómetros.

En caso de mantener el trazado actual, para garantizar que se cumple la distancia de seguridad establecida, se podría reconfigurar la salida, es decir, modificar el número de olas y cajones y el desfase entre olas. Con ello se podría suavizar las altas intensidades y densidades de corredores en los primeros kilómetros.

6. CONCLUSIONES

Las maratones se han convertido en los últimos años en las carreras más populares aglutinando a miles de corredores. Concretamente, la maratón de la ciudad de Valencia ha experimentado un crecimiento anual de un 10% entre sus ediciones de 2016 y 2019, lo que supone que en este último año se sobrepase la cifra de 21,000 participantes. A medida que estas carreras crecen en magnitud su gestión es más complicada y conocer el comportamiento de las variables que definen el flujo de corredores es clave para garantizar que la carrera se desarrolle en condiciones de seguridad. Entre otras cuestiones, la caracterización del comportamiento del flujo de corredores permitirá una mejora de la gestión relativa a la configuración de la salida – definición de olas y cajones –, la disposición de avituallamientos y el establecimiento del recorrido a partir de los anchos mínimos requeridos en cada sección. Este último aspecto todavía cobra mayor importancia en situaciones de pandemia como la actual en la que se debe respetar una distancia social.

Para caracterizar el comportamiento de los corredores esta investigación se ha centrado en el análisis de los maratones celebrados en la ciudad de Valencia (España) desde 2016 a 2019. Los datos generales e individuales de estas carreras están disponibles de manera gratuita en la web de la organización del evento y fueron obtenidos mediante un script de *web scraping* programada exclusivamente para tal fin. A partir de los datos filtrados se estimaron, entre otras variables, los ritmos individuales de cada corredor a su paso por cada punto de control, el desfase de tiempo en la salida, la intensidad de corredores en las secciones correspondientes a cada kilómetro de la carrera y la densidad de corredores por kilómetro.

Como resultado, se identificó un aumento de la participación de las mujeres a lo largo de los años, situándose en 2019 en alrededor de un 20%. En general, el grueso de la carrera se concentra en la franja de edad comprendida entre los 23 años y los 45 años. La presencia de cada una de las categorías restantes se va diluyendo con la edad.

En cuanto a la evolución de corredores en la salida, se verifica que cuanto menor es el tiempo objetivo ligado a la ola, mayor es la intensidad de descarga de corredores. Asimismo, en todas las olas se observa una reducción de la intensidad de descarga con el paso del tiempo.

En este sentido, los modelos calibrados podrían ser empleados para estimar el número de corredores máximo por ola y/o el desfase entre olas.

A la hora de participar en el maratón, cada participante proporciona un tiempo objetivo que la organización utiliza para la distribución de corredores en olas y cajones. Aunque en este caso solo se ha podido analizar el cumplimiento de este tiempo por olas, resulta bastante claro que el tanto por ciento de corredores que empeoran el resultado previsto aumenta conforme mayor es el tiempo objetivo, desde el 26% de corredores de la *Ola 1* al 65% de la *Ola 3*. Asociado a este incumplimiento, se ha verificado que cuanto mayor es el ritmo medio de la carrera, mayor es la variación del ritmo a lo largo de esta.

Concretamente, aquellos corredores que cumplen o empeoran el tiempo objetivo experimentan ritmos más rápidos en la primera mitad de la carrera y ritmos lentos o muy lentos en la segunda parte de la misma. Por el contrario, los corredores más rápidos – ritmos medios menores a 225 s/km – y los que mejoran su tiempo objetivo parecen ser más conservadores al inicio de la carrera y mantienen su ritmo constante a lo largo de esta.

Finalmente, el análisis de la intensidad y la densidad refleja que las secciones más críticas durante la carrera se encuentran al inicio de la misma, cuando ambas variables alcanzan sus valores más elevados. Conforme avanza la carrera, tanto la intensidad como la densidad se reducen considerablemente fomentando una llegada a meta con un flujo de corredores constante y pausado.

Conocer de manera previa estas dos variables es fundamental para la definición del recorrido de la prueba – condicionada por el ancho de las secciones – con el fin de garantizar que todos los corredores se encuentren en flujo libre – no condicionados por otros corredores – a lo largo de toda la carrera.

Todavía es más interesante si cabe la determinación del ancho mínimo requerido en cada sección de la prueba con el fin de garantizar una distancia social entre corredores – sobre todo en la situación actual de pandemia provocada por la COVID-19 –.

Este ancho mínimo puede ser estimado a partir de la intensidad máxima y el ritmo promedio que se producirá en cada sección del recorrido asumiendo el modelo teórico presentado en este trabajo.

Los resultados de esta investigación están limitados a los resultados obtenidos en los maratones de la ciudad de Valencia. Con el fin de generalizar las conclusiones obtenidas es necesario el análisis preferiblemente de otros maratones que también ofrezcan sus datos de manera abierta como, por ejemplo, la maratón celebrada en Berlín, Londres o Nueva York.

Asimismo, sería conveniente ampliar el análisis centrándose en cada cajón, para lo que sería necesario en algunos casos, como el del maratón de Valencia, la colaboración de la organización del evento, pues este tipo de datos habitualmente no es proporcionado ni se puede inferir de manera precisa, aunque sí podría ser estimado de manera aproximada por el desfase en la salida. Por último, sería interesante estudiar cómo la configuración de la salida influye en la intensidad y densidad de corredores en la parte inicial de la carrera con el fin de garantizar el cumplimiento, si es necesario, de la correspondiente distancia de seguridad por motivos sanitarios.

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SIMULACIÓN DE POLÍTICAS DE GESTIÓN DINÁMICAS DE APARCAMIENTO MEDIANTE UN MODELO DE MICROSIMULACIÓN DE TRÁFICO

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RESUMEN

A nivel mundial existen experiencias prácticas de políticas de gestión del aparcamiento en la calle basadas en tarifas dinámicas (San Francisco, Los Ángeles y otras ciudades) que han permitido administrar de forma más eficiente los espacios de parking y reducir el número de vehículos en busca de un espacio libre. Para ello, el presente trabajo analiza el impacto que podrían tener, en el comportamiento de los usuarios, diferentes políticas de gestión del aparcamiento en la vía pública.

Para simular los efectos de las distintas políticas, se ha creado un modelo de aparcamiento basado en un submodelo de elección de lugar de aparcamiento y en un submodelo de búsqueda de plaza de aparcamiento. Los parámetros de los submodelos han sido estimados con datos recolectados en un área del centro de la ciudad de Santander (España) y mediante una encuesta de preferencias declaradas respondida por usuarios de aparcamiento.

El modelo ha sido implementado en el software de simulación Aimsun, construyendo una API personalizada programada en Python 3.7. Este modelo ha permitido simular varias políticas centradas en la tarificación de los espacios de aparcamiento en la calle de forma dinámica con actualizaciones de la tarifa en intervalos cortos de tiempo de entre 5 y 15 minutos.

1. INTRODUCCIÓN

Debido al amplio uso de los vehículos privados, la oferta de aparcamiento es un componente clave en la generación de la congestión del tráfico y los altos niveles de contaminación atmosférica en las zonas urbanas.

En el pasado, la planificación y el desarrollo de políticas de aparcamiento tenían como objetivo ofrecer el mayor número de plazas de aparcamiento posible para facilitar el uso de los vehículos privados. Sin embargo, la búsqueda de plazas de aparcamiento se ha convertido en una dificultad para la mayoría de los usuarios de vehículos privados y en un problema importante que afecta a los sistemas de transporte en las ciudades. La planificación y gestión del transporte se ha enfrentado a varios retos en las últimas décadas.

La mayoría de las ciudades pretenden desincentivar el uso del vehículo privado y promover los modos de transporte no motorizados para la movilidad dentro de las zonas urbanas. Las administraciones públicas tratan de crear zonas peatonales y verdes que puedan dar lugar a ciudades más sostenibles, vivas y seguras. El número de plazas de aparcamiento disponibles en las ciudades se está reduciendo, y el suelo destinado a las actuales plazas de aparcamiento se está utilizando para otros fines con el fin de promover modos de movilidad alternativos y espacios públicos habitables. Por ello, la gestión de las plazas de aparcamiento se ha convertido en un factor esencial para conseguir sistemas de transporte eficientes.

La oferta de aparcamiento en la calle en las zonas urbanas conlleva varias consecuencias negativas. Según un estudio realizado por Shoup (2006), el proceso de búsqueda de aparcamiento representa aproximadamente el 30% del tráfico total en las zonas urbanas. Esta investigación concluyó que la búsqueda de aparcamiento dura entre 3,3 y 14 minutos en las ciudades estadounidenses. Por lo tanto, la búsqueda de aparcamiento conlleva un aumento considerable del tiempo total de viaje de todos los usuarios, no sólo de los que buscan aparcamiento, y un aumento del tráfico y la congestión.

Además, según la RAC Foundation (2012), los vehículos privados están aparcados el 80% del tiempo. Esto significa que hay una ocupación muy ineficiente e infrautilizada del suelo, especialmente en los centros de las ciudades, que de otro modo podría utilizarse para fines más eficientes, como carriles adicionales para el transporte público.

La búsqueda de aparcamiento contribuye a generar tráfico y congestión en las zonas urbanas. Esto conlleva un aumento considerable del tiempo total de viaje de todos los usuarios del transporte y la generación de emisiones de gases de efecto invernadero. La aplicación de políticas de aparcamiento puede ayudar a gestionar la demanda y reducir los problemas derivados del estacionamiento.

Este estudio pretende explorar y comparar diversas políticas de estacionamiento, especialmente en lo que respecta a la tarificación dinámica del estacionamiento y la limitación de la duración de la estancia en el mismo, para concluir qué medidas de restricción del estacionamiento son más favorables para reducir el impacto sobre el tráfico y el medio ambiente. En primer lugar, se va ha hacer un repaso al estado actual de la práctica en cuanto a modelos de aparcamiento y sistemas de tarificación dinámica.

A continuación, se describirá la metodología del modelo de aparcamiento diseñado y, posteriormente se realizará una aplicación práctica describiendo los principales resultados obtenidos para finalmente establecer las conclusiones del estudio.

2. ESTADO DEL ARTE

La mayoría de las políticas de aparcamiento se basan en estrategias que pretenden desincentivar el uso del vehículo privado (Buehler et al., 2017; Nurdden et al., 2007). Como se ha mencionado anteriormente, las administraciones públicas utilizan estrategias y políticas de aparcamiento para regular y gestionar la demanda y la oferta de aparcamiento.

En primer lugar, una de las estrategias más comunes para reducir la demanda de aparcamiento en las grandes ciudades es el peaje por conducir dentro de la ciudad. Aunque no es una política directa de aparcamiento, tiene un gran impacto en la demanda de estacionamiento. Los precios de los peajes pueden ser más bien fijos; basados en el horario, por lo que varían en función de la hora del día, siendo considerablemente más altos durante los periodos punta; o dinámicos. Por ejemplo, en 2003, la ciudad de Londres introdujo una tasa de congestión de 5 libras diarias por circular por la Inner Ring Road (Blow et al., 2003). Esta estrategia pretendía reducir el tráfico en la zona en un 15%.

En segundo lugar, otra estrategia de aparcamiento habitual es la denominada Park and Ride, que pretende descongestionar los centros urbanos mediante la implantación de aparcamientos en las afueras de las ciudades. Estos aparcamientos están conectados con el transporte público, que transporta a los usuarios al centro de la ciudad. Por ejemplo, la ciudad de Barcelona implementó una estrategia de Park and Ride para descongestionar y reducir las emisiones en la ciudad (Vila Serrano, 2019). En la actualidad hay aproximadamente 1500 plazas de aparcamiento en tres áreas de Park and Ride en las afueras de la ciudad, en los barrios de Besòs, Sarrià y La Ciudad de la Justicia, que se encuentran cerca de las estaciones de tren.

En tercer lugar, la limitación del tiempo de estacionamiento es otra estrategia que restringe el tiempo de estacionamiento para desalentar el estacionamiento de larga duración y promover la rotación del estacionamiento. Los periodos más cortos restringen las actividades de los usuarios, mientras que los periodos más largos fomentan la accesibilidad al aparcamiento para los habitantes de la zona de influencia. Las investigaciones recomiendan que las zonas comerciales establezcan un estacionamiento limitado a corto plazo en el 10-30% de las plazas de aparcamiento para aumentar la actividad de los negocios (Litman, 2020). Al mejorar la rotación de los aparcamientos, los administradores pueden favorecer a los negocios de la zona al aumentar el tránsito y la accesibilidad de los clientes. Aunque la limitación de tiempo es una estrategia eficaz, es difícil de aplicar debido a que los usuarios tienden a trasladar sus vehículos a otras plazas de aparcamiento una vez alcanzada la limitación de tiempo (Simićević et al., 2013).

En cuarto lugar, otras estrategias comunes de regulación del estacionamiento son (Litman, 2016): (i) limitación del acceso al estacionamiento en determinadas zonas solo para residentes u otros usuarios permitidos (vehículos de servicios públicos, usuarios de corta duración, etc.), (ii) restricción del estacionamiento en vías arteriales durante periodos de alta demanda para facilitar el tráfico, (iii) limitación del periodo de tiempo a determinadas horas del día en función del uso deseado del estacionamiento durante cada periodo de tiempo, etc.

Por último, el pago por estacionamiento es otra estrategia común de estacionamiento, en la que un usuario paga por ocupar una plaza de aparcamiento. Esta estrategia puede definirse como tarificación del aparcamiento (Shoup, 2017). El peaje del aparcamiento puede producir múltiples cambios en el sistema de transporte, como la reducción de la propiedad del coche privado, el cambio a modos de transporte activos, la modificación de la ubicación del aparcamiento, los cambios en el horario de transporte, la modificación de la duración de la estancia en el aparcamiento, la reducción del tiempo de viaje de los usuarios (Litman, 2010).

También se suele aplicar para lograr uno o varios de los siguientes objetivos: reducir la congestión del tráfico, disminuir los tiempos de búsqueda de aparcamiento, lograr la tasa de disponibilidad de aparcamiento deseada, aumentar los ingresos derivados de los impuestos de aparcamiento, etc.

En cuanto a políticas de precios, se pueden establecer 2 tipos de medias de gestión. Las tasas estáticas que son una de las tarifas más comunes de aparcamiento. Estás suelen aplicarse durante un periodo de tiempo establecido durante el día cuando se prevé que la demanda del aparcamiento sea mayor. El problema suele ser la infravaloración del precio del aparcamiento dando lugar a pérdidas de bienestar (Arnott & Inci, 2006).

Por otro lado, las tarifas dinámicas permiten adaptar el precio del aparcamiento para lograr una tasa de ocupación óptima. Estas políticas permiten una gestión de precios dinámica en base a la ocupación, sin alterar prácticamente la infraestructura existente, lo que las hace muy atractivas de implantar por los múltiples beneficios que ofrecen. Mediante la gestión de precios se alcanzan unas ratios bastante exitosas también en la reducción de tráfico de cruce y plazas libres ofertadas (Millard-Ball et al., 2014).

Finalmente, en lo que a modelos de aparcamiento se refiere, se ha realizado una comparativa de los principales modelos desarrollados en los últimos años Tabla 1.

Modelo	Tipo	Propósito	Método	Tratamiento del espacio	Modo de búsqueda	Software	Referencia
PARK-SIM	Micro	Simulación de elección de aparcamiento dentro de un lote	Eventos discretos	SI	Gestión de colas	CAD	Young and Thompson (1987); Young and Weng (2005)
SUSTAPARK	Micro.	Simulación de aparcamiento en la calle y fuera de la calle	Agentes/autómatas celulares	SI	Maximización de la utilidad desde 200m a destino	JAVA sobre ArcGIS	Spitaels and Maerivoet (2008); Steenberghen et al. (2012)
AGENT-BASED PARKING MODEL	Micro.	Simulación de aparcamiento en la calle	Agentes	SI	Asignación de radio de búsqueda y aumento progresivo del radio en función de la disponibilidad	MATLAB y MATSim	Waraich and Axhausen (2012)
PARK-ANALYST	Desag.	Cálculo de la dinámica temporal de la búsqueda de aparcamiento	Solución analítica	NO	Análisis de cada plaza hasta llegar a destino maximizando la utilidad y la expectativa de plazas en destino	-	Levy et al. (2013)
PARK-AGENT 1 y 2	Micro.	Simulación de aparcamiento en la calle (versión 1) y también fuera de la calle (versión 2)	Agentes	SI	Asigna un aparcamiento de pago en un tiempo definido tras no encontrar plaza de aparcamiento	Visual Basic/ C programado sobre ArcGIS	Benenson et al. (2008)

Tabla 1 Análisis de diferentes modelos de aparcamiento

3. METODOLOGÍA

A partir del análisis del estado del arte, se ha constatado la escasez de estudios en la literatura internacional sobre el análisis del impacto de la aplicación de diferentes políticas de aparcamiento en la vía pública. Por ello, se ha diseñado un modelo de aparcamiento que permita paliar las carencias de aquellos modelos desarrollados en el estado del arte.

3.1 Modelo de utilidad de plaza

El modelo, basado en agentes desarrollado se codificó en Python 3.7 y 2.7, requerido por la API de Aimsun, y se integró en Aimsun a través de la API proporcionada por este software. Aimsun permite modelar el comportamiento individual de los usuarios dentro de una red de tráfico basándose en diferentes teorías microscópicas de comportamiento, como (i) el seguimiento de coches, (ii) el cambio de carril y (iii) la aceptación de huecos.

El modelo permite simular el comportamiento de los usuarios a la hora de buscar una plaza de aparcamiento vacía en diferentes situaciones, políticas de precios de aparcamiento, porcentaje de usuarios informados, tasas de ocupación, etc. El modelo ayuda a establecer y analizar el efecto de diferentes políticas de tarificación, principalmente estáticas y dinámicas.

Para la definición de los parámetros de entrada se realizó un modelo logit multinomial que define las utilidades de cada una de las alternativas de acuerdo con las siguientes ecuaciones.

$$V(Libre) = \beta_0 + \beta_{TD}TD_{Libre} + \beta_{TB}TB_{Libre} + \beta_{OCU}OCU_{Libre} \quad (1)$$

$$V(Calle) = \beta_0 + \beta_{TD}TD_{Calle} + \beta_{TB}TB_{Calle} + \beta_{OCU}OCU_{Calle} + \beta_{TAR}TAR_{Calle} + \beta_{TMAX}TMAX_{Calle} \quad (2)$$

$$V(Sub) = \beta_0 + \beta_{TD}TD_{Sub} + \beta_{TB}TB_{Sub} + \beta_{OCU}OCU_{Sub} + \beta_{TAR}TAR_{Sub} \quad (3)$$

Según esta especificación, la elección de aparcar pagando en la calle depende de la tarifa del aparcamiento (*TAR*), del tiempo a destino (*TD*), del tiempo de búsqueda (*TB*), de la ocupación de las plazas (*OCU*) y del tiempo máximo posible de estancia (*TMAX*). La alternativa aparcamiento libre depende del tiempo de búsqueda (*TB*), del tiempo al destino (*TD*) y de la ocupación de las plazas libres (*OCU*). En el caso de la elección de aparcamiento privado fuera de la calle (parking subterráneo), la elección dependería de la tarifa (*TAR*), el tiempo al destino (*TD*), el tiempo de búsqueda (*TB*) y la ocupación de las plazas (*OCU*).

En el segundo nivel de elección de sección de aparcamiento, la elección depende de la utilidad que se derive por aparcar en una sección según la siguiente expresión:

$$V(seccion) = \beta_{TD}TD_{seccion} + \beta_{TB}TB_{seccion} + \beta_{OCU}OCU_{seccion} + \beta_{TAR}TAR_{seccion} + \beta_{TMAX}TMAX_{seccion} \quad (4)$$

Con parámetros y variables similares a las presentadas en la elección de tipo de aparcamiento.

$$V(seccion) = \beta_{TD}TD_{seccion} + \beta_{TB}(\gamma_{usuario}\, TB_{seccion} + TB_{acumulado}) + \beta_{OCU}OCU_{seccion} + \beta_{TAR}TAR_{seccion} + \beta_{TMAX}TMAX_{seccion} \quad (5)$$

La introducción del parámetro dummy $\gamma_{usuario}$ permite considerar un tiempo de búsqueda esperado igual a 0 en el caso de que el usuario esté informado y sepa que en esa sección encontrará sitio. Por otro lado, las variables ($OCU_{seccion}$) y ($TAR_{seccion}$) mediante su modificación, adoptando valores en tiempo real o estándar de la red basados en históricos, permiten introducir las variaciones que afectan a los diferentes usuarios informados o no informados teniendo en cuenta su comportamiento en el modelo.

Por lo tanto, la elección de sección para aparcar depende de la tarifa (*TAR*), el tiempo a destino (*TD*), el tiempo de búsqueda de aparcamiento (*TB*), la ocupación de la sección (*OCU*) y el tiempo máximo de estancia permitido (*TMAX*) así como del ya mencionado tipo de usuario ($\gamma_{usuario}$).

Finalmente, la elección conjunta de tipo y sección de aparcamiento consiste en la especificación de un modelo Logit Jerárquico (*HL*) en la que la utilidad de la alternativa aparcar en la calle depende de la utilidad máxima esperada de las alternativas que están relacionadas con ella, es decir, de las distintas posibilidades de aparcamiento en las secciones. Estas dos elecciones encadenadas se pueden esquematizar tal y como se muestra en la Figura 1. En este caso, la utilidad de aparcar en la calle vendría dada por la utilidad máxima esperada (*EMU*), es decir:

$$V(Calle) = \frac{1}{\lambda} EMU = \frac{1}{\lambda} ln\{\textstyle\sum_i e\,[\lambda V(seccion_i)]\} \quad (6)$$

En la que λ es el parámetro de escala de la distribución de los términos de error dentro del nido e *i* son el conjunto de secciones agrupadas dentro de la alternativa aparcar en la calle (o cierto subconjunto de ellas), las cuales pueden presentar un cierto nivel de correlación.

Este segundo tipo de modelización mediante LH permite que las distintas secciones de aparcamiento, en las que se puede aparcar en la calle, pueden presentar cierto nivel de correlación al tener características comunes tanto en su utilidad sistemática como en sus errores aleatorios.

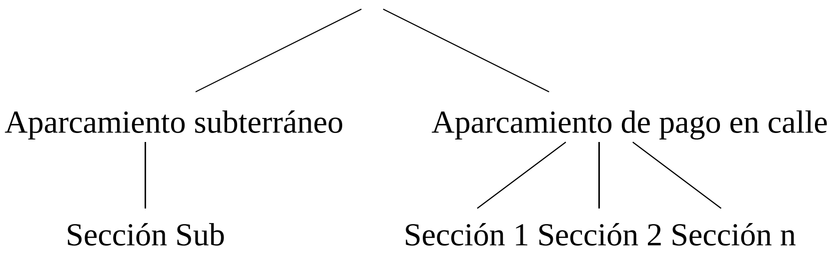

Figura 1 Modelo de elección de tipología y sección de aparcamiento

3.2 Modelo de búsqueda de aparcamiento

El modelo de búsqueda de aparcamiento, como se ha dicho, es un modelo basado en agentes, que, a diferencia de otros, tiene en cuenta diversos factores para asignar distintas utilidades a cada una de las secciones. Para la ejecución del modelo con cada uno de los vehículos se sigue la siguiente secuencia Figura 2

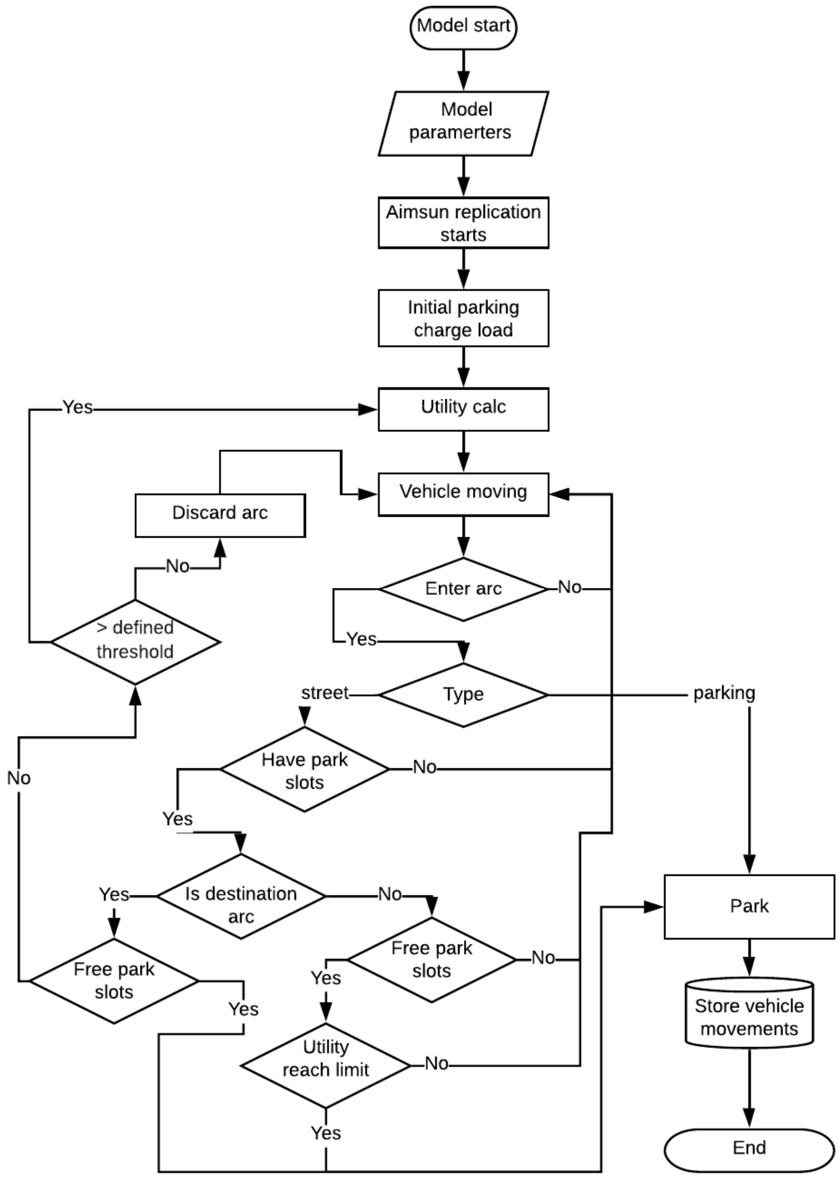

Figura 2 Funcionamiento del modelo de búsqueda

Además de los datos de demanda y oferta de aparcamiento, el modelo requiere la introducción de diversos parámetros del modelo y variables de restricción relacionadas con las políticas de aparcamiento, que se pretenden analizar en el presente estudio. Estos parámetros de entrada del modelo se enumeran la Tabla 2

Variables de entrada del modelo
Tiempo de maniobra de aparcamiento (s)
Tiempo mínimo de estacionamiento (s)
Tiempo máximo de estacionamiento (s)
Ocupación inicial (%)
Rangos de tarifas (€)
Rangos de ocupación (%)
Tarifa estándar en la calle (€)
Tasa estándar fuera de la vía pública (€)
Búsqueda del tiempo de aparcamiento: media y desviación (s)
Máxima utilidad relativa
Tiempo de actualización de la tasa (s)
Porcentaje de usuarios informados (%)

Tabla 2 Variables de entrada requeridas por el modelo

4. APLICACIÓN PRÁCTICA

Para la aplicación del modelo DYNAPARK en un ámbito de estudio real se ha procedido a la modelización de un área de la ciudad de Santander, simulando los escenarios descritos en la Tabla 3.

	Esc. 1	**Esc. 2**	**Esc. 3**
Aplica modelo aparcamiento		X	X
Aplica tarifa fija		X	
Aplica tarifa dinámica			X
Aplica tarifa actual		X	X

Tabla 3 Escenarios ejecutados

Para la aplicación de los cinco escenarios descritos se ha seleccionado un área céntrica de la ciudad de Santander que está ubicada en la zona oriental del centro urbano (Figura 3). El motivo de elección del área viene motivado por la existencia dentro de la misma de:

- Aparcamientos regulados de pago en la calle.
- Aparcamientos privados.
- Aparcamientos privados, de pago, de uso público fuera de la calle.

Figura 3 Área de estudio

Con el objetivo de extraer los parámetros del modelo se realizó una encuesta de preferencias declaradas a usuarios habituales y no habituales de esta zona de aparcamiento. Obteniendose los parámetros presentes en la Tabla 4

Variable	Parámetro	Z
Tarifa (€/h)	-0.95057	-4.88
Tiempo de Búsqueda (min)	-0.07261	-0.68
Tiempo a destino (min)	-0.07761	-1.15
Ocupación (%)	0.00707	0.71
Tiempo máximo de estancia (h)	0.52876	2.90
Constante Subterráneo	2.59822	4.58
Nido Calle	0.68133	2.79
Log-Likelihood	-69.515	
Log-Likelihood (Null)	-138.629	
Log-Likelihood (Constantes)	-136.591	
McFadden Pseudo R-squared	0.4985	

Tabla 4 Parámetros estimados para el modelo de elección de tipología de aparcamiento y utilidad

El valor elegido para los parámetros de entrada del modelo se ha establecido en base a varios criterios, se muestra en la Tabla 5. Algunos datos de entrada, como el tiempo máximo de estacionamiento y la tarifa general, se han extraído de las ordenanzas municipales que regulan el estacionamiento (Santander, 2014). Otros parámetros, como el precio por hora de los aparcamientos subterráneos, vienen dados por los gestores de éstos y son de conocimiento público. Por otro lado, las crecientes fuentes de información disponibles hoy en día de manera online han permitido la extracción de otros datos, como el tiempo medio de estacionamiento de los vehículos que ha sido obtenido a través de un análisis de los datos del portal de Open data de Santander (Santander, 2021).

Variable	**Unidades**	**Escenario 1**	**Escenario 2**	**Escenario 3**
Tiempo parada de estacionamiento	seg.	No se aplica el modelo, cada usuario acude a su centroide final y encuentra aparcamiento	22.3	22.3
Tiempo mínimo estacionamiento	seg.		300	300
Tiempo máximo estacionamiento	seg.		7200	7200
Ocupación inicial	%		95	95
Rangos tarifa aparcamiento on-street	€/h		En el caso de aplicación de la tarifa actual no es necesario aplicar tarifas dinámicas	[0.5,1,1.75]
Rangos ocupación on-street	%			[60,80,100]
Tarifa genérica on-street	€/h		0.75	0.75
Tarifa aparcamiento off-street	€/h		1.60	1.60
Tiempo de búsqueda medio	seg.		240	240
Tiempo de búsqueda desviación	seg.		120	120
Utilidad mínima relativa	%		90	90
Tiempo actualización tarifas	min.		15	15
Usuarios informados	%		No aplica	50

Tabla 5 Parámetros de entrada al modelo de búsqueda de aparcamiento

5. RESULTADOS

Se han realizado 15 simulaciones para cada uno de los escenarios propuestos lo cual permite eliminar la aleatoriedad de los resultados de realizar un número reducido de ejecuciones del modelo. Para poder comparar los resultados obtenidos de forma numérica, se han analizado varios parámetros de salida de la microsimulación como son: consumo de combustible, cola media generada, densidad de vehículos, distancia total viajada por los vehículos, flujo, tiempo de viaje, vehículos dentro de la red, velocidad y emisiones generadas, parámetros todos ellos que nos permiten tener una visión concreta para comparar los escenarios.

Para poder valorar las emisiones de contaminantes se ha usado el modelo descrito por el estudio de Lizasoain-Arteaga et al. (2020). Los resultados obtenidos para cada uno de los indicadores se muestran en la tabla 6. En dicha tabla se muestran algunos resultados desagregados para los coches en tránsito y los coches que aparcan identificados como "park".

Indicador	Unidades	Esc. 1	Esc. 2	Esc. 3
Cola Media - Coche	veh	7.02	22.49	16.59
Cola Media - Coche- park	veh	1.25	24.9	14.1
Consumo de Combustible - Coche	l	167.87	201.71	193.14
Consumo de Combustible - Coche- park	l	29.16	107.51	79.1
Densidad - Todos	veh/km	4.23	27.1	26.29
Densidad - Coche	veh/km	3.65	6.06	5.21
Densidad - Coche- park	veh/km	0.58	21.05	21.09
Distancia Total de Viaje - Todos	km	1056.95	1228.45	1199.76
Distancia Total de Viaje - Coche	km	925.28	920.71	936.17
Distancia Total de Viaje - Coche- park	km	131.67	307.74	263.59
Emisión - Coche - CO2	g	323719.01	384119.86	371121.39
Emisión - Coche - PM	g	99.05	113.53	111.22
Emisión - Coche- park - CO2	g	79239.64	242598.53	184244.02
Emisión - Coche- park - PM	g	29.21	71.95	59.03
Tiempo de Demora - Coche	seg/km	46.8	114.66	88.42
Tiempo de Demora - Coche-park	seg/km	57.25	242.24	212.69
Tiempo de Viaje - Coche	seg/km	116	183.84	157.62
Tiempo de Viaje - Coche-park	seg/km	128.62	312.56	282.49

Tabla 6 Resultados para los 3 escenarios simulados

Como era de esperar se producen 2 efectos. Por un lado, el escenario 1 muestra unos resultados teóricamente más beneficiosos en todos los factores que se han extraído. Sin embargo, en este escenario se ha excluido el tráfico de búsqueda de aparcamiento, por lo que sus resultados no son realistas. Por tanto, queda demostrada la influencia del tráfico generado por la búsqueda de aparcamiento (Shoup, 2005) tal y como se refleja en el incremento de los indicadores en los escenarios 2, y 3 respecto al escenario 1.

Comparando los resultados de los diversos escenarios con el escenario 1, se ve como algunos factores, como el tiempo que los coches permanecen en la red, aumentan significativamente hasta un 26%.

Evidentemente un aumento en el número de vehículos conllevará el consiguiente aumento del consumo de combustible, que se ha estimado en el entorno del 63%, provocando asimismo un aumento promedio del 60% en las emisiones reales que se producen durante el periodo estudiado en la zona. Estos resultados demuestran, por tanto, la relevancia de añadir una capa extra a la microsimulación de vehículos en las ciudades para tener en cuenta todas las maniobras que se llevan a cabo debido al aparcamiento y búsqueda de este. Un aspecto que respalda los estudios realizados sobre la gran influencia del tráfico de búsqueda de aparcamiento en la movilidad de las ciudades.

Una vez demostrada la influencia de los itinerarios de búsqueda y las maniobras de aparcamiento en las simulaciones, es posible analizar los resultados de aplicar un sistema de tarificación dinámica respecto a un sistema de cobro por uso tradicional mediante la comparativa de los escenarios 2 (tarifa actual) y 3. La tabla 7 contiene las variables de salida de la simulación como resultado de aplicar tarifas de forma dinámica. En dicha tabla se comparan los resultados obtenidos en el escenario 3 respecto al 2, donde las diferencias son aún mayores en cuanto a diferenciación de políticas. Todos los indicadores estudiados presentan datos más beneficiosos en el caso de aplicación de tarifas dinámicas y más aún en el caso de tener tarifas máximas más elevadas.

Parámetro	**Var. 2/3 (%)**	**Parámetro**	**Var. 2/3 (%)**
Cola Media - Todos	-35.2	Emisión IEM - Todos - CO2	-11.4
Consumo de Combustible - Todos	-12	Emisión IEM - Todos - PM	-8.2
Consumo de Combustible - Coche- park	-26.4	Tiempo de Demora - Todos	-22.7
Distancia Total de Viaje - Coche- park	-14.3	Tiempo de Viaje - Todos	-14.2

Tabla 7 Comparativa de resultados entre los escenarios 2/3

Es muy llamativa la diferencia que se produce en la variación de las colas medias y en el claro descenso entre escenarios de los consumos de combustible, especialmente de los usuarios que deciden aparcar en la zona. La existencia de usuarios informados, dentro de los escenarios dinámicos, facilita una buena distribución de las plazas, favoreciendo las reducciones observadas.

Al introducir tarifas dinámicas se producen 2 fenómenos, por un lado, la reducción del consumo de combustible y por otro de las emisiones.

Cuantificado el ahorro para esta zona en el caso más significativo, supondría un consumo de 24,40 litros menos de combustible cada hora, un ahorro de unos 0.10€ para cada usuario y aparcamiento en el caso analizado. En niveles de contaminantes supondría una reducción importante de emisiones de CO_2 y otros contaminantes a la atmósfera debido a la disminución del tráfico de paso, tanto al introducir tarifas dinámicas como al subir las tarifas.

En contraprestación, el modelo arroja que los usuarios aparcarían más lejos del destino, incrementando sus tiempos de acceso a la actividad para la que se desplazaban debido a la variabilidad de tarifas. Entre el escenario 3 dinámico y el escenario 2 actual se produce una diferencia de distancias en acceso a destino de 25 metros, siendo 155.78m para el escenario dinámico y de 130.03 para la situación actual. Este aumento de distancia es debido al mayor peso que tiene entre los usuarios aparcar en plazas más baratas y libres, al estar presentes las tarifas dinámicas, penalizando en cierta medida la cercanía con el destino final, pero mostrando unos resultados globales muy positivos en relación al resto de variables.

Por otro lado, empleando los datos de las 15 iteraciones para cada uno de los escenarios, se han extraído, mediante el empleo de la API del software de microsimulación y el empleo del lenguaje de programación Python, resultados comparativos de los usuarios que aparcan de los escenarios 2 y 3 en función del tipo de usuario tal y como se refleja en la tabla 8. Cabe destacar que el escenario 2 no contempla la diferenciación entre usuarios informados o no, por lo que se ofrece el conjunto de los resultados.

Parámetro	Esc. 2	Esc. 3		
Tipo usuario	Conjunto	Informado	No Informado	Conjunto
Distancia recorrida media	1163.92	650.31 (-44.13)	1258.16 (8.1)	943.86 (-18.91)
Distancia a destino media (m)	130.03	183.66 (41.24)	125.93 (-3.15)	155.78 (19.8)
Promedio de Intentos aparcamiento	3.43	1.01 (-70.55)	3.78 (10.2)	2.35 (-31.49)
Tiempo de búsqueda medio (min)	9.00	3.66 (-59.33)	7.32 (-18.67)	5.43 (-39.67)
Usuarios de aparcamiento off-street (%)	21.91	34.63 (58.06)	15.72 (-28.25)	25.5 (16.39)
Usuarios que aparcan en una sección diferente a la de máxima utilidad (%)	33.61	14.4 (-57.16)	36.58 (8.84)	25.11 (-25.29)

Tabla 8 Resultados de distintos indicadores en los escenarios con usuarios que aparcan (Entre paréntesis el porcentaje de variación respecto al Escenario 2)

Los indicadores ponen en evidencia la diferencia existente dentro de los mismos escenarios entre los tipos de usuario. En primer lugar, la distancia media recorrida por cada usuario desciende entre los escenarios dinámicos y con tarificación estática, e incluso se reduce un 48% entre usuarios informados y no informados en el escenario 3.

Estrechamente relacionado con la distancia recorrida, se puede analizar el promedio de intentos de aparcamiento, es decir, el número de veces que cada usuario intenta aparcar en una plaza en la calle. Este indicador baja significativamente en el conjunto de los usuarios, siendo inferior a 1, o en torno a 1, en el caso de tarificación dinámica más barata para usuarios informados, quienes en la mayor parte de los casos acuden directamente a plazas vacías o a aparcamientos privados, cuyo uso también refleja una clara variación. Se observa además un rechazo muy grande al uso del aparcamiento de pago fuera de la calle por su elevada tarifa, en el caso de usuarios no informados mientras que los usuarios informados, hacen un mayor uso de este. Otro de los indicadores relacionados es el tiempo de búsqueda, que se sitúa en torno a los 10 minutos en el caso del sistema sin tarificación dinámica, tiempo similar al de la encuesta realizada por el estudio de Antolín (2019).

Cabe destacar el aumento de la distancia al destino final de los usuarios informados, en parte por el uso del aparcamiento privado fuera de la calle y por acudir a zonas de aparcamiento más alejadas por el menor precio de estas.

5. CONCLUSIONES

En esta investigación se ha propuesto un modelo escalable de elección y búsqueda de aparcamiento basado en agentes. Este modelo se ha implementado en un software de simulación, el cual ha permitido aprovechar todas las características de este tipo de herramientas para la evaluación de distintos escenarios de aparcamiento. Además, el modelo se ha aplicado en un área de estudio concreto con el objetivo de simular escenarios de aparcamiento en la calle sin y con tarificación dinámica basada en la ocupación en tiempo real de los espacios de aparcamiento.

Las simulaciones realizadas han permitido demostrar la influencia del tráfico de búsqueda de aparcamiento, que no tienen en cuenta los softwares de microsimulación del tráfico existentes, en distintos indicadores. Así se ha comprobado que la densidad de tráfico puede incrementarse en torno al 50%, tal y como reflejaba White (2007) en su estudio para la ciudad de New York, un dato que evidencia la necesidad de simular este tipo de tráfico si quieren obtenerse estimaciones realistas.

Los resultados obtenidos verifican las hipótesis de partida respecto a que la introducción de tarifas dinámicas permite obtener mejoras significativas en todos los indicadores analizados reduciéndose las emisiones (-11.4%), el consumo de combustible (-26.4%) y el número de vehículos en el interior de la zona (-30.3%). Se comprueba la influencia evidente de las subidas de precios en los escenarios analizados, pudiéndose constatar que las mayores tarifas producen unos mejores resultados globales en los principales indicadores analizados. La distribución de los usuarios entre diversos modos de aparcamiento con un aumento del uso de aparcamientos privados del 16.4%, favorece la utilización óptima del área urbana destinada al aparcamiento y permite reducir el tráfico de paso.

Además, se ha probado la influencia de la introducción de usuarios informados de las tarifas y las ocupaciones dentro de la red y se ha modelado su comportamiento a través de un parámetro en el modelo de elección de utilidad de plaza. Este análisis ha arrojado unos resultados positivos para el fomento de las políticas de implantación de información al usuario y se han verificado las predicciones realizadas por investigaciones anteriores (Panja et al., 2011). Los resultados obtenidos arrojan mejoras muy significativas para el tiempo de búsqueda, que se reduce en torno al 60% mediante la introducción de tarifas dinámicas. Estas tarifas también han servido para obtener menores tasas de ocupación, con tan solo una hora de simulación.

Con el desarrollo del modelo y la aplicación de tarifas dinámicas se abren un gran abanico de posibilidades de investigación en este campo de estudio para tratar de detectar tarifas óptimas y estudiar, en un futuro, la influencia de nuevas formas de movilidad como la que pueden generar la irrupción de vehículos autónomos y sus capacidades de estacionamiento también autónomo.

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THE GRAVITY MODEL AS A TOOL FOR DECISION MAKING. SOME HIGHLIGHTS FOR INDIAN ROADS

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ABSTRACT

For many decades, there have been plenty of analyses all over the world about the relationship between socio-economic attributes and transport flows. One of the most fruitful tools is the gravity model, in the beginning used for road transport, but recently widely used for air transport and international trade.

India is an outstanding example of complexity, with a mixture of megapolises and vast rural areas. Its road network shows plenty of six and four lane expressways spanning hundreds of kilometers, complemented by a dense web of State and local secondary and tertiary links.

In the last decades, National and State Governments have improved vast tracts of roads, but there is still a huge gap. Investment priorities are usually decided on the ground of existing congestion or strategic issues, but not much on demand analyses.

For ascertaining whether in India socio-economic structure and transport flows follow a common pattern, complete corridor OD matrices were calibrated from partial screen matrices for a sample of long-distance corridors (NH-1, NH-6, NH-8, NH-58, NH-73). These matrices were later analyzed by means of gravity models that included parameters such as population or GDP per district (as zone attributes) and road distance among district centroids (as friction factors). Several formulae were tested, and the best fit was selected.

Results for main corridors are rather homogeneous, and rather consistent with research carried out in other countries. Simple formulae have a high explanatory capacity, even if the huge mega-cities of Delhi and Mumbai are included in the analysis. But results for rural corridors are much less consistent, probably due to a less mature structure in terms of spatial distribution and transport relationships.

1. BACKGROUND AND OBJECTIVES

India is one of the largest countries in the world, with well above 1.2 billion inhabitants and a road network of around 3.3 million kilometers. This size in itself entails a high complexity, with huge long distance corridors spanning hundreds of kilometers linking very large cities, surrounded by a web of secondary links, many of which have local importance. Although the road network has greatly improved in the recent past, it still needs important investments for implementing further improvements in terms of quantity and quality. Owing to the importance of the investment needs, priorities should be clearly supported by analytical tools. But data are scarce and scattered and, accordingly, it is not easy to have a clear, simple vision of traffic flows beyond the usual, *ad hoc* vehicle traffic counts.

This paper's objective is to find out whether in India, as in other countries, there is a simple explanation for the traffic flow volume between different cities and, in particular:

- Taking into account the vast extension of the country and its huge diversity, do traffic flows in India follow a common, simple pattern on all long distance corridors? Are there groups of different corridors?
- Since the city size is highly diversified, does the size of cities on different corridors affect their traffic flow structure? Do huge metropolitan areas behave differently to the rest of cities?
- In spite of the general scarcity of data, are there any independent variables that can explain the aforementioned patterns?
- If any common flow pattern does exist, can it be used for supporting the investment decision-making process?

2. THE GRAVITY MODEL

Gravity models have been widely used in many fields of human activity, from phone calls to commuting trips, to describe behaviors that follow patterns that are somehow similar to the gravitational interaction as described by the famous Newton's law of gravity. There is some dispute as to who introduced this idea in the analysis of land use and transport. In the 1860s H. Carey first applied Newtonian Physics to the study of human behavior by means of the so-called "gravity equation" but it seems that it was H.N. Pallin, a Swedish researcher, who in 1930 (Schmidt & Campell, 1956), came up with the first gravity formula for metropolitan traffic.

For some time this gravity model got wide and deep attention, not just because of the mentioned similarity to Newton's law, but because it was found to have the potential of a higher level of generality (Wilson, 1970).

With this broader approach, the flows between any pair of zones (T_{ij}) are the “dependent” variables and have to be explained by some “independent” variables (x_i, x_j, f_{ij}).

$$T_{ij} = f(x_i , x_j, f_{ij}) \qquad (1)$$

where:

- x_i and x_j are attributes of the origin and destination, such as population, domestic product, etc.
- f_{ij} are “friction factors”, such a trip time or distance between zones.

Lately the gravity model has been used in many studies, to predict both freight and passenger flows, as well as international trade (Kepaptsoglou, Karlaftis & Tsamboulas, 2010). Its usefulness has been demonstrated for other transport modes, such as air transport. (Arvis & Shepherd, 2011).

In India, the gravity model has been used for freight flows at national level within a comprehensive several-steps model: it provided the distribution of generated and attracted flows (Dalvi & Das, 1983). It has also been widely used for India’s international trade analysis (Batra, 2004; Bhattacharyya & Banerjee, 2006) and, to a large extent, for urban transport. (Jaiswal & Sharma, 2012).

3. METHOD

The analysis of long-distance flows requires information on origin and destination of trips that is not easily available in India. Although there are some databases with some information on traffic, there is a general lack of structured information and most researches and consultancy studies on road traffic are carried out with information collected on an ad-hoc basis, by means of vehicle traffic counts and screen origin-destination surveys. In fact, there are several procedures clearly defined by the codes published by the Indian Road Congress (The Indian Road Congress, 1988 & 2001).

This usual method provides information that describes, with some detail, the attributes of users crossing the screen where the survey in question is being done. But, owing to the physical impossibility of obtaining statistically balanced and representative samples for all flows, some flows may be under-represented, while others may be over-represented.

Besides, some flows may cross several screens while others may cross only one. In order to solve this problem, the most used method (Ortuzar & Wilumsen, 1995) is a procedure of maximum likelihood calibration, by means of which a “seed matrix”, obtained as a combination of matrices obtained in the survey, is assigned to the network and the traffic volumes estimated by the model are compared to the vehicle traffic counts.

Any mismatches are adjusted on an iterative process to make sure the final traffic flows reproduce the traffic counts with enough accuracy.

The next step is to try to explain the matrices obtained. After an analysis of available socio-economic data, the ones that seemed best suited as independent variables were the following:

- "Attraction factors" (x_i): Population per district or, alternatively, domestic product per district. Also some other attempts were made with other variables that could be related to traffic: the most obvious candidate was the number of vehicles per district.
- "Friction factors" (f_{ij}): distance between districts' centers of gravity.

A further problem was this of the heterogeneous time reference, since for some variables there were reliable data for some years, but for others the time reference was different. Some simple algorithms to overcome this problem, such as making the assumption that GDP or population at District level has evolved at the same pace as the corresponding whole State, just introduces more hypothesis. Therefore, it was decided not to make any changes to the official data, except in the case when for the same variable there were different horizons (notably in the case of vehicle data). As a consequence, all values for each variable were referred to the same year, but different variables could be referred to different years, which changes formula as follows:

$$T_{ij\,y'} = k\,\frac{x_i^{\alpha\,y''}\,x_j^{\alpha\,y''}}{f_{ij}^{\beta\,y'''}} \tag{2}$$

Where y', y'' and y''' are the reference years for each variable.

Formula (2) can be calibrated easily thanks to the use of logarithms that transform the expression into a linear one, which allows for a very simple regression calibration. The software used was Microsoft's Excel.

4. CASES AND DATA AVAILABLE

In order to have a proper picture of the situation in India, a broad sample was needed: covering different parts of the country as well as different corridor types. According to the information available to the researchers, the following corridors were chosen:

- **NH-1**: Panipat - Jalandhar. 285 km. NH1 is, as expected from its code name, one of the main corridors in India. It connects the Indo-Pakistan border to Delhi. Major towns are Panipat, Jalandhar, Ambala, Ludhiana, Chandigarh and Delhi. Panipat oil refinery and industries at Ambala, Jalandhar and Ludhiana are major centers of activity.

Ludhiana is home to 90% of all woolen garments in India and Jalandhar is known for its sports good industry. There are many short distance and long distance routes competing with this corridor.

- **NH-6**: Gujarat/Maharashtra border - Amravati. 484 km. NH6 is the major national highway connecting East India to West India. Main cities around the corridor are Amravati, Akola, Jalgaon, Dhule, Nagpur, Surat and Mumbai. The project corridor mainly lies in the most backward economic regions of Maharashtra state with agriculture as the main occupation. The corridor is full of many small local bypasses and long alternate routes.
- **NH-8**: Kishangarh – Udaipur - Ahmedabad. 555km. This corridor runs through some feebly populated areas of Rajasthan, but it connects Delhi to Mumbai via many important economic hub cities like Jaipur, Kishangarh, Ahmedabad, Vadodara and Surat. NH3 could potentially compete with NH8, but its poor current condition prevents it from being a real alternative.
- **NH-58**: Meerut - Muzaffarnagar. 79 km. This corridor runs through the sugar belt of India wherein sugarcane production and processing is the main industry. Meerut, Ghaziabad and Muzaffarnagar are known for many industrial and agro-based activities. Sacred sites of Haridwar and Rishikesh attract thousands of pilgrims all year round. SH57 is a major competing route for NH58, though it is in a very poor condition at present.
- **NH-73**: Yamunanagar - Panchkula. 108 km. Chandigarh and Panchkula are major cities near or along the corridor. Yamunanagar, Ambala and Saharanpur are industrial towns around the corridor. Baddi, an industrial township near Panchkula, is being developed as pharmaceuticals industry capital of India. NH1 and a combination of some State highways pose choices to users of NH73 for both short and long distance routes.

For each of the aforementioned corridors, data on volume of traffic and on origin-destination flows on the very road and on competing ones were available on many screens, as shown in Table 1. On the other hand, independent variables were available from official sources at different years. The distance between District capitals was easily obtained by means of TransCAD on the corresponding network graphs.

Corridor	Section	Year	Number of traffic count screens	Number of OD screens	Number of OD surveys
NH-1	Panipat-Jalandhar	2010	34	14	15,675
NH-6	Gujarat/Maharashtra border-Amravati	2012	10	10	18,376
NH-8	Kishangarh-Udaipur-Ahmedabad	2011	17	14	(*)
NH-58	Meerut-Muzaffarnagar	2013	2	2	2,423
NH-73	Yamunanagar to Panchkula	2011	11	2	6,035

(*) The precise figure was not available, but the sample was between 15,000 and 20,000 vehicles.

Table 1 – Year of available traffic data and number of screens per analyzed corridor

5. INTERMEDIATE RESULTS: OD MATRICES

Not all previous studies available had the same vehicle type structure, because they had been merged according to particular needs.

Therefore, the first step was a calibration of OD matrices following the existing vehicle types.

The goodness of fit between OD matrix and traffic counts was high in all cases, as shown in Table 2.

Corridor	Car/Van/Jeep	LCV/Minibus	2AT/3AT/Bus	2AT/Bus	3AT	MAV
NH1	0.992	0.992	0.974	n.a.	n.a.	0.982
NH6	0.997	0.996	n.a.	0.943	0.870	0.932
NH8	0.992	0.992	n.a.	0.969	0.966	0.976
NH58	1.000	1.000	1.000	n.a.	n.a.	1.000
NH73	0.997	0.995	n.a.	0.965	0.763	0.998

LCV = Light Cargo Vehicle; 2AT = Two Axle Truck; 3AT = Three Axle Truck; MAV = Multiaxle vehicle (> 3 axles); n.a. = not available.

Table 2 – Coefficient of determination (R2) of regression analysis between assigned traffic values and traffic counts

This somehow heterogeneous classification of vehicles prevented from a detailed, homogeneous analysis of vehicle types, but this was not a big hurdle, as the lack of proper independent variables made it useless to try a very detailed analysis of dependent variables.

Besides, the classical differentiation between passenger vehicles and goods vehicles could not be done in detail due to the mixture of types within some matrices (e.g. LCV and minibuses, trucks and buses).

The decision made was to distinguish between light and heavy vehicles for two reasons:

- This aggregation is fully compatible with existing data.
- This definition is based on the nature of the presumed distance for which each vehicle is best suited, which is coherent with the distance as the friction factor.

Therefore, two matrices were obtained for each corridor:

- One matrix for light vehicles, which in practice was almost reduced to cars and small cargo vehicles.
- One matrix for heavy vehicles, that is, buses and trucks of any size, which is in practice mostly trucks of any size.

6. FINAL RESULTS: GRAVITATION MODEL CALIBRATION

In order to have a broader analysis, the parameter k in the aforementioned formula was considered under two hypothesis: fixed (k=1) and calibrated. Thanks to the data available, for all large corridors (NH1, NH6, NH8) it was possible to carry out the regression analysis taking into account population, GDP or number of vehicles. For second-rank corridors (NH58 and NH73) it was possible only with population and GDP. In all cases, the friction factor was the distance.

When it was assumed that $k = 1$, results showed a high coefficient of determination, with values of 0.9 or above for all calibrations.

Corridor	Attraction factor	Light vehicles				Heavy vehicles			
		R2		F significance		R2		F significance	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
NH1	Population	0.92	0.92	0.0%	0.0%	0.92	0.92	0.0%	0.0%
	GDP	0.92	0.92	0.0%	0.0%	0.92	0.92	0.0%	0.0%
	N of vehicles	0.92	0.92	0.0%	0.0%	0.89	0.90	0.0%	0.0%
NH6	Population	0.99	0.99	0.0%	0.0%	0.99	1.00	0.0%	0.0%
	GDP	0.99	0.99	0.0%	0.0%	0.99	1.00	0.0%	0.0%
	N of vehicles	0.99	0.99	0.0%	0.0%	0.99	1.00	0.0%	0.0%
NH8	Population	0.96	0.97	0.0%	0.0%	0.96	0.97	0.0%	0.0%
	GDP	0.96	0.97	0.0%	0.0%	0.96	0.97	0.0%	0.0%
	N of vehicles	0.95	0.97	0.0%	0.0%	0.94	0.98	0.0%	0.0%
NH58	Population	0.98	0.98	0.0%	0.0%	0.94	0.94	0.0%	0.1%
	GDP	0.98	0.98	0.0%	0.0%	0.94	0.94	0.0%	0.1%
	N of vehicles	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NH73	Population	0.94	0.94	0.0%	0.0%	0.95	0.95	0.0%	0.0%
	GDP	0.94	0.94	0.0%	0.0%	0.95	0.95	0.0%	0.0%
	N of vehicles	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

(1) With Delhi and Mumbai; (2) Excluding Delhi and Mumbai; n.a. = data not available

Table 3 – Values of coefficient of determination by corridor, type of city and independent variable

Focusing on the first-rank corridors (NH1, NH6, NH8), the sample excluding Delhi and Mumbai showed a slightly better coefficient of determination, but again in negligible amounts. In all cases, population, GDP and number of vehicles were good independent variables, not much different to one another in statistical significance. The values obtained for the calibrated parameters are presented in Table 4.

Corridor	Attraction factor	Light vehicles				Heavy vehicles			
		α		β		α		β	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
NH1	Population	0.44	0.50	-1.58	-1.91	0.45	0.48	-1.75	-1.92
	GDP	0.47	0.52	-1.61	-1.90	0.48	0.51	-1.77	-1.92
	N of vehicles	0.49	0.55	-1.56	-1.92	0.51	0.55	-1.30	-1.46
NH6	Population	0.39	0.43	-1.36	-1.57	0.29	0.32	-0.80	-0.98
	GDP	0.47	0.49	-1.60	-1.70	0.37	0.38	-1.06	-1.11
	N of vehicles	0.52	0.58	-1.64	-1.93	0.45	0.46	-0.94	-0.98
NH8	Population	0.46	0.63	-1.60	-2.55	0.36	0.56	-1.10	-2.22
	GDP	0.59	0.78	-2.04	-2.97	0.48	0.71	-1.51	-2.67
	N of vehicles	0.51	0.87	-1.57	-3.29	0.36	1.05	-0.53	-3.13
NH58	Population	0.26	0.21	-0.45	-0.14	0.17	0.12	-0.19	0.13
	GDP	0.26	0.23	-0.34	-0.09	0.18	0.13	-0.14	0.15
	N of vehicles	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
NH73	Population	0.75	0.75	-3.51	-3.51	0.64	0.64	-2.92	-2.92
	GDP	0.72	0.72	-3.08	-3.08	0.62	0.62	-2.61	-2.61
	N of vehicles	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

α = power of attraction factors; β = power of friction factor (distance); (1) With Delhi and Mumbai; (2) Excluding Delhi and Mumbai; n.a. = data not available.

Table 4 – Values of parameters calibrated by corridor, type of city and independent variable

For all first-rank corridors (NH1, NH6, NH8), the sign of the powers of the attraction variables (population, GDP, number of vehicles) and friction (distance) were correct, while the two lesser corridors showed problems of sign consistency (NH58) or of statistical significance (NH73).

According to values in Table 4, the introduction or exclusion of the largest cities meant interesting variations in the values of the calibrated parameters: for corridors with only one of these large metropolitan areas in the surroundings (Delhi for NH1, Mumbai for NH6) the variation in the values was relatively low (from 3% to 23%, depending on the cases), but when both cities were relevant (NH8) the variation was much larger (above 32% and up to 491%).

A deeper analysis of values obtained for the power (β) of the distance is shown in Table 5, where minimum, maximum and non-weighted average values are presented by type of vehicle and independent variable.

Attraction factor	Light vehicles						Heavy vehicles					
	With Delhi & Mumbai			Excl. Delhi & Mumbai			With Delhi & Mumbai			Excl. Delhi & Mumbai		
	Min	Max	Av	Min	Max	Av	Min	Max	Av	Min	Max	Av
Population	-1,60	-1,36	-1,51	-2,55	-1,57	-2,01	-1,75	-0,80	-1,22	-2,22	-0,98	-1,71
GDP	-2,04	-1,60	-1,75	-2,97	-1,70	-2,19	-1,77	-1,06	-1,45	-2,67	-1,11	-1,90
N of vehicles	-1,64	-1,56	-1,59	-3,29	-1,92	-2,38	-1,30	-0,53	-0,92	-3,13	-0,98	-1,86

Min = minimum; Max = Maximum; Av = non-weighted average.

Table 5 – Values of power (β) of the distance as friction factor

According to Table 5, average values of this β parameter are quite homogeneous:

- In absolute terms, taking into account Delhi and Mumbai, they are around 0.9-1.5 for heavy vehicles and around 1.5-1.8 for light vehicles.
- Without these metropolitan cities, values are around 1.7-1.9 for heavy vehicles and around 2.0-2.4 for light vehicles.

It is noteworthy that for NH58 the values of this β parameter are much lower (in absolute terms, from 0.2 to 0.5), this showing again the difference between large corridors of National relevance and corridors of mere local importance.

The introduction of the parameter k reduced the accuracy of the calibration, which showed low values of the coefficient of determination.

7. CONCLUSIONS

The analysis summarized in this paper clearly shows the following:

- In India, as in all other developing countries, the lack of data introduces some degree of inaccuracy in traffic analyses. But results described in this paper are so consistent that can be considered, at least, good orders of magnitude.
- In large corridors, volumes of vehicles can be explained by the classical gravity model. Population, GDP and number of vehicles at District level have a noticeable explanatory capacity. Parameter values are remarkably homogeneous: as a rule, the friction due to distance has exponent values between 1.0 and 2.0 if all cities are included and between 1.5 and 3.0 if the largest cities are excluded. These values are not very much different from the ones obtained in more developed countries. Probably people tend to behave similarly in trips between large cities all over the world.

- In corridors in rural areas, the parameters are quite different from one area to another. There are no obvious patterns and each corridor has its own characteristics. It remains to be seen whether these rural corridors converge to the pattern found in the largest ones when GDP grows or whether their peculiarities are intrinsic.

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ESTIMACIÓN DE DENSIDAD DE PASAJEROS EN EL SISTEMA DE METRO DE MADRID PARA TOMA DE DECISIONES OPERATIVAS BASADA EN MODELIZACIÓN

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RESUMEN

Un correcto seguimiento del funcionamiento del sistema de Metro de Madrid desde la perspectiva del usuario exige disponer de información del número de viajeros en todo momento y para cada elemento del sistema: estaciones, vestíbulos, andenes y vehículos. La contraposición de volúmenes y capacidades de cada uno de estos elementos permiten deducir densidades que se relacionan de forma directa con el concepto de calidad del servicio.

Frente a la opción de monitorización ubicua de los volúmenes de viajeros a lo ancho del sistema, Metro de Madrid ha optado por una inteligente combinación de datos de registros discretos (vinculados a los accesos al sistema), datos de patrones de movilidad espaciales y dinámicos (basados en encuestas y uso de títulos de transporte) y el uso de técnicas de modelización para completar una fotografía permanentemente actualizada del uso de cada elemento del sistema de Metro.

La comunicación que se presenta describirá la arquitectura y problemática enfrentada, así como el desempeño actual del sistema y planteamiento de futuro.

Finalmente, la comunicación incluirá una descripción de cómo tal sistema, diseñado y elaborado con anterioridad a la situación pandémica actual, ha resultado clave para la construcción de sistemas de control dinámico automatizado de las instalaciones de acceso a la red mediante la explotación de las estimaciones de flujo de viajeros proporcionadas por el modelo.

1. INTRODUCCIÓN: PLANTEAMIENTOS ESTRATÉGICOS PARA LA GESTIÓN AVANZADA DEL TRANSPORTE PÚBLICO

La correcta supervisión y gestión del funcionamiento de un sistema de transporte como el Metro de Madrid exige disponer de información de volúmenes de viajeros en todo momento y para cada elemento del sistema: acceso a estaciones, vestíbulos, andenes y vehículos.

La contraposición de volúmenes y capacidades de cada uno de estos elementos permiten deducir densidades que se relacionarán de forma directa con el concepto de calidad del servicio.

Todo operador de transporte que aspire a colocar al cliente y su experiencia de viaje en el centro debe de procurar tener bajo control este parámetro.

Al mismo tiempo, la optimización en la toma de decisiones operativas implica pasar de la mera observación del "fenómeno" a tratar de predecir su evolución. Así, el operador aspira a pasar del enfoque reactivo de resolución de incidencias al proactivo de evitación de éstas.

Este sería el contexto conceptual en el que tienen cabida los trabajos descritos en la presente comunicación. Trabajos que, es importante destacar, parten de la propia compañía de transportes contando con colaboraciones externas especializadas, procedentes del mundo académico y de la investigación.

En un plano más prosaico, se daba la circunstancia de que la *División de Operación* venía recibiendo de su homóloga de *Calidad*, entre otras, requerimientos de informes periódicos que incluyeran indicadores del tipo: densidad de personas en puntos de la red, zonas de mayor tránsito o volumen de viajeros afectados por determinados fallos en la operación.

Estos fallos podían hacer referencia a situaciones tales como retrasos en servicios o afecciones por escaleras mecánicas averiadas.

Para poder dar respuesta a estos requerimientos, el equipo de *Movilidad* del *servicio de Planificación y Estudios de Operación de Metro de Madrid* (en adelante, "Metro") venía explotando una herramienta de modelización cuya configuración había quedado obsoleta, como diagnosticó la auditoría técnica encargada a los servicios profesionales de *PTV Group*.

Es en ese momento cuando Metro decide reformular el sistema al completo (no solo el modelo) para dar respuesta adecuada al reto planteado y al mismo tiempo preparar las bases para nuevas formas de explotar la información disponible en beneficio de los procesos de programación de la oferta de servicio.

Idealmente, pudiera pensarse que una opción hubiera sido la de monitorizar de forma ubicua, mediante dispositivos, los volúmenes de viajeros a lo ancho del sistema. Sin embargo, tal opción, a pesar de proporcionar información situacional valiosa se demostraría insuficiente, además de costosa por la extensión y complejidad de la Red, si no se completara con algún tipo de artefacto predictivo. Dicho lo cual, no se descarta ampliar en el futuro las capacidades de monitoreo para aprovechar la evolución de la tecnología especializada para recuento y transmisión de datos.

De otra manera, podría confiarse en la realización de encuestas origen – destino de forma periódica, como ya se venía trabajando. Sin embargo, las encuestas OD solo se podían realizar cada 4 o 5 años por su elevado coste y las simulaciones que se basaban en sus resultados pronto perdían fiabilidad a pesar del esfuerzo en mantenerlas actualizadas mediante el uso de técnicas de corrección. Y es que la encuesta OD no deja de ser una foto fija del momento, lo que no permite afrontar el tratamiento, no ya de incidencias, sino tampoco de actualizaciones de la red, como se puso de manifiesto al introducir las últimas ampliaciones del Metro.

El análisis de las asignaciones de esas matrices permitía estimar únicamente los movimientos en el total del día y en hora punta de la mañana de un día genérico, sin poder acceder al detalle de lo que sucedía durante el resto del día, ni en los días especiales como festivos o fines de semana. Otra limitación de esta manera de proceder es que las simulaciones están basadas en las encuestas realizadas un determinado día.

Todo ello llevó a plantear qué cambios había que hacer para conocer mejor el comportamiento de los viajeros y así ayudar a planificar la oferta de trenes de manera óptima.

Así es cómo Metro decidió optar por buscar una combinación de datos de registros discretos (vinculados a los accesos al sistema), datos de patrones de movilidad espaciales y dinámicos (basados en encuestas y uso de títulos de transporte) y el uso de técnicas de modelización para completar una fotografía permanentemente actualizada del uso de cada elemento del sistema de Metro.

El resultado es una herramienta de simulación con actualización continua de la representación teórica de los viajes que se realizan cada día con origen y destino en estaciones de Metro y del volumen de pasajeros a bordo de los trenes de las distintas líneas a lo largo de la jornada.

Este modelo diario constituye el soporte esencial para diversos procesos de adecuación de la oferta a la demanda, optimización del servicio programado y cálculo de indicadores corporativos, así como para dar respuesta a múltiples consultas que plantean frecuentemente tanto los departamentos de Metro como algunos organismos externos.

La imprevista llegada de la Covid-19 planteó un reto no previsto inicialmente: cómo utilizar el sistema desarrollado para la producción de estudios de demanda de soporte a la adecuación a corto plazo de las condiciones de servicio de Metro a las restricciones impuestas por el Consorcio de Transportes de Madrid.

Entre las muchas actuaciones orientadas a asegurar el viaje en condiciones sanitarias adecuadas en lo referente a la ocupación de los trenes, la autoridad de transporte requirió a Metro garantizar que los trenes no superaran cierto umbral de número de viajeros por Metro cuadrado (densidad de viajeros) y que se limitara el número de asientos disponibles.

El cumplimiento de las restricciones de densidad ha supuesto, por una parte, ajustes en la oferta de servicios y, por otra, limitaciones al acceso de viajeros en estaciones. Este requisito plantea la cuestión de en qué estaciones aplicar la limitación, cuándo y en qué cantidad.

Dado que la saturación en un tren, entendida como superación del umbral de densidad, es originada por el acceso en estaciones “aguas arriba” del tramo saturado, se precisa de una aplicación que identifique con anticipación los tramos en los que, si no se actuara, registrarían saturación. A continuación, el procedimiento debe identificar las estaciones que más contribuyen a la carga de las secciones críticas y, como resultado final, ayude a calcular unas cuotas máximas de viajeros compatibles, para cada intervalo de tiempo, con el criterio límite de saturación.

Esta comunicación presenta el esquema general del sistema de modelización de Metro y expone en concreto la utilización de las prestaciones de *PTV Visum* que participan en el sistema de cálculo de cuotas para control dinámico de acceso.

2. PLANTEAMIENTO Y METODOLOGÍA

2.1. Enfoque global

En un primer momento se planteó la posibilidad de mejorar la precisión de las asignaciones de las matrices origen-destino proveniente de las encuestas mediante el uso de “series temporales”. Las “series temporales” en *Visum* distribuyen la demanda de la matriz en el tiempo, típicamente en intervalos horarios del día tipo.

Además, con objeto de precisar el ajuste al comportamiento real de la demanda, *Visum* permite aplicar series temporales diferentes a distintas categorías de pares origen-destino que presenten similitudes en su distribución temporal de la demanda.

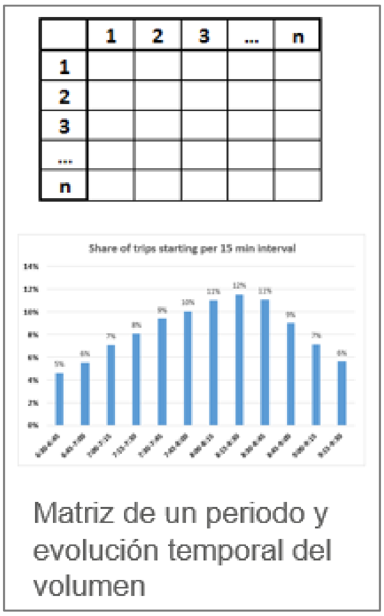


Fig. 1: Ilustración de la consideración de la dinámica de la demanda mediante aplicación de una serie de temporal de proporciones a una matriz OD

No obstante, este procedimiento pronto se reveló insuficiente porque no recogía adecuadamente la dinámica de la demanda a lo largo de la jornada, razón por la cual se optó por un procedimiento alternativo más detallado.

Bajo este nuevo enfoque, las estaciones pasan a modelizarse de forma independiente y los intervalos de tiempo a efectos de análisis de la demanda pasan a ser de 15 minutos aprovechando para ello la información de registros de entradas al sistema disponibles.

Fig. 2: Ilustración de consideración de la dinámica de la demanda mediante series de matrices OD por intervalos de tiempo

Desde una perspectiva metodológica, el proceso consta de tres etapas:

a. Explotación de los datos de las validaciones recurriendo a técnicas Big Data para:
   i. Inferir el destino del viaje
   ii. Estimar matrices de viajes origen-destino para intervalos de 15 minutos
   iii. Estimar unos intervalos de trenes teóricos según las frecuencias de paso previstas

En esta etapa se infieren las matrices diarias que alimentan la siguiente etapa del proceso. Para ello Metro de Madrid ha realizado un desarrollo software propio cuya descripción excede el alcance de esta comunicación.

b. Explotación de un modelo de transportes utilizando *Visum* para determinar los tramos de mayor intensidad

En esta etapa se aprovecha toda la potencia de la herramienta para simular el comportamiento de los usuarios tanto espacialmente, en sus decisiones de itinerarios a tomar, como temporalmente.

c. Establecimiento de un sistema de cuotas

Se trata de un proceso iterativo de optimización cuyo resultado son las cuotas de paso, entendidas como límites al acceso de viajeros, a aplicar en las estaciones de origen para reducir el riesgo de congestión en tramos críticos de la red.

Estas cuotas son grabadas en ficheros que son leídos por los sistemas de gestión de las instalaciones de peaje (pasos de entrada en estaciones).
Esta etapa ha precisado de desarrollos ad-hoc en comunicación con utilidades nativas del software de modelización.

Los bloques funcionales a) y b) corresponden al proceso básico que construye la actualización diaria del modelo, mientras que el bloque c) constituye el caso de uso específico de elaboración del listado de cuotas.

Es preciso mencionar que el sistema completo denominado *"Control temporal de accesos de Metro de Madrid"* se compone de varios subsistemas: el software de telemando de los elementos físicos que abren/cierran el paso según las órdenes recibidas, los recursos de comunicación y gestión de datos para analizar el comportamiento real, los procedimientos y el despliegue de personal que vigila in situ el correcto desarrollo de los dispositivos y cuida la atención a los viajeros, la información local en las estaciones mediante megafonía y teleindicadores y, finalmente, la presentación del estado de las barreras de peaje en la app oficial que los usuarios pueden consultar on line desde sus dispositivos móviles.

La descripción del sistema completo excede el ámbito de este artículo, por lo que, en este contexto, debe entenderse que por “control de acceso” se hace referencia exclusivamente al software de elaboración de los listados de cuotas, como pieza de cálculo que alimenta al resto de componentes.

2.2 Detalles de configuración

Respecto a la herramienta de modelización, se ha empleado el “gestor de escenarios” disponible en la versión más reciente de *Visum*. Esta funcionalidad permite estructurar los distintos escenarios de análisis sobre un mismo modelo base común sobre el que se aplican modificaciones relativas a la oferta de servicios o a la demanda que los solicita.

Con periodicidad anual se genera un nuevo proyecto del gestor de escenarios. En él se integran los distintos escenarios, cada uno de los cuales hace referencia a un periodo diario.

Estos escenarios pueden hacer referencia bien a días tipo (por ejemplo, un día tipo laborable del mes de octubre) o a días concretos del calendario (por ejemplo, el 28 de octubre).

Asimismo, los escenarios pueden ser *a posteriori*, esto es, con datos de demanda de días pasados y por tanto reales, o *a priori*, esto es, con datos de demanda previstos para días futuros.

Cada escenario consta de tres entradas básicas: la red de Metro, la oferta de servicios (oferta de trenes en terminología Metro), y las matrices Origen-Destino de los viajes.

La red de Metro es fija, y por tanto común a todos los escenarios, aunque sufre cambios circunstanciales en determinados periodos, como cortes de línea o estaciones cerradas al público que se manejan con estudios específicos para simulación de cambios en la infraestructura.

La oferta de trenes se introduce como una relación de expediciones teóricas, que es fija para cada periodo del año y para cada tipo de día, por ejemplo, las expediciones teóricas de un día laborable de invierno.

Las matrices Origen-Destino son únicas para cada día.

La Figura 3 representa el esquema conceptual de la metodología utilizada:

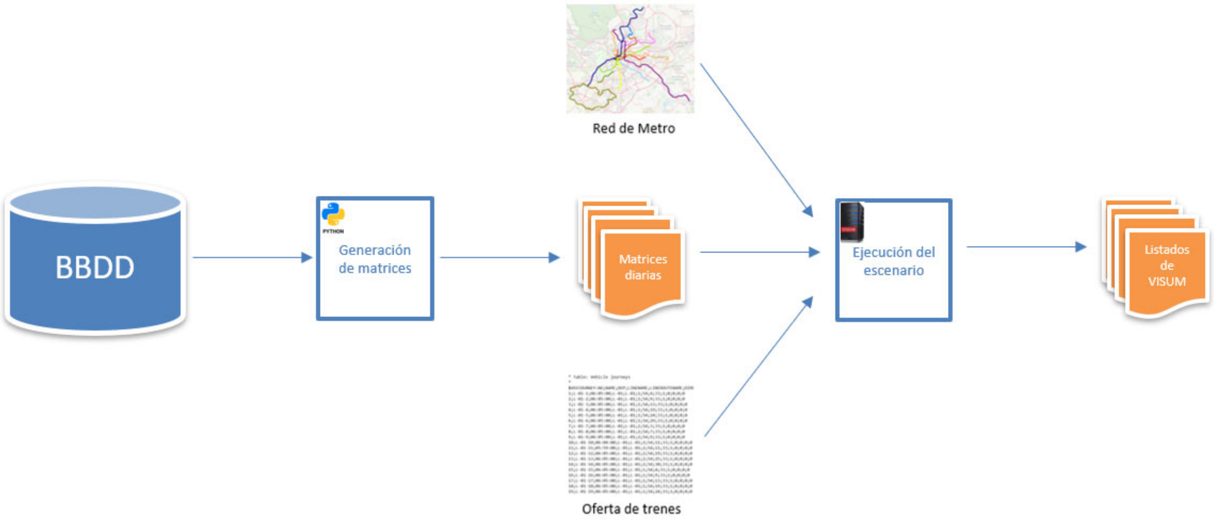


Fig. 3. Esquema conceptual del proceso metodológico

2.3 Evolución tecnológica y acceso a datos: el recurso a Big Data para la modelización y análisis de la demanda

Como ya se ha indicado, el punto de partida convencional para la modelización son los datos que proporcionan las encuestas y aforos, de gran valor estadístico, pero con los inconvenientes de estar referidos a un determinado momento y de no cambiar hasta que se realiza un nuevo trabajo de campo, con un importante coste asociado.

Desde 2019, Metro viene utilizando los registros de paso con tarjetas "inteligentes" de transporte, para construir matrices Origen-Destino diarias.

La base de datos de los pasos con tarjetas sin contacto informa de forma individualizada pero anónima en qué estación y a qué hora se producen las entradas por las barreras de peaje. Mediante inferencia de los destinos de los viajes por la actividad subsiguiente de las tarjetas, y técnicas de corrección de matrices, se obtiene un conjunto de matrices Origen-Destino para los intervalos de tiempo relevantes.

En este caso se han elegido periodos de 15 minutos, por lo que, para cada jornada completa, se construyen 96 matrices O-D.

Estos datos aportan la ventaja de estar siempre actualizados sin necesidad de realizar ninguna encuesta ni aforo. De esta forma, la utilidad de las encuestas y aforos pasa a ser la de su uso para comprobar si el modelo generado está bien calibrado o es necesario realizar algún ajuste.

El esquema lógico conceptual de esta fase del proceso desarrollado es el que ilustra la Figura 4.

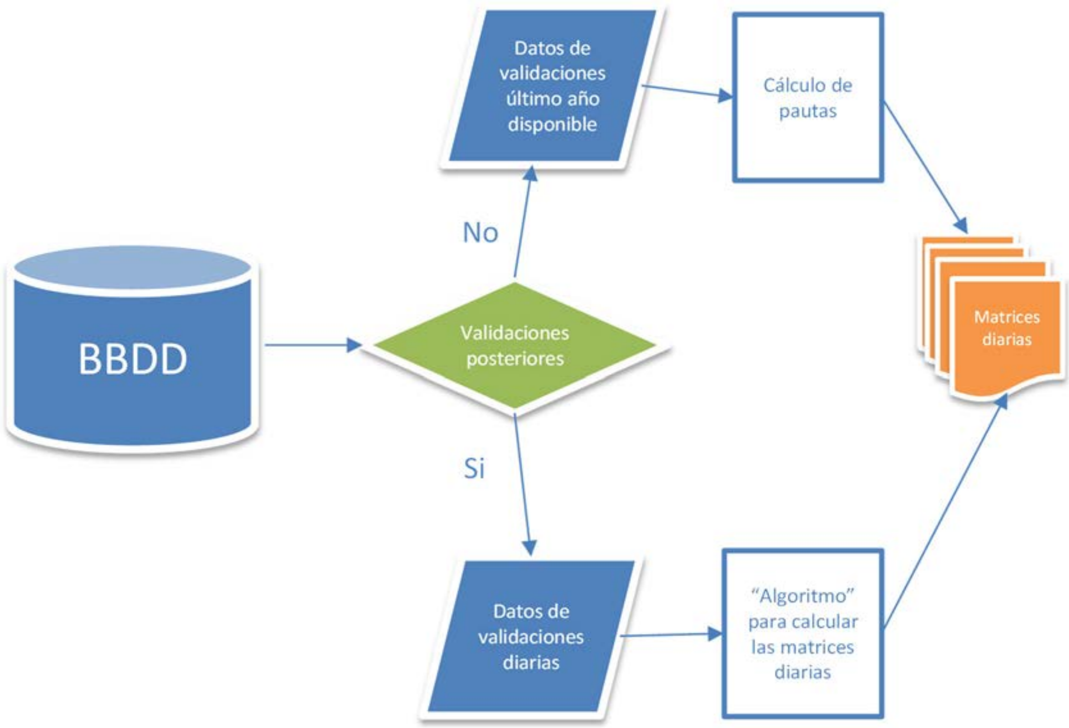


Fig. 4. Esquema lógico de la generación de matrices OD a partir de las validaciones

Dado que la mayor parte de la red de Metro tiene salida abierta, para completar la información de origen de los viajes con los destinos se emplean diversas técnicas de asignación en las que se combinan factores como el tiempo de viaje, tipo de estación, frecuencia de viaje, y pautas repetitivas, a partir de las cuales se aplican como reglas de decisión para la asignación de punto de salida más probable.

También hay que señalar que los tipos de títulos más usados, los abonos de transporte y los billetes de 10 viajes, tienen validez en otros operadores de la ciudad, lo que añade la necesidad de aplicar reglas especiales para reconstruir los trayectos multimodales y derivar la parte que corresponde exclusivamente a etapas en Metro.

El algoritmo desarrollado genera asignaciones de destino para los orígenes de viaje y califica la calidad de dicha asignación en función de las condiciones y certezas que se han podido aplicar en cada caso según los patrones reconocidos.

2.4 Validación de resultados y construcción del modelo diario de movilidad

A pesar de las limitaciones mencionadas, el contraste de resultados realizado mediante observación directa en campo ofrece un nivel de confianza muy elevado.

La calidad de las matrices Origen – Destino diarias así generadas se ha visto avalada también por la utilización en otros sistemas de información que se deriva de las mismas, como es por ejemplo, la estimación estadística de la carga de trenes a su paso por cada estación, por franjas temporales discretas.

Con el grado de ajuste actual, se estima que el 86% de las asignaciones de destino tienen una probabilidad de acierto “ALTA” y que de ellas, la probabilidad es “MUY ALTA” en el 62% de los casos. La asignación de destinos se ajusta mejor en días laborables que en fines de semana porque los viajes obligados, por trabajo o estudios, presentan pautas más repetitivas.

Estos resultados se consideran suficientemente fiables como para permitir el paso siguiente: realizar la modelización diaria de la movilidad por la red a lo largo de todo el horario de servicio y para todos los tipos de día.

Para ello, se cargan en *Visum*:

- Las 96 matrices del conjunto de matrices Origen-Destino por jornada que genera la aplicación, cada una de las cuales corresponde a los datos de entrada a la red cada 15 minutos.

- El fichero con información de la red. Este fichero incluye la descripción de los distintos tipos de día que se contemplan, algunas características de las líneas, los distintos perfiles de tiempo de recorrido, o las expediciones teóricas en función del periodo (invierno, verano, …), visualizado gráficamente en la Figura 5.

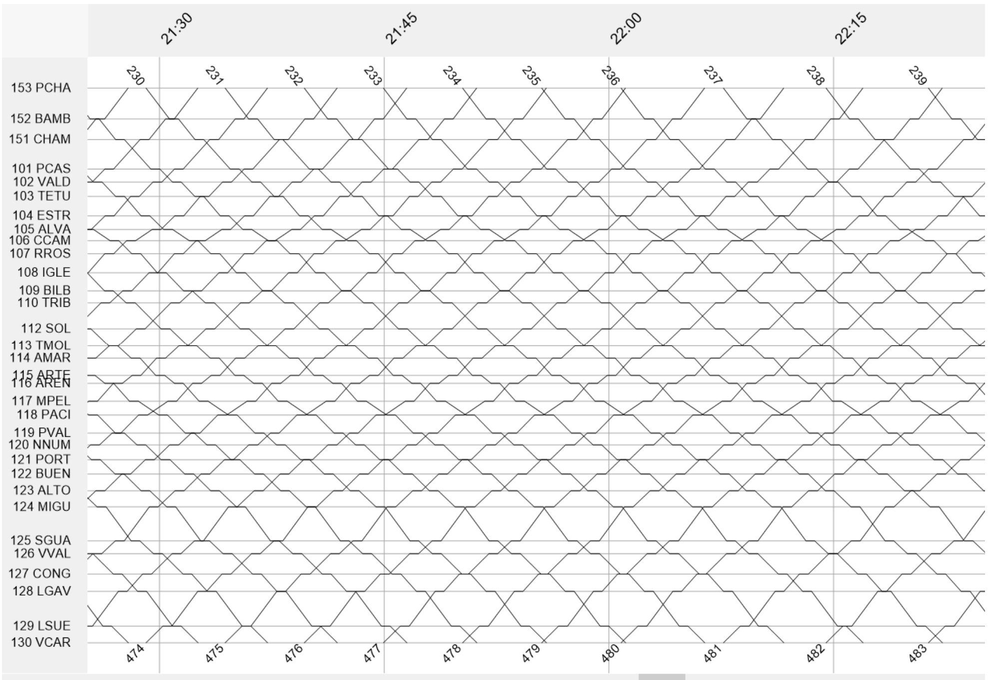


Fig. 5. Gráfica de trenes teóricos

La asignación del escenario en *Visum* proporciona la identificación de todos los viajes realizados, asequible en forma de listados (Figura 6), que muestran la secuencia de unidades de viaje elementales (*vehicle journey item* en vocabulario de *Visum*), y da información de la densidad (en pasajeros/m^2) que hay al paso de cada tren por cada estación:

Number: 125	TimeP	VehJo	Index	TimeProfileIten	TimeProfileItem\LineRouteItem\Stop	VehJourneyNo	Dep	ExtArriva	ExtDepa	PassBoard(AP	PassOrigin(AP	PassAlight(AP	PassDestinati	Vol(AP)	Densidad	VehJo	VehJourney	VehJourney
1	L-10A	Via 2	9	21011012	Príncipe Pío	17019	07:48:35	07:47:47	07:48:35	290,9	130,9	53,6	18,8	686,0	2,78	0	180	1274
2	L-12-M	Via 1	25	11211206	Móstoles Central	19942	14:23:33	14:22:57	14:23:33	89,3	89,3	70,5	70,5	321,2	2,73	0	78	631
3	L-10A	Via 2	11	21011010	Tribunal	17010	07:22:58	07:22:10	07:22:58	35,6	10,2	26,5	7,4	670,2	2,69	0	180	1274
4	L-10A	Via 2	12	21011009	Alonso Martínez	17010	07:24:39	07:23:52	07:24:39	63,6	7,7	64,0	21,2	669,8	2,69	0	180	1274
5	L-06	Via 1	11	10610611	Conde de Casal	8876	07:17:29	07:16:41	07:17:29	89,8	89,8	46,6	46,6	658,0	2,69	0	158	1272
6	L-10A	Via 2	9	21011012	Príncipe Pío	17010	07:19:09	07:18:21	07:19:09	299,5	119,7	96,0	22,6	663,0	2,65	0	180	1274
7	L-10A	Via 2	10	21011011	Plaza de España	17010	07:21:06	07:20:19	07:21:06	51,0	15,8	52,9	20,1	661,1	2,64	0	180	1274
8	L-01	Via 2	12	20110119	Puente de Vallecas	1360	06:54:21	06:53:46	06:54:21	73,1	73,1	5,8	5,8	434,7	2,64	0	144	804
9	L-12-M	Via 1	26	11211207	Pradillo	19942	14:25:08	14:24:33	14:25:08	45,4	45,4	58,2	58,2	308,4	2,59	0	78	631
10	L-12-M	Via 1	24	11211205	Universidad Rey Juan Carlos	19942	14:21:27	14:20:52	14:21:27	179,0	179,0	18,5	18,5	302,4	2,52	0	78	631
11	L-06	Via 1	12	10610612	Sainz de Baranda	8896	08:21:28	08:20:41	08:21:28	62,0	11,9	33,2	26,7	624,7	2,51	0	158	1272
12	L-10A	Via 2	13	21011008	Gregorio Marañón	17010	07:26:47	07:26:00	07:26:47	122,1	6,4	157,4	28,2	634,5	2,50	0	180	1274
13	L-10A	Via 2	11	21011010	Tribunal	17019	07:52:24	07:51:36	07:52:24	54,6	11,7	51,7	17,9	632,3	2,49	0	180	1274
14	L-01	Via 2	12	20110119	Puente de Vallecas	1359	06:46:53	06:46:18	06:46:53	78,5	78,5	8,4	8,4	416,8	2,48	0	144	804
15	L-06	Via 1	11	10610611	Conde de Casal	8882	07:37:16	07:36:28	07:37:16	71,8	71,8	44,0	44,0	618,8	2,48	0	158	1272
16	L-10A	Via 2	10	21011011	Plaza de España	17019	07:50:32	07:49:45	07:50:32	48,3	18,2	104,9	36,7	629,4	2,47	0	180	1274
17	L-06	Via 1	10	10610610	Pacífico	8876	07:15:39	07:14:52	07:15:39	124,8	28,6	56,5	18,3	614,8	2,46	0	158	1272
18	L-10A	Via 2	12	21011009	Alonso Martínez	17005	07:02:21	07:01:34	07:02:21	86,8	5,0	40,8	14,3	624,4	2,44	0	180	1274
19	L-06	Via 1	13	10610613	O'Donnell	8896	08:23:19	08:22:31	08:23:19	24,8	24,8	40,6	40,6	608,9	2,42	0	158	1272
20	L-03	Via 1	12	10310305	Lavapiés	3981	07:42:23	07:41:47	07:42:23	24,6	24,6	3,2	3,2	403,8	2,37	0	138	810

Fig. 6. Información de densidades (en viajeros/m2) al paso de cada tren por cada estación

O en forma gráfica, en la Figura 7 se muestra, sobre la malla de expediciones, cuán cargadas han ido éstas para un determinado día.

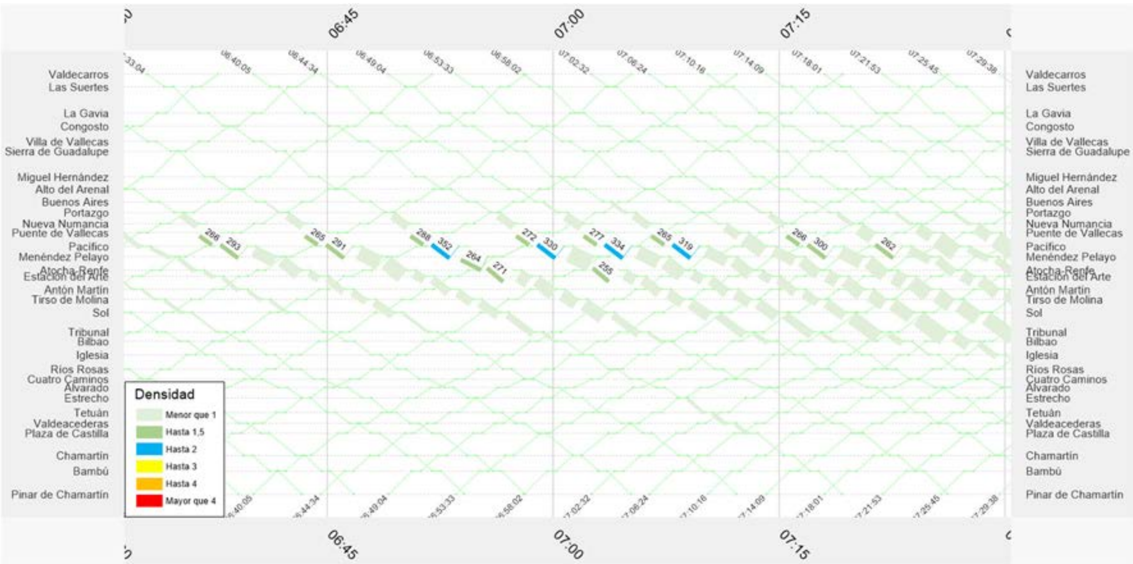


Fig. 7. Carga de trenes teóricos para una demanda dada en un periodo dado

La información detallada en cada punto de la red, en concreto, los datos de subidos y bajados en cada parada, así como el volumen de viajeros en cada inter-estación son datos clave.

Estos datos se calculan tanto para cada día concreto, como para cada patrón de día (laborables, viernes, sábados, y festivos) y periodo (un mes concreto o un periodo especial) que interese estudiar.

Los datos se obtienen desagregados a nivel de expedición y parada y, por tanto, se pueden tratar al nivel que interese: jornada completa, periodos significativos del día (hora punta de mañana, hora punta de mediodía, hora punta de tarde y periodos valle) o a nivel de hora o de media hora.

El contraste continuo con fuentes de información cualitativa permite mantener un adecuado nivel de confianza en la parametrización de los procesos automáticos. Como ejemplo de la necesaria calibración, se realizaron unos aforos en ciertas estaciones que llevaron a la conclusión de que había que realizar ciertos ajustes en los tiempos de trasbordo entre andenes en la estación de Nuevos Ministerios. O en las estaciones de Moncloa y Argüelles, que constituyen una singularidad por ser dos estaciones consecutivas en las que se puede realizar transbordo entre las líneas 3 y 6 de Metro. La medición real del tiempo que se tarda en transbordar en una y en otra, proporciona unos resultados que modificaron los datos asociados a ambas estaciones para que el porcentaje de transbordos en una y otra estación se ajustase a la realidad.

El modelo así construido está sirviendo actualmente de apoyo a múltiples decisiones operativas, permitiendo, por ejemplo:

- Anticipar el efecto de cortes planificados en líneas, tramos o estaciones. La redistribución de la demanda reflejada en el modelo en tales casos permite tomar las decisiones oportunas para canalizarla convenientemente en la realidad. Asimismo, la consideración temporal de la demanda permite apoyar decisiones relativas a la programación de estas afecciones al servicio.
- Analizar el efecto sistémico en la red de cambios en la demanda en determinadas estaciones debida a alteraciones puntuales tales como la celebración de eventos públicos en su proximidad o cambios en la oferta de transporte en superficie.

Con independencia de estas aplicaciones particulares del modelo, las asignaciones de demanda diaria, agregadas por periodos estacionales de demanda estable y días tipo, se han convertido en pieza fundamental de la planificación operativa de Metro en lo que se refiere a la adecuación de la oferta de servicios a la demanda en todo momento.

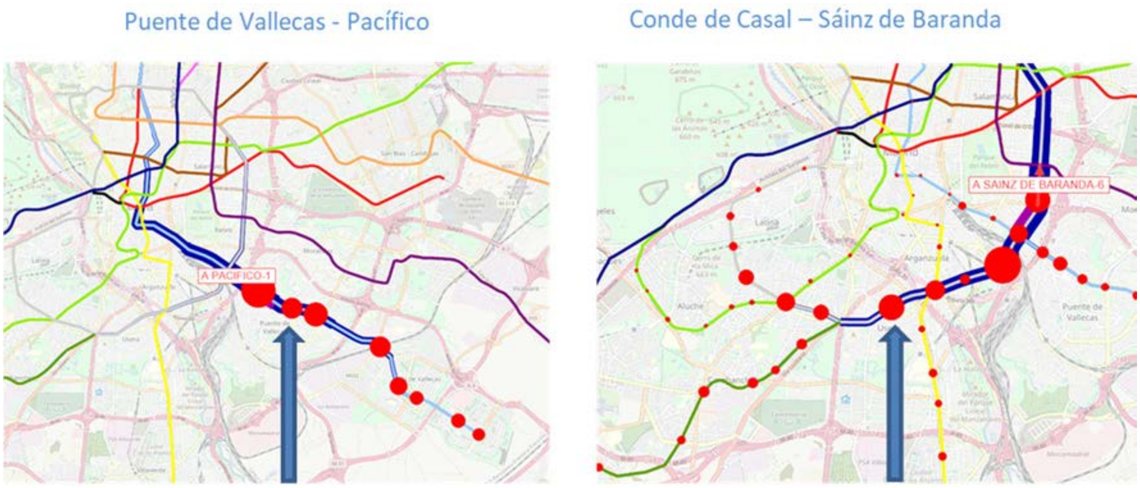
Desde que se dispone de matrices Origen-Destino basadas en los registros de acceso con tarjetas de transporte el modelo diario se está utilizando para todos los propósitos en los que hasta el momento se contaba con modelos estáticos ajustados periódicamente, y se han abierto nuevas posibilidades de explotación, inabordables antes de disponer de una estimación con gran nivel de detalle y de un soporte tecnológico adecuado.

3. UN CASO DE USO ASOCIADO A COVID-19: CÁLCULO DE CUOTAS DE ACCESO PARA PREVENIR LA SATURACIÓN DE LOS TRENES

Una situación de congestión, valorada como tal por superación de la densidad límite establecida, en un tren en una determinada inter-estación, viene provocada por la entrada de viajeros no sólo por la estación en que se inicia, sino por las entradas y trasbordos acumulados desde otras estaciones anteriores en la misma expedición. Por tanto, uno los objetivos de la aplicación desarrollada es determinar en qué estaciones hay que limitar el acceso de viajeros y en qué cantidad, para que no se congestione la red en ningún punto.

De esta manera, es necesario identificar en primer lugar en qué puntos de la red se presenta riesgo de exceso de carga a bordo y buscar a continuación por dónde han entrado los viajeros que lo provocan. Con esto, es posible calcular una cuota teórica de entrada en dichas estaciones para un cierto periodo de tiempo que reduciría el riesgo de que llegara a producirse.

En la implementación de este procedimiento, *Visum* juega un doble papel. Por un lado, ofrece un listado detallado de caminos denominado *PuT Path Legs* (en terminología *Visum)* que permite trazar el origen de cada viaje que pasa por un determinado punto de la red en un determinado momento, como el que ilustra la Figura 8 para dos casos distintos.



origzoneno	estacion	15min	Viajes
120	Nueva Numancia	6:00:00	57
120	Nueva Numancia	6:15:00	122
120	Nueva Numancia	6:30:00	196
120	Nueva Numancia	6:45:00	177
120	Nueva Numancia	7:00:00	65
120	Nueva Numancia	7:15:00	74

origzoneno	estacion	15min	Viajes
606	Usera	6:00:00	34
606	Usera	6:15:00	61
606	Usera	6:30:00	2
606	Usera	6:45:00	19

Fig. 8. Utilización de Visum para el análisis de los orígenes de secciones críticas de la red

Por otro lado, una vez se ha establecido la cuota de cada estación y se han generado matrices corregidas, es necesario comprobar que el nuevo conjunto de matrices no genera congestión en ningún otro punto de la red.

La Figura 9 ilustra la lógica de este procedimiento iterativo, para el que es preciso establecer condiciones de convergencia compatibles con la realidad del tránsito por las estaciones. Este procedimiento automatizado precisa de la actuación del personal de Metro que, basado en su experiencia, valida la idoneidad de la solución propuesta, haciendo balance del perjuicio ocasionado a viajeros a los que se deniega el acceso con el beneficio esperado en los sectores en riesgo de congestión.

Esta parte de la lógica está implementada mediante un software complementario a los procesos estándar de *Visum*.

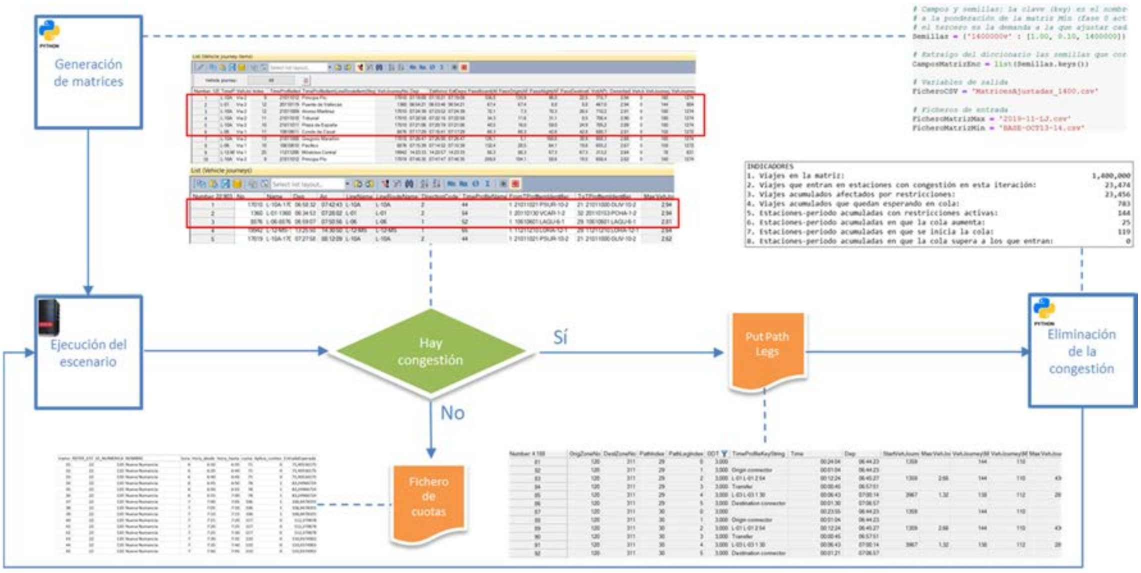


Fig. 9. Establecimiento de cuotas por estación y periodo de 5 minutos

Es preciso insistir en que los productos de este caso de uso tienen una repercusión directa e inmediata en la percepción de los viajeros, que pueden verse detenidos unos momentos en las barreras de paso sin conocer el motivo, situación cuando menos incómoda para ellos y difícil de manejar para el personal de las estaciones. Por este motivo, el procedimiento implantado trata con la misma importancia la exactitud de los cálculos teóricos como la oportunidad de aplicarlos en la práctica.

4. IMPLEMENTACIÓN Y RESULTADOS PRELIMINARES

El producto de la ejecución del proceso descrito en el apartado anterior es un listado con la cuota máxima de viajeros por estación y periodo de 5 minutos, como el que ilustra la Figura 10.

tramo	ID_NUMERICA	NOMBRE	hora	Hora_desde	Hora_hasta	cuota	Aplica_conteo	EntradaEsperada
31	120	Nueva Numancia	6	6:30	6:35	70	0	70
32	120	Nueva Numancia	6	6:35	6:40	70	0	70
33	120	Nueva Numancia	6	6:40	6:45	70	0	70
34	120	Nueva Numancia	6	6:45	6:50	78	1	83
35	120	Nueva Numancia	6	6:50	6:55	78	1	83
36	120	Nueva Numancia	6	6:55	7:00	78	1	83
37	120	Nueva Numancia	7	7:00	7:05	95	1	96
38	120	Nueva Numancia	7	7:05	7:10	95	1	96
39	120	Nueva Numancia	7	7:10	7:15	95	1	96
40	120	Nueva Numancia	7	7:15	7:20	118	0	113
41	120	Nueva Numancia	7	7:20	7:25	118	0	113
42	120	Nueva Numancia	7	7:25	7:30	118	0	113

Para la estación 120 (Nueva Numancia) y los periodos 34 (6:45 – 6:50), 35 (6:50 – 6:55) y 36 (6:55 – 7:00):

- **cuota = 78 -> La cuota máxima de viajeros es 78 (234 en los 15 minutos)**
- **Aplica_conteo = 1 -> Es necesario establecer dispositivo para limitar el acceso**
- **EntradaEsperada = 83 -> Se estima que 83 (249 en los 15 minutos) viajeros quieren acceder**
- **83 – 78 = 5 -> Se quedan 5 viajeros esperando en cada periodo (15 en los 15 minutos)**

Fig. 10. Ejemplo del establecimiento de cuotas.

Este listado con las cuotas se utiliza en los sistemas de control de los accesos que programan los torniquetes de entrada en las estaciones, de forma que para cada lapso se permita o no la entrada de viajeros en función de si el recuento de entradas en tiempo real cumple los cupos parametrizados mediante dicho listado.

Para asegurar el buen funcionamiento del sistema completo de "control de aforos", el personal de la estación y el del puesto de telemando se encarga de comprobar continuamente todos los componentes y proporciona el retorno tanto a los mantenedores de los equipos físicos de peaje y de información a viajeros, como a los responsables del establecimiento de cuotas.

5. CONCLUSIONES

El proceso de estimación de la ocupación de los trenes en Metro de Madrid ha presentado hasta el momento grandes dificultades por la ausencia de medios físicos de conteo a bordo.

Actualmente, la Compañía estudia diferentes prototipos de diversas tecnologías. No obstante, la red de Metro de Madrid es extensa, compleja en sus infraestructuras y equipamientos y con un gran parque móvil. Por tanto, el desarrollo e implantación de los citados prototipos se realizará cuando lo aconsejen las condiciones de retorno de la gran inversión que supone su instalación y, sobre todo, su despliegue completo.

Con los medios de simulación disponibles para los estudios de Movilidad y Planificación de Operación, se ha construido un sistema de estimación de densidades de viajeros basado en los registros de entradas al sistema con resultados muy satisfactorios.

El modelo de asignación de demanda elaborado sobre la plataforma *Visum* de PTV Group constituye una de las piezas clave del motor de cálculo del sistema. Sus potentes procedimientos de asignación y análisis proporcionan las herramientas básicas para resolver el problema de relacionar numéricamente el origen de los viajes con la carga a bordo de las expediciones teóricas de los trenes para cada unidad elemental de la red por localización y unidad de tiempo.

Son muchas las utilidades prácticas a las que Metro aplica el modelo diario de movilidad.

Es este artículo se ha presentado una de ellas, el cálculo de cuotas para control temporal de acceso que permite reducir el riesgo de congestión en las secciones críticas de la red. Esta práctica, siempre importante, pero particularmente sensible en las actuales condiciones sanitarias en las que la distancia interpersonal en el transporte público no es ya un asunto de confort sino una necesidad social.

La experiencia expuesta muestra como la comunicación entre desarrolladores de software especializado y operadores de transporte público constituye un campo de colaboración fructífero. Con la ayuda de empresas de desarrollo que aportan profesionales de alta categoría para materializar los objetivos, y con la acertada visión global desde la academia y organismos transversales, se pueden obtener productos de gran beneficio a coste asequible gracias a la inteligencia de la modelización teórica avanzada.

Esperamos seguir avanzando juntos por este camino.

AGRADECIMIENTOS

Los autores quieren reconocer la aportación al sistema de monitorización y gestión de la demanda de Metro descrito en este artículo a:

- Resto de áreas de la compañía de Metro de Madrid que intervienen en la operación del sistema: Área de Comunicación y Tecnologías de Información, Área de Ingeniería de Instalaciones y al Área de Medios.
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- Servicios profesionales y de soporte técnico de PTV Group

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DEL DATO COLABORATIVO A MÚLTIPLES RUTAS ENTRE PARES ORIGEN-DESTINO: HERRAMIENTAS PARA OBTENER RUTAS MEDIANTE LA LIMPIEZA, FILTRADO, TRATAMIENTO Y ENRIQUECIMIENTO DE REDES DE OPEN STREET MAPS (OSM).

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RESUMEN

Disponer de datos correctos, adecuados y actualizados de las redes de transporte es una condición necesaria tanto para la correcta modelización del transporte, como también para la comercialización de diferentes productos que requieran el uso de dichas redes. Aunque actualmente existen multitud de servidores, tanto abiertos como de acceso con licencia, conseguir el dato que se necesita puede convertirse en una tarea de bastante dificultad.

Una alternativa, disponible a escala mundial y con gran detalle también en países en vías de desarrollo, es el mapa colaborativo online Open Street Maps (OSM). Pese a que OSM, por su naturaleza de proyecto colaborativo y abierto a todo aquel que quiera contribuir, suele presentar redes topológicamente incorrectas o falta de algunos atributos, en él se pueden encontrar soluciones de manera automática a gran parte de estos problemas con herramientas basadas en software libre.

Dentro del proyecto HIPROMO, actualmente en versión para uso interno, se ha desarrollado un conjunto de herramientas en Python para QGIS que permiten limpiar, filtrar, tratar, enriquecer con otras fuentes de datos y transformar a las especificaciones propuestas en la aplicación de la directiva INSPIRE las redes viarias de OSM. Las redes tratadas se transforman en grafos adaptados a cada tipo de transporte disponible para, posteriormente, poder obtener haces de rutas entre diferentes orígenes y destinos.

1. INTRODUCCIÓN

El proyecto HIPROMO surge de la necesidad de construir una herramienta inteligente de prognosis de movilidad. El objetivo principal del proyecto es predecir con exactitud las rutas que toman los usuarios en sus desplazamientos gracias a los datos que se recogen a través de las antenas de telefonía móvil.

En este documento se muestra la primera parte de HIPROMO basándose en la obtención de una red fiable con capacidad de obtener haces de rutas óptimas y veraces, mediante una adaptación del algoritmo “link penalty” propuesto por (Park D. y Rilett LR., 1997), con las que poder trabajar. Esta funcionalidad ofrece múltiples posibilidades de utilización; como el análisis de tráfico ante cortes de carreteras por mantenimiento, el impacto de la movilidad frente a la peatonalización de zonas urbanas, entre otras. En definitiva, la herramienta ofrece una solución rápida y eficaz para la obtención de datos correctos, adecuados y actualizados de las redes de transporte.

A lo largo del documento se describe cómo se obtienen los datos, cómo se tratan y transforman para la obtención de la red deseada y finalmente se muestran los resultados obtenidos.

2. METODOLOGÍA

2.1 Herramientas utilizadas

Para la construcción de la herramienta se ha utilizado el siguiente software libre:

- QGIS (3.12.3): lectura de datos, ejecución de los procesos y visualización de los resultados.
- Python (3.7): lenguaje de programación utilizado.
- PostgreSQL (11.5) y su extensión de PostGIS (3.0.3): almacenamiento de los datos

2.2 Elementos de la red

La red de HIPROMO está compuesta por arcos y nodos, cada uno de los arcos representa una carretera, calle, vía, etc. y los nodos representan el inicio y fin de cada arco. Se cumplen las siguientes propiedades:

- Todo arco tiene un nodo origen y un nodo destino
- Al menos uno de los dos nodos de cada arco será uno de los dos nodos de otro arco.

Este nodo compartido por dos o más arcos es en el que se podrá cambiar de arco.

- Los arcos se pueden cortar sin generar un nodo en el punto de cruce si no es posible cambiar de arco en ese punto, por ejemplo, arcos a distintos niveles (puentes y túneles). Cuando en alguno de los niveles existe una intersección real en la misma ubicación que en el caso general del punto, se establece un nodo ficticio entre arcos de diferente nivel.
- Los arcos tienen definidos sentidos de circulación y se permite realizar cualquier cambio de arcos en aquellos nodos en los que la combinación de sentidos de los arcos afectados lo permitan.

2.3 Procesos

Los procesos de HIPROMO se dividen en dos bloques, el primero construye la red y el segundo extrae los datos que se desean de la red y calcula las rutas entre cada par Origen-Destino (OD).

Dentro del primer bloque se encuentran los siguientes procesos:

- h11_OSM2postGIS: recoge los datos en bruto de OSM y los carga en la base de datos.
- h12_Network_ExternalInformation: alimenta a la herramienta con información externa que no viene incluida en los datos de OSM.
- h13_postGIS2Network: realiza una depuración y transformación de la red de OSM a un formato más amigable.
- h14_Network_Hierarchies: procesos para asegurar la conectividad de la red en todos los niveles de jerarquía de la red.
- h15_Turn_Restrictions: analiza e incluye las restricciones de giro a la red.
- h16_Network_ImpedanceModificators: (opcional) alimenta a la red con las zonas del suelo y establece unos factores de reducción a la velocidad según dichas zonas.

Los procesos que se ejecutan en el Segundo bloque son:

- h21_CreateGraphs: se realiza un filtrado de la red según las especificaciones del usuario y se genera una nueva red.
- h22_GetRoutes: calcula las rutas entre cada par OD dado.

Todo el control de la herramienta se realiza desde QGIS. Una vez se tiene definida la zona de estudio que se desea, se realiza la descarga de los datos de OSM para dicha zona y se puede comenzar la ejecución de la herramienta.

2.3.1 h11_OSM2postGIS

El primer proceso recoge los datos descargados y ejecuta el programa "Osm2pgsql" que carga los datos sin procesar de OSM a la base de datos de PostGIS.
Todo el funcionamiento de este programa viene explicado en la página web de (Hoffmann, 2020).

2.3.2 h12_Network_ExternalInformation

Una vez se tienen los datos en bruto cargados, se pasa al siguiente proceso, que es el encargado de alimentar la base de datos con toda la información externa que no viene incluida en los datos de OSM.

- Fichero de anexos con la parametrización de los procesos.
- Fichero de velocidades legales de la región. Este fichero es necesario ya que muchos de los arcos vienen sin velocidad asignada por OSM, por lo que es necesario asignarles una velocidad según el tipo de vía y tipo de vehículo.
- Factores de reducción (opcional): contiene las reducciones a la velocidad de las carreteras, según los usos del suelo, tipo de vía y la hora a la que se recorre esa vía.
- Coste de los peajes (opcional): Contiene el coste monetario necesario para el uso de las carreteras de peaje. Se utiliza para calcular las diferentes rutas alternativas teniendo en cuenta el coste económico que supondría el viaje.

2.3.3 h13_postGIS2Network

En este proceso se hace una depuración exhaustiva de los datos en bruto de OSM para tener una primera versión de la red. Se le pide una serie de datos al usuario: el nivel de red que desea (los arcos tienen una clasificación jerárquica de 7 niveles distintos de red) y el número de componentes conexas que debe tener la red. En un primer paso se recoge toda la información de los arcos para los niveles de vía seleccionados para obtener el conjunto de arcos que interesa. Una vez se tienen los arcos se realizan una serie de arreglos topológicos para mejorar la calidad de la red: (a) unir los arcos contiguos con mismos atributos y sin intersecciones; (b) solucionar errores de tolerancia; (c) analizar las intersecciones que existen entre los arcos viendo en cada caso si las intersecciones se realizan en el mismo nivel o por el contrario existe algún puente o túnel, en el caso de que se produzca al mismo nivel, el arco se segmenta y se divide en dos arcos generando un nuevo nodo en la intersección de ambos arcos; (d) asignar nuevos identificadores a cada arco y a cada nodo; (d) calcular la longitud de cada arco y el centroide.

Al final del proceso se mira el número de componentes conexas que tiene la red y dicho número debe coincidir con el número introducido por el usuario. Con este análisis eliminamos posibles errores que vienen de origen, por ejemplo, si estamos trabajando con una ciudad, solo debería haber una componente conexa, si existe algún grupo de arcos aislados se deberá a un error de origen por lo que sería eliminado o, por el contrario, si se está trabajando con un conjunto de islas habrá que introducir el número de componentes que serán igual al número de islas del estudio.

Toda la información es clasificada en 7 tablas (Fig. 1), donde la tabla de arcos es alimentada con la información del resto de las tablas.

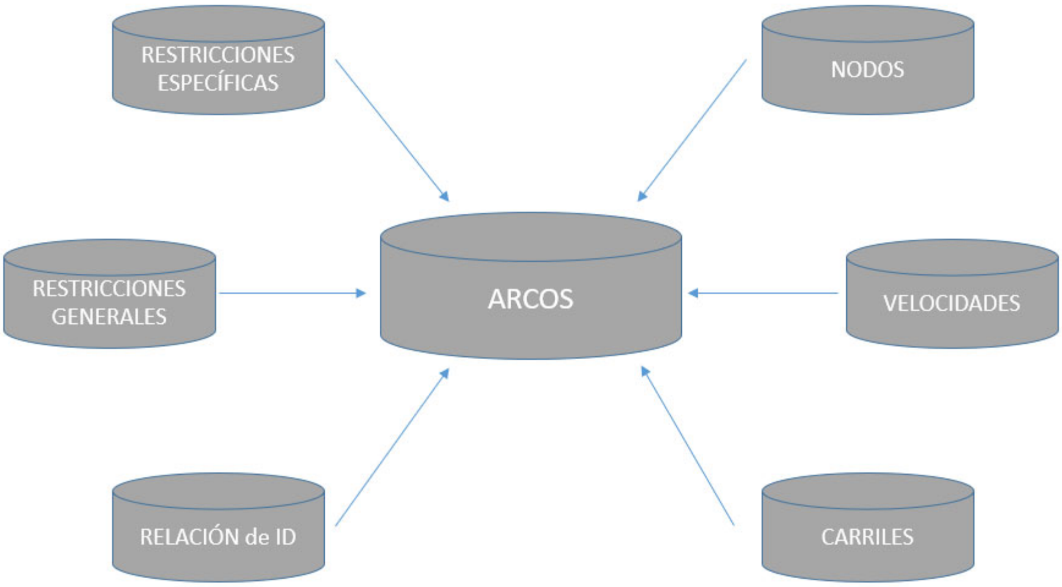

Fig 1- Relación de las tablas de HIPROMO. Fuente: los autores.

- Arcos: contiene la información de los arcos y sus características (tipo de vía, dirección del arco, nombre de la vía, etc.)
- Nodos: contiene la localización de los nodos, que indican el inicio y fin de cada uno de los arcos.
- Carriles: número de carriles que tiene cada arco.
- Velocidades: velocidad máxima y mínima en cada uno de los arcos por tipo de vehículo.
- Restricciones generales: indica que arcos tienen algún tipo de restricción general (peaje, carretera privada, carretera de uso estacional, etc.) y a qué vehículos afecta.
- Restricciones específicas: restricciones de peso, altura, longitud y ancho del vehículo que afectan a cada arco.
- Relación de id: guarda la trazabilidad entre los identificadores que han sido asignados en la herramienta de HIPROMO con los identificadores que vienen del dato origen en OSM.
-

Este conjunto de tablas es la red principal con la que se va a trabajar.

2.3.4 h14_Network_Hierarchies

Como se ha comentado anteriormente los arcos se clasifican en diferentes niveles de jerarquía según el tipo de vía:

Nivel de jerarquía	Tipo de vía
Red Principal	"motorway", "motorway_link", "trunk", "trunk_link"
1ª clase	"primary, "primary_link"
2ª clase	"secondary, "secondary_link"
3ª clase	"tertiary, "tertiary_link"
4ª clase	"residential, "road", "unclassified"
5ª clase	"living_street, "service"
6ª clase	"pedestrian, "track"

Tabla 1 -Niveles de jerarquía. Fuente: los autores.

En este proceso, se comprueba que la red es conexa en cada uno de los niveles de jerarquía, es decir, que si se selecciona como filtro de nivel de la red “Red principal” la red resultante será conexa. En caso de que algunos arcos queden sueltos y la red sea inconexa se utiliza los niveles inferiores, en este caso 1ª y 2ª clase, y se comprueba que arcos son necesarios para hacer conexa la red. Dichos arcos utilizados para hacer la red conexa se suben de categoría.

En el caso que se desee un nivel inferior de jerarquía el proceso comprobará que la red es conexa con los arcos del nivel seleccionado teniendo en cuenta los arcos de los niveles superiores.

2.3.5 h15_Turn_Restrictions

Anteriormente hemos visto que se tienen restricciones específicas y restricciones generales, pero ninguna de las dos contiene la información de las restricciones de giro.

Existen dos tipos de restricciones de giro:

- Restricciones de giro por circulación. Este tipo de restricciones se obtiene de los datos origen de OSM. Hace referencia a dos arcos que tienen un nodo en común, por lo que según la definición de la red se podría cambiar de arco, pero legalmente en ese arco está prohibido girar en esa dirección.
- A parte de las restricciones de giro que vienen de los datos origen, se ha incluido una restricción de giro dependiendo del ángulo de giro entre dos arcos, es decir, si dos arcos comparten un nodo y por definición se podría cambiar de arco, pero en cambio el ángulo que forman ambos arcos es menor a “x” grados donde ”x” lo define el usuario de la herramienta, se le aplica una restricción de giro.

Toda la información de restricciones de giro se almacena en una nueva tabla que alimenta a la tabla de arcos.

2.3.6 h16_Network_ImpedanceModificators

Este proceso es opcional. Se le asigna a cada arco unos factores para la reducción de velocidad utilizando el fichero cargado en el proceso donde se alimenta la herramienta de información externa.

Los factores de reducción se asignan según las características del arco. Se tiene en cuenta el tipo de vía, el uso del suelo en el que se encuentra el arco y la hora a la que se desea recorrer el arco, ya que recorrer un arco de una zona urbana en hora punta no se puede realizar a la velocidad máxima permitida de la vía. Para poder hacer una asignación de factores de reducción a los arcos es necesario disponer de una capa de usos del suelo de la zona de estudio con la que poder asignar a cada arco su uso del suelo para hacer una correcta asignación de las reducciones de velocidad a cada arco.

2.3.7 h21_CreateGraphs

Los procesos del primer bloque han definido una red principal, esta red principal alimenta todos los procesos del segundo bloque. Este primer proceso del segundo bloque genera redes más pequeñas según los filtros que elige el usuario (fig.2).

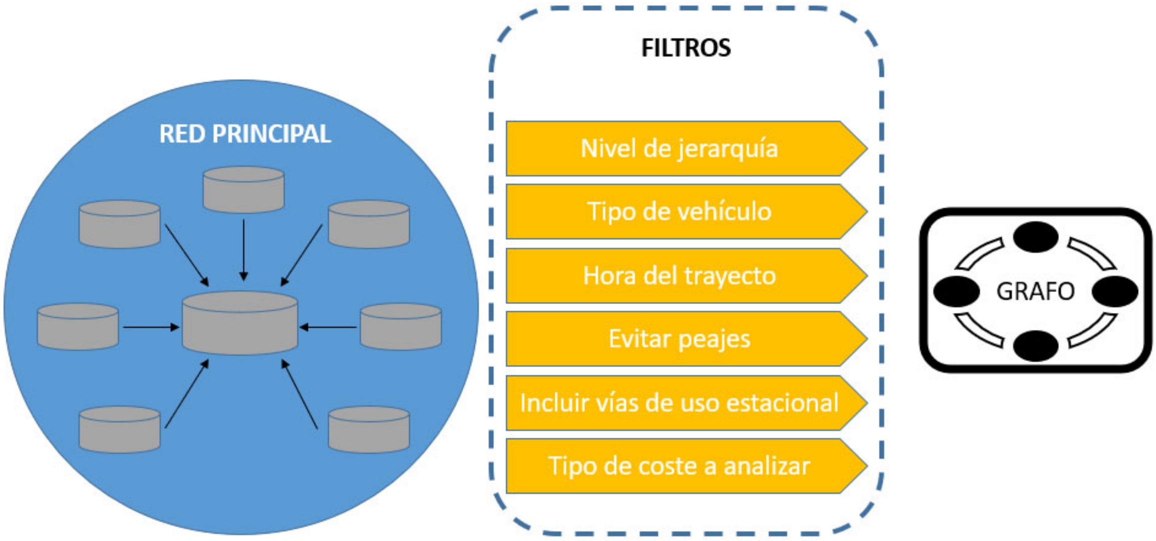

Fig 2- Filtros para la generación de grafos. Fuente: los autores.

Las opciones que tiene el usuario para definir los grafos son:

- Nivel de la red: Nivel de la jerarquía de la que se desea generar el grafo (escenario), se debe tener en cuenta que el nivel de la red del grafo que se desea generar no puede ser inferior al que se ha generado la red principal.

- Tipo de vehículo: existe una larga lista de vehículos (coche, bici, peatón, vehículo para transporte de mercancías, etc.), dependiendo del vehículo elegido los arcos que se podrían recorrer, así como el coste a la hora de recorrerlos varía.
- Incluir carreteras de peaje: Sí/No
- Incluir carreteras de uso estacional: Sí/No
- Coste que se desea analizar: el algoritmo utilizado para calcular las rutas para cada par OD minimiza el coste a la hora de recorrer los arcos entre dos puntos dados. Los costes que se pueden elegir son tres: (1) ruta más corta, teniendo en cuenta la distancia; (2) ruta más rápida, mirando el tiempo que se tarda; y, por último, (3) el coste generalizado que es el coste económico que supone ir del origen al destino.
  Este último tipo de coste, se ha calculado en función del estudio sobre el coste generalizado del transporte (Tool Alfa S.L., 2020) en el cuál para vehículos ligeros se tiene en cuenta el tiempo del trayecto con un coste generalizado de 20,97 €/h, y para vehículos pesados se tiene en cuenta la distancia con un coste generalizado de 0,289 €/km. Si alguna de las rutas utiliza carreteras de peaje, este coste económico también se incluye a la hora de calcular la ruta más económica. Los costes de distancia se miden en metros, el tiempo en minutos y el coste generalizado en euros.

El resultado que se obtiene al finalizar el proceso es un grafo en donde cada arco tiene asociado el coste que supone recorrer dicho arco. Este proceso se puede ejecutar tantas veces como se desee. Para cada ejecución se creará un grafo distinto y se almacenará en la base de datos.

2.3.8 h22_GetRoutes

El h22_GetRoutes es el proceso final de la herramienta. En este proceso se calculan las diferentes rutas entre cada par OD dado para el grafo seleccionado. Se utiliza el algoritmo "pgr_trsp" de pgrouting (pgRouting Contributors, 2021), el cuál devuelve la ruta más corta entre dos puntos dados teniendo en cuenta las restricciones de giro.

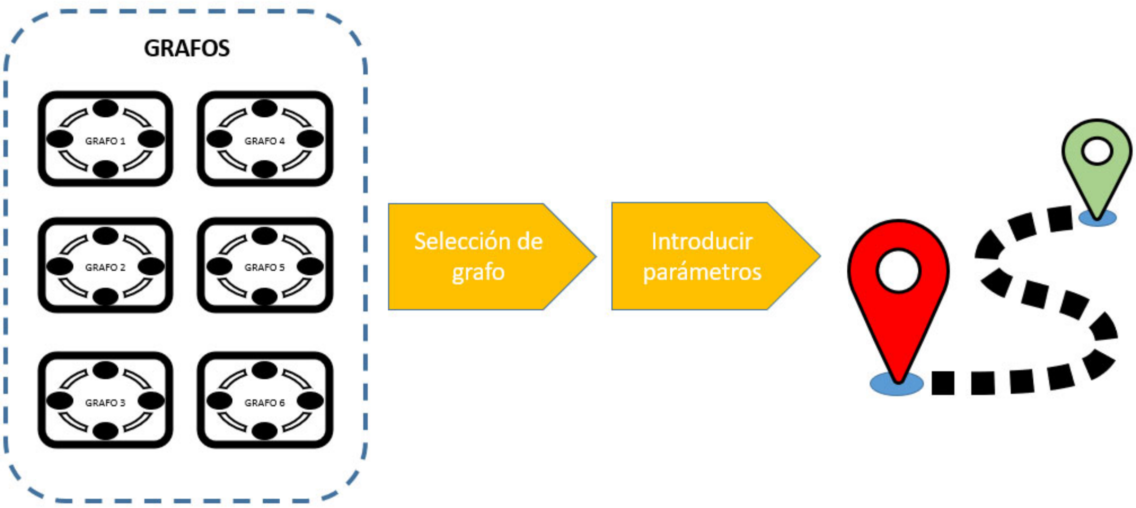

Fig 3- Filtros para la generación de grafos. Fuente: los autores.

En la ejecución del proceso influyen varios parámetros que afectan considerablemente el cálculo de las rutas óptimas.

Estos parámetros son introducidos por el usuario a la hora de ejecutarlo por lo que es necesario tener un conocimiento claro de cómo influye cada parámetro a la hora de generar las rutas. Los parámetros necesarios para el cálculo de las rutas son:

- Número de rutas máximo a calcular para cada par OD: número de rutas que vas a obtener como máximo en la salida del proceso. Primero se calcula la ruta óptima y luego se obtienen las rutas alternativas.
- Desviación máxima permitida: porcentaje, el cual, no pueden desviarse las rutas alternativas con respecto a la ruta óptima calculada.
- Máximo solape entre rutas: indica el porcentaje de arcos en común que puede tener las rutas calculadas.
- Incremento de impedancia en cada iteración: porcentaje que se incrementan los costes de los arcos que han sido utilizados, es decir, cuando se utiliza un arco, el coste de dicho arco aumenta, para que la siguiente ruta alternativa busque otras rutas diferentes.
- Zona cerna a origen y destino sin incremento de impedancia: tamaño del buffer en los puntos de origen y destino a los que no se va a aplicar el aumento de la impedancia.
-

Para saber si las rutas obtenidas son robustas se hace una prueba de sensibilidad, la cual consiste en modificar ligeramente los parámetros necesarios para el cálculo de las rutas, y ver si las rutas obtenidas son iguales. Si con parámetros ligeramente diferentes se obtienen las mismas rutas, dichas rutas serán robustas.

3. RESULTADOS

Se han realizado una gran variedad de pruebas de la herramienta, generando redes para diferentes niveles de jerarquía y para los diferentes tipos de vehículo. Se han calculado rutas dentro de una misma ciudad, rutas entre distintos municipios de una provincia y viajes entre provincias. Todas las rutas han sido comparadas con las obtenidas de Google Maps obteniendo resultados muy positivos.

A continuación, se ilustra el proceso con un ejemplo de la zona de Alicante; para ello se ha realizado una descarga de la zona desde la web de OSM y se han cargado los datos en bruto en la herramienta (fig.4).

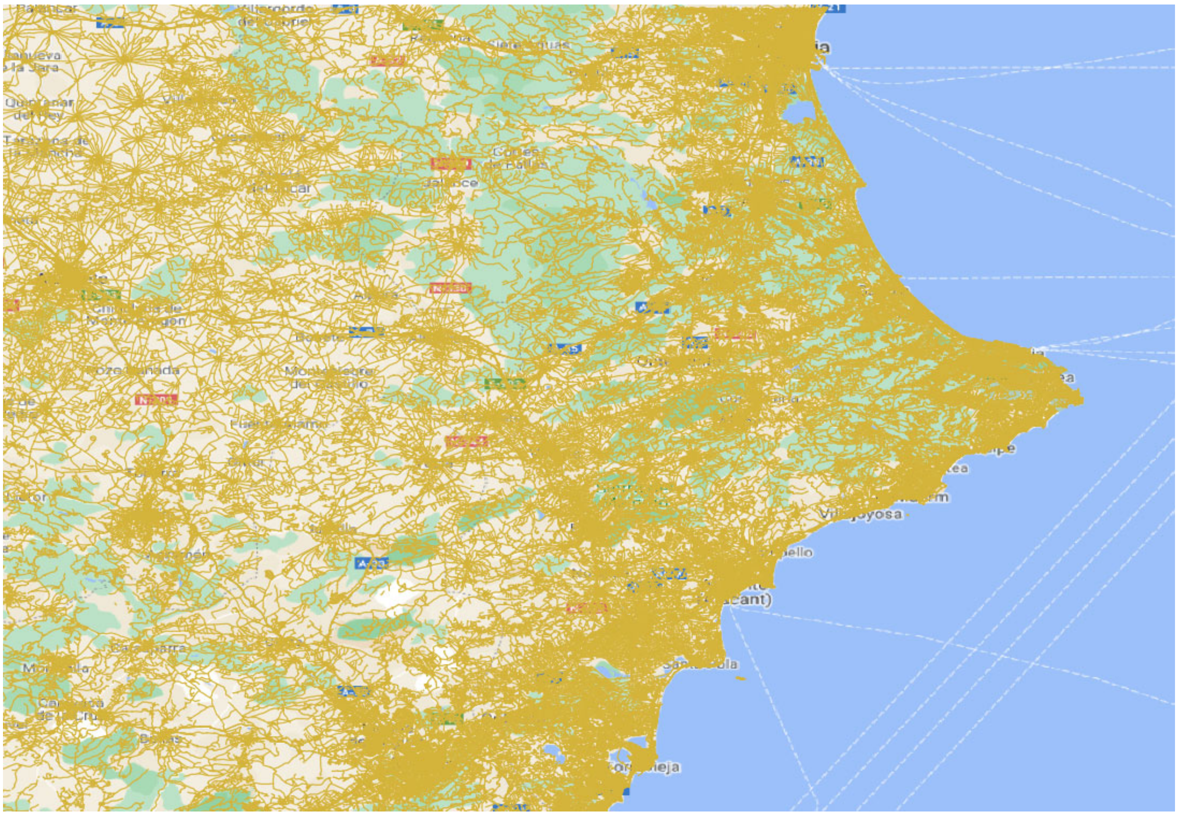

Fig 4- Red obtenida de Open Street Maps. Fuente: los autores.

Hay mucha información, pero no viene bien estructurada, y en muchos casos la información no viene completa. En la tabla 2 se pueden ver varios ejemplos de cómo viene la información de OSM, donde las características del arco vienen en un único campo, y muchos de ellos vienen sin información.

ID del arco	tags
543004957	"name"=>"Carrer del Escultor Leonardo Julio Capuz", "oneway"=>"yes", "highway"=>"residential"
543004957	"ref"=>"A-31", "name"=>"Autovía de Alicante", "lanes"=>"2", "oneway"=>"yes", "highway"=>"motorway", "maxspeed"=>"120"
299525589	"access"=>"private", "oneway"=>"yes", "highway"=>"residential"
41060120	"ref"=>"CV-905", "name"=>"Carretera Benijófar - Torrevieja", "lanes"=>"2", "oneway"=>"yes", "highway"=>"secondary", "surface"=>"asphalt"
331962212	"ref"=>"AP-7", "name"=>"Autopista del Mediterráneo", "toll"=>"yes", "lanes"=>"2", "oneway"=>"yes", "highway"=>"motorway"

Tabla 2 -Datos en bruto de Open Street Maps. Fuente: los autores.

Sobre esta red, HIPROMO realiza los arreglos topológicos para mejorar la calidad de la red, extrae la información de cada uno de los arcos y la almacena de manera bien estructurada.

En los casos en los que falte información, se intenta completar con las características disponibles del arco o por una fuente externa, como es en el caso de las velocidades, ya que la mayoría de los arcos vienen sin una velocidad límite incluida, por lo que se le asigna una velocidad según el reglamento general de circulación (Ministerio de la Presidencia, 2003) y con la modificación de dicho reglamento aprobada el 21 de Noviembre del 2020 (Ministerio de la Presidencia, 2020).

El resultado final es una red bien estructurada, completa y con la información bien detallada. Para el caso de la red de la zona de Alicante, se ha seleccionado un nivel de jerarquía de 4ª clase, filtrando toda la información de los niveles 5 y 6 que hacen referencia a vías peatonales o más residenciales, ya que no se van a necesitar. La red resultante después de aplicar el primer bloque de procesos de HIPROMO se puede observar en la figura 5.

Fig. 5- Red principal de HIPROMO. Fuente: los autores.

La información obtenida tras aplicar el primer bloque de procesos se encuentra estructurada en las siguientes tablas de base de datos. La información mostrada en las tablas no es completa, sino una pequeña muestra para ver el dato real.

TABLA DE ARCOS					
ID	**fromnode**	**tonode**	**Nivel de jerarquía**	**longitud**	**dirección**
371550	296546	296695	mainRoad	635,04059	inDirection
200597	299306	299310	firstClass	29,55969	bothDirections
232858	301527	301555	secondClass	13,91384	bothDirections
418277	184310	184357	thirdClass	76,03465	inDirection
239271	302446	302301	forthClass	98,2555	bothDirections

Tabla 3 -Tabla de arcos de HIPROMO. Fuente: los autores.

TABLA DE VELOCIDADES				
ID	**Tipo de vehículo**	**Tipo velocidad**	**velocidad**	**fuente**
371550	carWithTrailer	maxspeed	80	regulation
371550	carWithTrailer	minspeed	60	regulation
371550	passengerCar	maxspeed	120	regulation
371550	passengerCar	minspeed	60	regulation
371550	privateBus	maxspeed	100	regulation
371550	privateBus	minspeed	60	regulation
371550	pedestrian	maxspeed	0	regulation
371550	pedestrian	minspeed	0	regulation

Tabla 4 -Tabla de velocidades HIPROMO. Fuente: los autores.

La tabla de velocidades (tabla 4) almacena para cada arco, las velocidades por tipo de vehículo. Si un tipo de vehículo tiene velocidad máxima 0, es que tiene prohibida su circulación por dicha vía, como es el caso de los peatones en autopistas. También en esta tabla viene un campo de fuente, que indica de donde se ha obtenido el valor de la velocidad, si viene directamente de los datos de OSM vendrá con un “OSM”, en caso de venir del reglamento general de circulación tendrá el valor “regulation”.

TABLA DE CARRILES		
ID	**dirección**	**Número de carirles**
371550	inDirection	2
200597	bothDirections	2
232858	bothDirections	2
418277	inDirection	2
239271	bothDirections	2

Tabla 5 -Tabla de carriles HIPROMO. Fuente: los autores.

La tabla de carriles (tabla 5) contiene el número de carriles por cada arco, en el caso de que sea de doble sentido "bothDirections", el número de arcos será la mitad para cada sentido. Por último, tenemos las tablas de restricciones que son 3: (i) restricciones generales (tabla 6); (ii) restricciones específicas (tabla 7); y (iii) restricciones de giro (tablas 8).

TABLA DE RESTRICCIONES GENERALES		
ID	**Restricción**	**Tipo de vehículo**
371550	forbiddenLegally	bicycle
371550	forbiddenLegally	pedestrian
291000	seasonal	allVehicle
134701	toll	allVehicle
140293	private	allVehicle

Tabla 6 -Tabla de restricciones generales HIPROMO. Fuente: los autores.

Hay diferentes restricciones generales, "seasonal" o "toll", que a la hora de construir los grafos en el bloque dos, se pregunta si se desea incluirlas, y luego se tiene "forbiddenLegally" y "private" en las cuales no se permite circular dependiendo del tipo de vehículo.

TABLA DE RESTRICCIONES ESPECÍFICAS		
ID	**Restricción**	**Valor**
277325	maxheight	4,5
277325	maxweight	15
290068	maxlength	10
179654	maxlength	8
411667	maxwidth	2,5

Tabla 7 -Tabla de restricciones específicas HIPROMO. Fuente: los autores.

Las restricciones específicas (tabla 7) informan que arcos tienen algún límite de peso, altura, anchura y longitud.

TABLA DE RESTRICCIONES DE GIRO			
Arco Origen	**Arco Destino**	**Vía**	**Tipo de vehículo**
311869	155358	39891	passengerCar
136165	239679	49542	passengerCar
413346	192814	67329	allVehicle
282141	424689	166399	allVehicle
282142	88218	166405	allVehicle

Tabla 8 -Tabla de restricciones de giro HIPROMO. Fuente: los autores.

El formato de las restricciones de giro es diferente a las otras dos tablas de restricciones.

En este caso se tiene el arco por el que estás circulando “Arco Origen”, el “Arco Destino” es al cual está prohibido hacer el giro desde el arco origen, y hay un campo más, que es el “Vía” que indica la intersección entre ambos arcos. Este último puede ser tanto un arco como un nodo. Las tablas anteriores la información de la red principal o red maestra. A partir de esta información se pueden empezar a generar los grafos que uno necesita para realizar el análisis. Gracias a la estructura de tablas que tiene la herramienta la convierte en una herramienta muy flexible facilitando la entrada de información proveniente de otras fuentes.

A partir de la red principal, se han ido generando grafos, los cuáles se incluyen en la base de datos, con la finalidad de poder saber cuántos grafos han sido generados, con qué características y saber cuál utilizar para calcular las rutas (tabla 9). Por lo que la herramienta permite tener una gran variedad de grafos con diferentes características, lo que a la hora de trabajar facilita su identificación y utilización.

LISTA DE GRAFOS						
ID Grafo	**Tipo de vehículo**	**Coste**	**Nivel de jerarquía**	**Hora de viaje**	**Peaj e**	**Seasonal**
1	passenger Car	Tiempo	forthClass	Mañana	Si	Si
2	passenger Car	Tiempo	mainRoad	Mañana	No	No
3	transportT ruck	Coste generalizado	forthClass	Sin horario	No	No
4	passenger Car	Distancia	forthClass	Tarde	Si	Si

Tabla 9 -Tabla de lista de grafos. Fuente: los autores.

La tabla anterior sólo muestra el listado de grafos que existen en la base de datos, es una especia de índice, por lo que si se desea saber toda la información de los grafos se encuentra en la tabla de detalle (tabla 10), en la cual seleccionando el grafo que se quiere analizar, se obtiene los arcos que pertenecen a dicho grafo, el coste de recorrer el arco (según el coste seleccionado para el grafo), el coste de recorrerlo a la inversa (si el arco es de doble sentido), y la longitud de este.

DETALLE DE GRAFOS						
ID Grafo	**ID Arco**	**Fromnode**	**Tonode**	**Coste**	**R-coste**	**Longitud**
1	160264	150327	150535	0,1296	0,1296	60,0571
1	225581	195981	195914	0,7055	-1	95,2385
1	199822	240777	240706	0,0774	0,0774	59,7900
1	330234	241643	241675	0,0109	0,0109	15,2786
1	109728	241539	241423	0,0717	-1	66,4214
1	324117	210709	210696	0,0498	0,0498	38,5188

Tabla 10 -Tabla de detalle de grafos. Fuente: los autores.

Al final la tabla 10 no es más que la información de un grafo dirigido con pesos, donde la estructura de la tabla facilita la utilización del algoritmo del cálculo de rutas. La utilidad de esta información es muy amplia, ya que es aplicable a muchas áreas de estudio, no sólo para el cálculo de rutas.

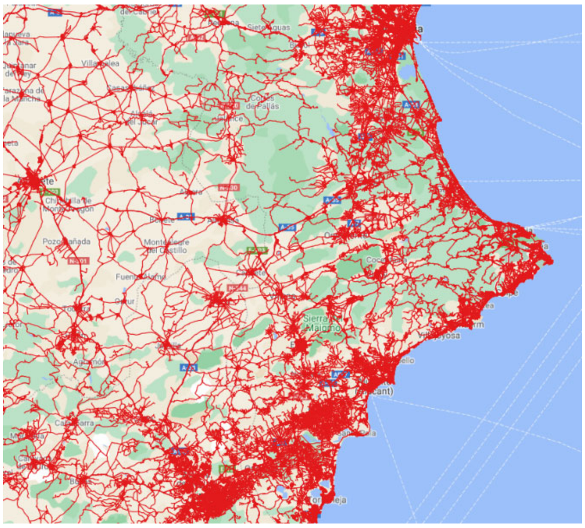

Fig 6- Grafo 1. Fuente: los autores.

Fig 7- Grafo 2. Fuente: los autores.

Se pueden generar tantos grafos como uno desee. Al final del proceso se tiene un conjunto de grafos con toda la información necesaria para poder calcular haces de rutas entre los diferentes orígenes y destinos.

Para el último proceso se ha seleccionado el grafo 1 (Fig. 6) para calcular las diferentes rutas tomando como origen la ciudad de Valencia, y como destino las ciudades de Murcia, Albacete y Almería. Los resultados obtenidos han sido comparados con los que ofrece Google Maps obteniendo unos resultados muy parecidos (figs. 8, 9 y 10).

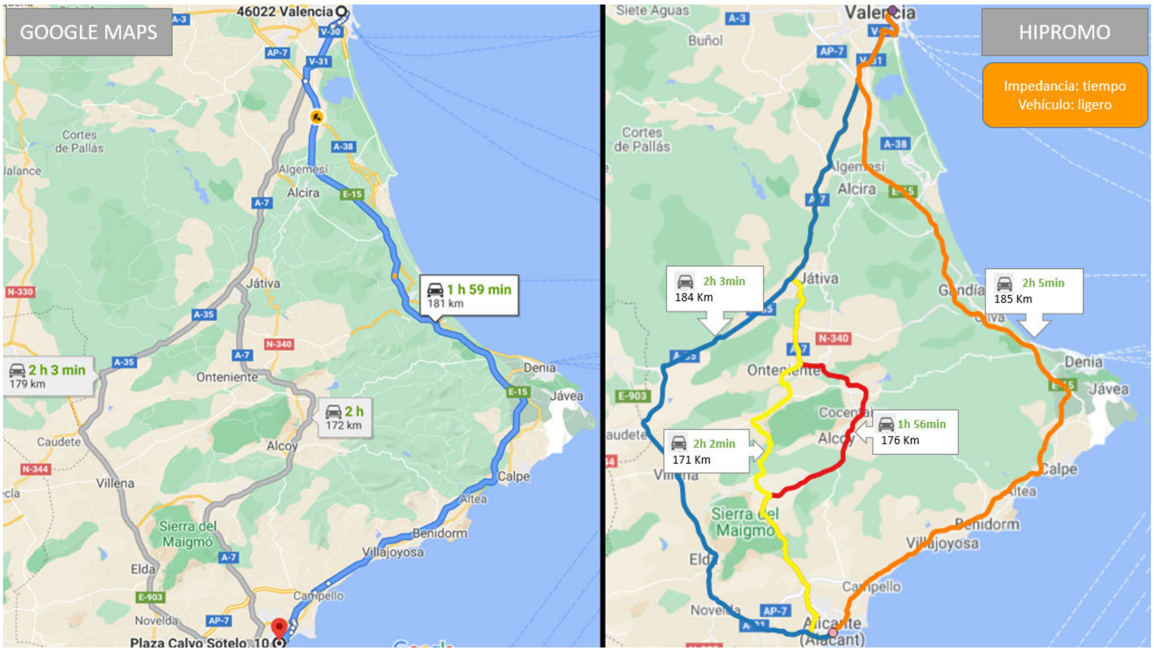

Fig. 8- Rutas Valencia - Alicante. Fuente: los autores.

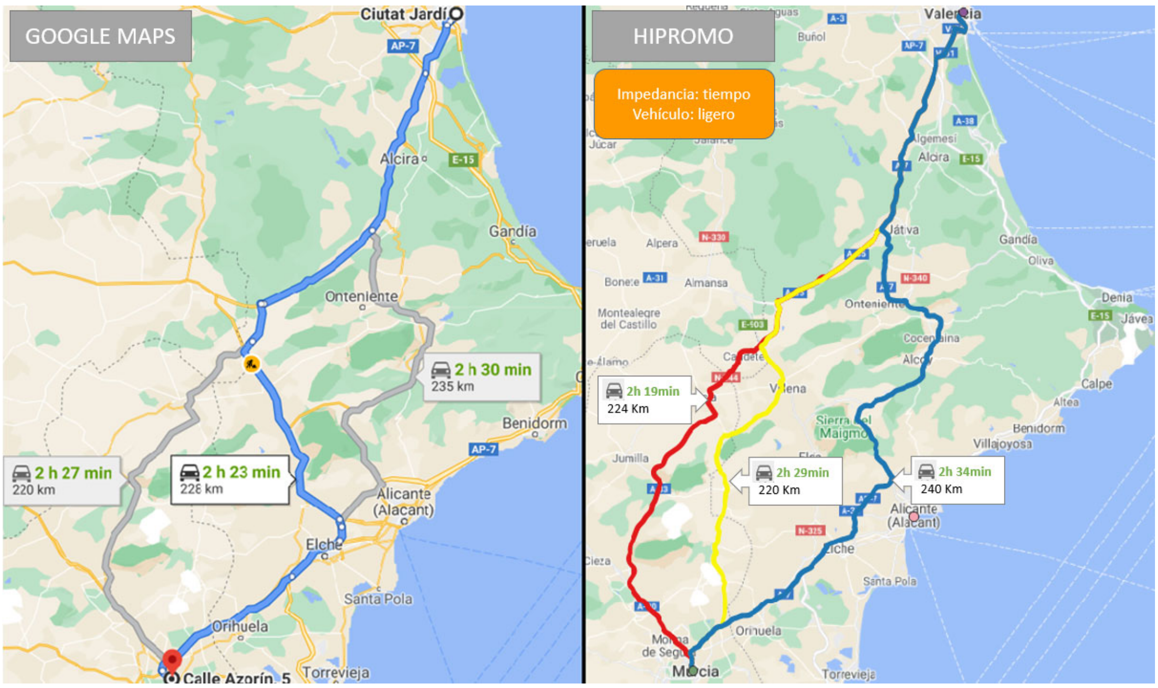

Fig. 9- Rutas Valencia - Murcia. Fuente: los autores.

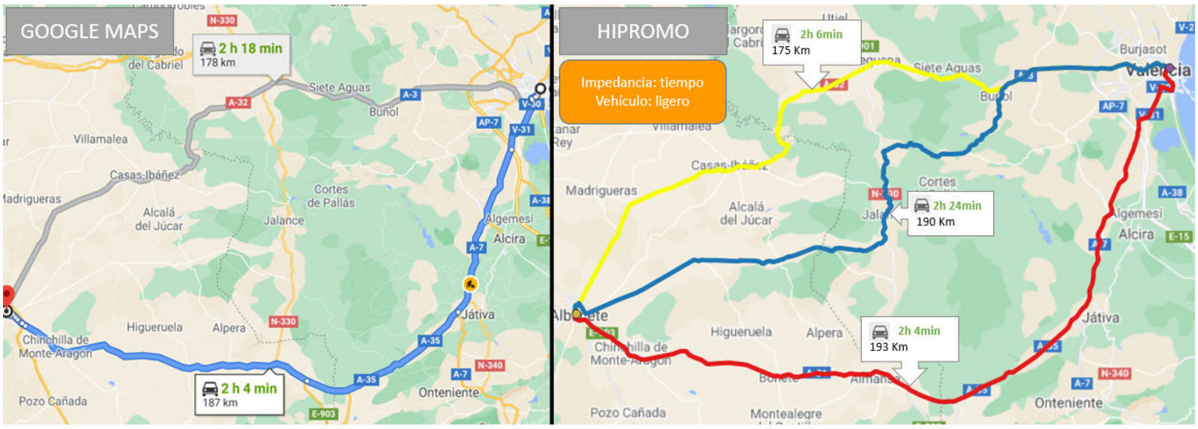

Fig. 10- Rutas Valencia - Albacete. Fuente: los autores.

Como se puede observar en los resultados anteriores, las rutas calculadas por HIPROMO son muy semejantes a las rutas calculadas por Google Maps, la principal diferencia es que las rutas de HIPROMO podemos acceder a todo el detalle de estas, así como acceder a la red principal e incluso a los datos origen de OSM gracias a la trazabilidad de la herramienta.

El detalle de las rutas se guarda en base de datos (tabla 11), donde se puede consultar la secuencia de la ruta, es decir, de que arco a que arco se va moviendo y el coste acumulado según va avanzando. La ruta óptima o de menor coste, siempre será la ruta “0”, las rutas alternativas serán las siguiente (1,2, 3, …) dependiendo del número de rutas alternativas que se desee obtener.

DETALLE DE RUTAS								
ID Grafo	**OD**	**Ruta**	**Sec. Ruta**	**ID Arco**	**Coste**	**Coste Agregado**	**Longitud**	**Longitud Agregada**
1	1-4	0	0	175023	0,1593	0	124,7134	0
1	1-4	0	1	123753	0,6335	0,1593	62,7148	124,7134
1	1-4	0	2	123750	0,5220	0,7928	10,3388	187,4282
1	1-4	0	3	351037	0,6706	1,3148	80,1169	197,767
1	1-4	0	4	351032	0,6972	1,9854	92,6219	277,8839
1	1-4	0	5	395695	0,1491	2,6826	92,8417	370,5058

Tabla 11 -Tabla de detalle de grafos. Fuente: los autores.

4. CONCLUSIONES

En el presente estudio se presenta la metodología de uso de la red de HIPROMO, la cual se ha elaborado a partir de Python para QGIS que permite limpiar, filtrar, tratar, enriquecer determinadas fuentes de datos. La idea principal es la obtención de unos datos flexibles y fiables con lo que poder trabajar en diversos estudios, ya que cuando se quiere estudiar una determinada zona requiere bastante tiempo y esfuerzo el conseguir unos datos óptimos con los que poder trabajar. Esta herramienta da respuesta a este problema, y permite la obtención de una red completa, con una información detallada de la zona de una manera rápida y sencilla, ahorrando mucho tiempo, dinero y esfuerzo en la obtención, limpieza y transformación de los datos. Otra ventaja, es que la red principal está preparada de manera que se puedan obtener redes (grafos) según los diferentes parámetros que uno desea para el estudio obteniendo un abanico muy amplio de posibilidades, ya que, se puede generar redes para cada tipo de vehículo (coche, bici, moto, etc.) y cada una de ellas da como resultado distintos grafos con distinta información.

Cabe destacar la importancia del software colaborativo, en cómo utilizando herramientas de software libre se puede crear una herramienta capaz calcular haces de rutas entre diferentes orígenes y destinos con unos resultados bastante buenos, y poder disponer de todo el detalle para poder trabajar con la información.

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UN ALGORITMO PARA PLANIFICAR RUTAS MÁS RÁPIDAS CON ARCOS DEPENDIENTES DEL TIEMPO EN REDES URBANAS

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RESUMEN

Los sistemas de navegación implementados en los dispositivos móviles permiten a los usuarios buscar las rutas más cortas entre pares de puntos. Muchos de los productos comerciales existentes suponen de manera simplificada que el tiempo de viaje para atravesar cada arco de una red de carreteras es fijo, una vez establecida una hora de inicio. Sin embargo, el tiempo real de viaje a lo largo de un tramo de carretera dentro de las ciudades depende de muchos factores que están relacionados con la congestión del tráfico, las condiciones climáticas, posibles incidencias, etc. y, en consecuencia, depende del tiempo.

Como se puede mostrar fácilmente, la determinación de los itinerarios más cortos en un contexto dependiente del tiempo puede dar como resultado diferentes rutas óptimas desde el mismo origen según diferentes horarios de salida. Suponiendo la disponibilidad de los datos estimados del tiempo requerido para transitar a lo largo de cada tramo de la red de calles, una vez que se ha fijado previamente la hora de salida, proponemos en este trabajo un algoritmo eficiente de obtención de rutas más rápidas sobre arcos dependientes del tiempo, de tal modo que la suma de los tiempos de conducción se minimice, lo que en paralelo permite mejorar el consumo de combustible y reducir las emisiones contaminantes asociadas. Una evaluación experimental se lleva a cabo para mostrar la efectividad del algoritmo aportado.

1. INTRODUCCIÓN

La determinación de itinerarios óptimos en las redes de carreteras es un ingrediente básico en la planificación logística y la simulación del tráfico. En los problemas de planificación de rutas de acuerdo con un simple objetivo, se tiende a seleccionar un único mejor camino desde un origen a un destino.

Debido a su eficiencia y eficacia, el algoritmo de Dijkstra (Dijkstra, 1959) se suele utilizar preferentemente para obtener la solución al problema de la determinación del camino más corto entre dos nodos de un grafo conexo. Se puede afirmar por consiguiente que, desde un punto de vista teórico, el problema de encontrar un camino más corto desde un nodo a otro en un grafo con longitudes (o tiempos de viaje) fijas sobre sus arcos está satisfactoriamente resuelto. De hecho, la implementación de la estructura de datos conocida como montículo de Fibonacci en el algoritmo de Dijkstra requiere sólo un tiempo O (m + n log n), donde n es el número de nodos y m el número de arcos del grafo subyacente (Cormen et al., 1994).

Sin embargo, este algoritmo puede resultar impráctico en varios escenarios de aplicación real.

Uno de estas situaciones surge cuando las ponderaciones asociadas al tránsito entre dos nodos adyacentes son dependientes del tiempo. Esta circunstancia puede darse tanto en la determinación de rutas óptimas de transporte público (autobús, metro o redes densas de trenes de cercanía) como en las de transporte privado (vehículo motorizado propio, bicicleta o similar). Entre las variantes del problema de la determinación del camino más corto estudiadas en Dreyfus (1969) está aquella en la que los tiempos de viaje requeridos para las conexiones entre nodos son dependientes del tiempo de partida de los vehículos.

Esta específica perspectiva es la que se analiza en el presente trabajo, aunque no es la única que puede despertar interés en la literatura especializada en el transporte.

Por ejemplo, los usuarios del transporte público pueden mostrar diferentes preferencias desde una percepción personal (punto de vista del usuario), lo que implicaría una adaptación de los algoritmos iniciales para dar cabida a la existencia de otros tipos de preferencias. Entre estas adaptaciones está la consideración del uso de algoritmos que produzcan K-caminos más cortos (problema denominado KSP) para obtener un número razonable (K) de caminos factibles más cortos y jerarquizarlos a partir de la incorporación de las preferencias del usuario. Las preferencias de los usuarios del transporte público suelen ser varias. A modo de ejemplo:

1. Lograr un tiempo mínimo de recorrido, lo que significa llegar al destino en el menor tiempo posible a partir de la hora de salida establecida como inicio desde el punto origen.
2. Minimizar el número de transbordos: algunos viajeros prefieren viajar en un único vehículo (autobús o tren), antes que soportar los inconvenientes de los transbordos, a pesar de que la duración global del trayecto pudiera ser más larga.
3. Conseguir un recorrido de distancia mínima de desplazamiento: un viajero cargado con objetos pesados o incómodos podría preferir caminar hasta la parada de autobús más cercana, como primera etapa, en lugar de recorrer una distancia mayor hasta otra parada de autobús, aunque esta segunda opción le supusiera una ruta más rápida en tiempo.

La planificación de rutas para vehículos en general sobre mapas geográficos a escala ciudad, región o país, es un problema importante y bien conocido, debido a su amplia gama de aplicaciones para cualquier medio de transporte (Preuss y Syrbe, 1997). El cálculo rápido de las rutas más rápidas de punto a punto en redes de carreteras muy extensas y cuyos arcos dependan del tiempo debe llevarse a cabo mediante la participación de servicios centralizados de información basados en una web accesible, donde se gestionen tanto los patrones de congestión como datos actualizados de tráfico en tiempo real. Para un servidor central que tuviera que responder a un número potencialmente muy grande de peticiones on-line de clientes a través de una interfaz www, sería deseable que el tiempo máximo de respuesta del sistema, proporcionando una buena solución, estuviera limitado superiormente de una forma razonable (Delling y Wagner, 2009). Asimismo, debe tenerse en cuenta que las soluciones que quedarían registradas en estos servicios de información de viajes podrían proyectar su influencia hacia los patrones de congestión que fueran utilizados para asesorar futuras decisiones en la determinación de rutas óptimas sometidas a tráfico en tiempo real.

Se denomina enrutamiento al proceso de seleccionar las “mejores” rutas en un grafo $G = (V, A)$, donde V es un conjunto de nodos y A es un conjunto de arcos. La mayoría de los estudios sobre problemas de enrutamiento se han realizado bajo el supuesto de que toda la información necesaria para formular los problemas es invariante en el tiempo (Toth y Vigo, 2014). En muchas aplicaciones prácticas, esta suposición generalmente no se verifica dado que los tiempos de recorrido pueden variar de manera exógena debido a la congestión del tráfico, las condiciones climáticas, etc., o de manera endógena, en función las decisiones que libremente adopte en conductor modificando a su criterio la velocidad del vehículo (por ejemplo, para ajustar el consumo de combustible) o alterando el tiempo de viaje mediante la inclusión de periodos de descanso en la conducción. Una clasificación de los problemas de enrutamiento dependientes del tiempo con respecto a varios criterios puede verse en Pillac et al. (2013).

El cálculo de rutas que ofrece Google Maps, como navegador integrado en las prestaciones de un vehículo, permite que los usuarios puedan conocer el tiempo estimado de llegada al destino seleccionado. Dicho cálculo se supone que se realiza utilizando una serie de parámetros. Entre ellos, la velocidad máxima permitida y la velocidad recomendada en cada tramo. Además, estos tiempos se promedian teniendo en cuenta los datos históricos registrados de las velocidades medias a lo largo de esas carreteras y calles por las que pasan las rutas consideradas, así como los tiempos que han invertido otros usuarios en anteriores ocasiones (si tal información estuviera disponible). Otros datos que suponemos que deben intervenir en este cálculo son, por supuesto, los de tráfico, con la información en tiempo real que afecta especialmente al tiempo estimado. El éxito de las predicciones a futuro obtenidas sobre los tiempos estimados de llegada ofrecidas por Google Maps son muy dependientes de la posible concurrencia de tales incidencias.

En cualquier caso, el resultado de estas predicciones se basa en estimaciones calculadas mediante procedimientos sometidos a confidencialidad empresarial.

Actualmente, hay múltiples operadores que proporcionan información del estado del tráfico basándose en la velocidad observada de circulación de los vehículos a lo largo de los tramos. Sin embargo, esta información no es completa ya que no cubre la totalidad de vehículos circulantes, bien porque existe una porción de vehículos “no conectados” en el parque, o bien porque las fuentes de esta información no cubren la totalidad de navegadores, de los operadores de telefonía o de las flotas de vehículos. Por ejemplo, Google-Traffic e InfoTransit son dos servidores de información de tráfico en tiempo real que operan en España y que se basan en datos de operadores de telefonía, flotas específicas de vehículos (aseguradoras, transportistas, clubes de automovilistas, etc.), sensores fijos de tráfico fijos y sistemas de navegación GPS. Eglese et al. (2006) examinan los problemas relacionados con la construcción de una base de datos de tiempos de recorrido dependientes del tiempo para una red de carreteras y evalúan los beneficios de los sistemas de planificación y enrutamiento de vehículos dependientes del tiempo para una aplicación desarrollada en Inglaterra.

Asimismo, los problemas de enrutamiento dependientes del tiempo se han tratado en el ámbito del denominado Vehicle Routing Problem (VRP) como una variante del mismo en múltiples contextos. Entre ellos (ver Gendreau et al., 2015):

- Planificación de rutas aeronaves, barcos o submarinos en el espacio bidimensional o tridimensional, donde las decisiones incluyen no sólo la determinación del itinerario, sino también el ajuste de potencia. El factor de dependencia del tiempo puede ser causado por las corrientes de aire, oleaje en el océano o el flujo submarino. El objetivo a minimizar suele ser la duración del trayecto, el consumo de combustible (o, equivalentemente, las emisiones de CO2) o una combinación de ellos (Perakis y Papadakis, 1989; Norstad et al., 2011).
- Otras causas de dependencia del tiempo que pueden alterar la duración de recorrido en el VRP sería la necesidad de reabastecer unidades móviles (Helvig et al., 2003), o la necesaria interceptación de trayectorias de otros vehículos (Jiang et al., 2005).
- Finalmente, la presencia de obstáculos en movimiento podría ser también un factor determinante en la planificación del movimiento de robots que puede modificar el tiempo de recorrido de los tramos (Sutner y Maass, 1988; Latombe, 1990; Fujimura, 1995).

2. FORMALIZACIÓN DEL PROBLEMA

Sea el grafo $G = (V,A)$ donde V es un conjunto finito de n nodos o vértices y A es un conjunto finito de m aristas o arcos que conectan los nodos. Cada arco puede ser denotado como el par (i, j) cuando se corresponda con el par de vértices i y j.

En general, para este tipo de problema se considera que los pares (*i*, *j*) son ordenados. Sean *O* (vértice origen o inicial) y *D* (vértice destino o terminal) dos nodos dados de *G*; se define un camino *p* desde *O* hasta *D* en *G* como la secuencia alternada de vértices y arcos:

$$p = \{O = v_0, a_1, v_1, a_2, v_2, \ldots, a_k, v_k = D\} \quad (1)$$

tal que se cumple:

- $a_i \in A, \forall i = 1, \ldots k;\; v_i \in V,\; \forall i = 1, \ldots k-1.$
- $a_i = (v_{i-1}, v_i) \in A, \forall i = 1, \ldots k.$
- $O, D \notin \{v_1, v_2, \ldots, v_{k-1}\}.$

Se define el costo asociado al arco $a = (i, j)$ como el número real positivo $c(a) = c_{ij} \geq 0$. De esta forma, el costo de un camino *p* equivaldrá a la suma acumulada de los costos de los arcos que lo componen: $c(p) = \sum_{(i,j)\in p} c_{ij}$.

Sea P_{ij} el conjunto de todos los caminos de *i* a *j* en el grafo *G*. Siguiendo la notación de Dreyfus (1969), el problema de encontrar el camino más rápido entre los puntos *O* y *D* donde el tiempo de viaje entre el punto *i* y el punto *j* dependa del tiempo de partida del punto j se puede formular como sigue. Denotemos mediante los valores positivos $d_{ij}(t)$ dicho tiempo de viaje invertido y mediante $f_i(t)$ al mínimo tiempo de viaje invertido hasta alcanzar el destino *D* partiendo desde el punto *i*.

El esquema recurrente

$$\begin{cases} f_i(t) = \min_{j \neq i} \left[d_{ij}(t) + f_j(t + d_{ij}(t)) \right] \\ f_O(t) = 0 \end{cases} \quad (2)$$

nos permite diseñar un algoritmo iterativo que, a partir del procedimiento ideado por Dijkstra (1959), proporcione la ruta más rápida en este contexto de tiempos de recorrido en los arcos dependientes del tiempo. Dicho algoritmo se describe más abajo.

2.1 Algoritmo de Dijkstra (entorno estático)

1. **Read** grafo **G=(V,A),** matriz de adyacencia **Ady** y matriz de costes **D** de desplazamiento entre pares de puntos adyacentes.
2. **Construir** vector **f** que almacena los mínimos costes de desplazamiento al origen desde cada nodo de G (inicialmente, sólo los nodos adyacentes con el origen no tendrán valor infinito).

3. **Construir** vector **p** que almacena los nodos sucesores a cada nodo de G en el camino óptimo (inicialmente, sólo los nodos adyacentes con el origen podrán estar determinados).
4. **Inicializar** conjunto **S** de nodos explorados con el origen sólo. **Inicializar** conjunto **LIST** de nodos por explorar dándole el valor complementario LIST=G\S.
5. **While** LIST no sea el vacío:
   5.1 Identificar el índice **j***
   $$j^* = Arg\left[\min\left\{f(j) : j \in LIST\right\}\right]$$
   5.2 Remove índice j* de LIST
   5.3 For each sucesor **k** de j* incluido en LIST:
   If *f(k) > f(j*) + C(j*, k)* **then**
   a. *f(k):= f(j*) + C(j*, k)*
   b. *p(k):= j**
6. **End**.

A continuación, se expone el mismo ejemplo que se usa en Wen et al. (2014) para ilustrar el funcionamiento del algoritmo de Dijkstra y sus limitaciones cuando la red es dependiente del tiempo.

En la Figura 1 se considera una situación estática, donde los pesos de los arcos no varían con el tiempo.

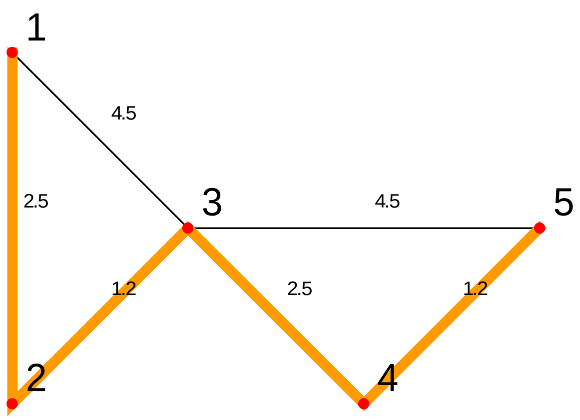

Fig. 1 –Camino más rápido entre nodos 1 y 5 usando el algoritmo de Dijkstra

Como se ilustra en la Figura 1, la solución al problema es el camino 1-2-3-4-5, y el tiempo invertido es 7.4 (2.5+1.2+2.5+1.2) minutos, como puede comprobarse aplicando el algoritmo paso a paso.

Inicio:
Vector f= (0, 2.5, 4.5, infinito, infinito)
Vector p= (- , 1, 1, - , -)

Conjunto S={1}. Conjunto LIST={2,3,4,5}

Paso 1:

j*= 2

Conjunto LIST={3,4,5}. Sucesores de j*= 2 en LIST= {3}

k=3. ¿Es f(3)=4.5 Mayor que la suma de f(2)=2.5 y C(2,3)=1.2? → Sí.

Entonces: f= (0, 2.5, 3.7, infinito, infinito); p= (- , 1, 2, - , -)

Paso 2:

j*= 3

Conjunto LIST={4,5}. Sucesores de j*= 3 en LIST= {4,5}

k=4. ¿Es f(4)=infinito Mayor que la suma de f(3)=3.7 y C(3,4)=2.5? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, infinito); p= (- , 1, 2, 3 , -)

k=5. ¿Es f(5)=infinito Mayor que la suma de f(3)=3.7 y C(3,5)=4.5? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, 8.2); p= (- , 1, 2, 3, 3)

Paso 3:

j*= 4

Conjunto LIST={5}. Sucesores de j*= 4 en LIST= {5}

k=5. ¿Es f(5)=8.2 Mayor que la suma de f(4)=6.2 y C(4,5)=1.2? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, **7.4**); p= (- , 1, 2, 3 , 4)

Paso 3:

j*= 5

Conjunto LIST= Vacío. **END**

A partir del vector de nodos precedentes p= (- , 1, 2, 3 , 4) se puede reconstruir fácilmente el camino óptimo entre los nodos 1 y 5.

Supongamos ahora que el arco 3-5 dependa del tiempo de la forma siguiente:

- Para valores del tiempo entre 0 y 4, el tiempo necesario para recorrer el arco 3-5 es como en el caso anterior (estático) de 4.5 minutos.
- A partir de t=4, como novedad, el tiempo de recorrido del arco decae hasta valer 1,3 minutos.

En ese caso, como se expone en la Figura 2, el camino más rápido entre los nodos 1 y 5 sería la secuencia 1-3-5, siendo el tiempo invertido de 5.8 (4.5+1.3) minutos.

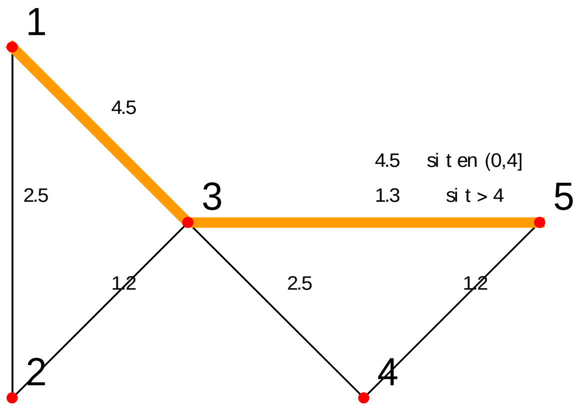

Fig. 2 –Camino más rápido entre nodos 1 y 5 en arcos dependientes del tiempo con prohibición de esperas en los nodos.

Para tratar de adaptar el algoritmo de Dijkstra a este nuevo contexto se debería incluir al menos una referencia temporal que recogiera la hora de inicio del recorrido de cada arco cuando se determina la ruta más rápida. Estas referencias temporales para cada uno de los nodos se deberían almacenar temporalmente como componentes de un vector. El nuevo punto 3 del algoritmo adaptado sería:

> **3'. Construir** vector **p** que almacena los nodos sucesores a cada nodo de G en el camino óptimo y, además, el vector **t** que almacena las horas de comienzo para la validez de esa sucesión.

Habría, asimismo, que modificar la instrucción **5.3** para incluir una actualización del vector t cada vez que se cumpliera la condición $f(k) > f(j^*) + C(j^*, k)$.

Sin embargo, se puede comprobar que la simple introducción de estas dos variantes no serviría para determinar la solución óptima. Aplicando el algoritmo modificado al ejemplo anterior, se puede apreciar que la dependencia en el tiempo del coste asociado al arco 3-5 no tiene efecto en el resultado final del algoritmo porque pasaría inadvertido.

Inicio:

Vector f= (0, 2.5, 4.5, infinito, infinito). Vector t= (- , 0, 0, - , -).
Vector p= (- , 1, 1, - , -).
Conjunto S={1}. Conjunto LIST={2,3,4,5}

Paso 1:

j*= 2
Conjunto LIST={3,4,5}. Sucesores de j*= 2 en LIST= {3}
k=3. Para t=0, ¿es f(3)=4.5 Mayor que la suma de f(2)=2.5 y C(2,3)=1.2? → Sí.
f= (0, 2.5, 3.7, infinito, infinito); t= (- , 0, 2.5, - , -); p= (- , 1, 2, - , -)

Paso 2:

j*= 3

Conjunto LIST={4,5}. Sucesores de j*= 3 en LIST= {4,5}

k=4. Para t=2.5, ¿es f(4)=infinito Mayor que la suma de f(3)=3.7 y C(3,4)=2.5? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, infinito); t= (- , 0, 2.5, 3.7 , -); p= (- , 1, 2, 3 , -)

k=5. Para t=2.5, ¿es f(5)=infinito Mayor que la suma de f(3)=3.7 y C(3,5)=4.5? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, 8.2); t= (- , 0, 2.5, 3.7 , -); p= (- , 1, 2, 3, 3)

Paso 3:

j*= 4

Conjunto LIST={5}. Sucesores de j*= 4 en LIST= {5}

k=5. Para t=3.7, ¿es f(5)=8.2 Mayor que la suma de f(4)=6.2 y C(4,5)=1.2? → Sí.

Entonces: f= (0, 2.5, 3.7, 6.2, **7.4**); t= (- , 0, 2.5, 3.7 , 6.5); p= (- , 1, 2, 3 , 4)

Paso 4:

j*= 5

Conjunto LIST= Vacío. END

Nótese que efectivamente el vector final p no ha variado (sigue valiendo (- , 1, 2, 3 , 4)), por lo que sería necesario introducir una nueva estrategia para el algoritmo. Proponemos la incorporación de una instrucción en la que se ampliara el grafo de conexiones, replicando cada nodo j* tantas veces como cambios a la baja se produzcan en los valores de los arcos salientes. En la Figura 2, el arco 3-5 toma dos valores, antes y después de t=4 minutos. El primer nodo de este arco que visita el algoritmo es el nodo 3 para t= 3.7 minutos. Este nodo se decide redefinirlo 3a y hereda las conexiones del nodo original (entre ellas, la conexión 3-5 valorada para t=3.7 minutos). Además, se replica un nuevo nodo 3b con las siguientes características:

- El nodo 3a se conecta de forma unidireccional al nuevo nodo 3b con el necesario tiempo de espera t=4-3.7=0.3 minutos.
- El nuevo nodo 3b replica todas las conexiones que tenía el nodo 3 en el grafo original salvo la conexión con el predecesor del nodo 3a en el camino que se está calculando. Los valores de estas conexiones se deberán aplicar en las respectivas ponderaciones a partir del tiempo referenciado de t=4 minutos.

En la Figura 3 se muestra el grafo ampliado según se ha descrito, así como el camino más rápido entre los nodos 1 y 5, que sería ahora la secuencia 1-2-3a (etiquetado como 3)-3b (etiquetado como 6)-5, lo cual implicaría una espera en el nodo 3 de 0.3 minutos, siendo el tiempo total invertido de 5.3 (4+1.3) minutos.

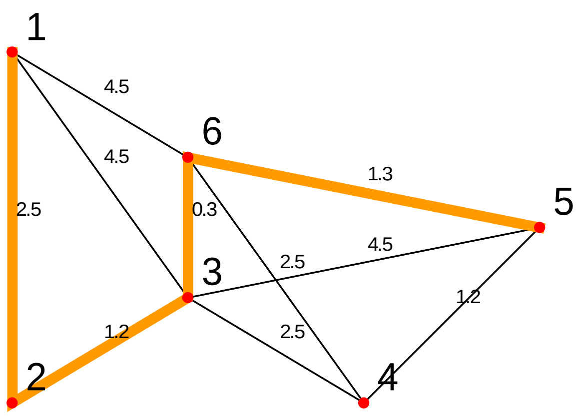

Fig. 3 –Camino más rápido entre nodos 1 y 5 en arcos dependientes del tiempo sin prohibición de esperas en los nodos.

3. UN ALGORITMO ADAPTADO

El algoritmo que se presenta a continuación incluye las modificaciones necesarias para poder determinar caminos más rápidos entre pares de nodos dentro de una red, estando las ponderaciones de sus arcos sometidos a variaciones según horario conocido o pronosticado con antelación.

3.1Un Algoritmo de Dijkstra adaptado a arcos dependientes del tiempo

1. **Read** grafo **G=(V,A),** matriz de adyacencia **Ady** y matriz de costes **D** de desplazamiento entre pares de puntos adyacentes.
2. **Construir** vector **f** que almacena los mínimos costes de desplazamiento al origen desde cada nodo de G (inicialmente, sólo los nodos adyacentes con el origen no tendrán valor infinito).
3. **Construir** vector **p** que almacena los nodos sucesores a cada nodo de G en el camino óptimo (inicialmente, sólo los nodos adyacentes con el origen podrán estar determinados).
4. **Inicializar** conjunto **S** de nodos explorados con el origen sólo. **Inicializar** conjunto **LIST** de nodos por explorar dándole el valor complementario LIST=G\S.
5. **While** LIST no sea el vacío:

    5.1 Identificar el índice **j***

    $$j^* = Arg\left[\min\left\{f(j) : j \in LIST\right\}\right]$$

    5.2 If los arcos de salida del nodo j* no cambian en el tiempo **then**

    5.2.1 **Remove** índice j* de LIST

    5.2.2 **For each** sucesor **k** de j* incluido en LIST:

    If *f(k) > f(j*) + C(j*, k)* **then**

    i. *f(k):= f(j*) + C(j*, k)*

    ii. *p(k):= j**

else

5.3 Por cada arco de salida nodo j* que cambie en el tiempo y por cada modificación de la ponderación del arco:

5.3.1 **Replicar el nodo j* (sea j*'), actualizando** el conjunto V.

5.3.2 **Repetir** para el nuevo nodo j*' las **conexiones** que tenía j* (con las mismas ponderaciones, si no fuera el arco de salida considerado), **excluyendo** la conexión de j* con su precedente en el camino.

5.3.3 **Añadir un enlace dirigido de j* a j*'**, ponderado con el tiempo de espera requerido en el nodo j*.

5.3.4 **Actualizar** el conjunto A según 5.3.2 y 5.3.3.

5.3.5 **Incluir** en el conjunto LIST el nuevo nodo j*'.

6. End.

El bloque de programación que se añade está etiquetado como 5.3, y este se activa cuando se detecte la existencia de arcos de salida que dependan del tiempo. La complejidad del algoritmo depende precisamente del número de arcos cuyas ponderaciones están sometidas a cambios dependientes del tiempo, así como del número de cambios incorporados.

4. CONCLUSIONES

En este artículo se ha analizado el problema de la determinación de caminos más rápidos con arcos dependientes del tiempo en redes de transporte. Son numerosas las contribuciones bibliográficas existentes relativas a esta temática, debido principalmente a la relevancia que adquiere esta cuestión en la planificación logística y de viajes para todo tipo de usuarios.

Se ha estudiado específicamente la metodología presentada en Wen et al. (2014), donde se propusieron dos métodos heurísticos para resolver el problema de la ruta de costo mínimo entre un par de nodos con una red de carreteras que varía en el tiempo y existe además un cargo por congestión.

La herramienta desarrollada por estos autores se basaba en modificaciones del algoritmo de Dijkstra, donde se había establecido una prohibición de espera en los nodos.

La técnica de búsqueda algorítmica de caminos más rápidos con arcos dependientes del tiempo introducida en esta contribución sigue esa línea metodológica de adaptación del algoritmo de Dijkstra a este contexto, lo cual garantiza un alto nivel de eficiencia para el cálculo de soluciones.

En cambio, la contrapartida, como ha quedado constatado en la redacción del procedimiento, está en que el grafo original se deba ampliar convenientemente, tanto en número de nodos como en nuevos arcos (algunos de ellos unidireccionales, que son los que indican el avance del tiempo). Sería posible, no obstante, limitar este crecimiento del grafo contenedor de soluciones, considerando sólo la incorporación de aquellos nodos y arcos que pudieran mejorar la solución actualmente calculada y obviando aquellas otras ampliaciones que claramente derivaran en empeoramientos.

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ANALYSIS OF THE VEHICLE-BICYCLES INTERACTION ON TWO-LANE RURAL ROADS USING A DRIVING SIMULATOR BASED ON FIELD DATA

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ABSTRACT

The presence of cyclists on Spanish two-lane rural roads is common, so they have to interact with motor vehicles. Due to the speed differential and vulnerability of cyclists, overtaking is one of the most dangerous and frequent interactions. Therefore, a minimum distance of 1.5 m must be observed. The overtaking manoeuvre depends on road section and cyclist group distribution. Interaction between cyclists and vehicles has been characterized in the past but overtaking to cyclist groups has barely been studied. This study uses a driving simulator to analyse how the presence of cyclists and their group configuration affect traffic operation and safety on two-lane rural roads. A fixed driving simulator has been adapted to incorporate cyclists, using speed and lateral position obtained from field studies. Based on field data, a physical scenario and different traffic scenarios have been recreated, so volunteers can drive the simulator – emulating a motor vehicle – tracking their speed, lateral position, and other variables. These results can be compared to those observed for checking the validity of this methodology. The driving simulator offers some results which are difficult to obtain through other methodologies, enabling a better analysis of the phenomenon. By sorting different bicycle patterns and including several volunteers, the impact of bicycle pelotons on traffic performance and safety can be characterized. This will help in offering recommendations to integrate cyclists and motor vehicles in a safer way.

1. INTRODUCTION

Nowadays, there is an increasing presence of bicycle traffic on Spanish two-lane rural roads, which must be considered when analysing safety and operation of traffic on these roads. Most of the cyclists who use rural roads are sport cyclists, and they usually ride individually or in groups. Due to the differences between cyclists and motorized vehicles, the severity of the accidents registered on rural roads are higher than on urban environment. In fact, in 2019, the 60% of the fatal accidents with cyclists involved were registered in rural roads, despite most of the accidents with cyclists involved (72%) were registered on urban environment (DGT, 2019).

Due to the speed differential and vulnerability of cyclists, overtaking is one of the most dangerous and frequent interactions. The overtaking manoeuvre has been studied in many research using different methods and analysing different variables. Most of these previous studies were focused on the safety point of view, and they analysed mainly the lateral clearance between the overtaking vehicle and the bicycle and the overtaking vehicle speed. Regarding the method used to develop these studies, most of them used instrumented bicycles to collect real data (Llorca et al., 2017; Dozza et al., 2016; García et al., 2019; López et al., 2020). Other studies used naturalistic data (Debnath et al., 2018) or test track data (Rasch et al., 2020). Another methodology that allows obtaining data of the overtaking manoeuvre to cyclists is the use of driving simulators (Bella and Silvestri, 2017; Bianchi-Piccinini et al., 2018; Farah et al., 2019; Mecheri et al., 2020; Goddard et al., 2020; Rossi et al., 2021).

This methodology allows obtaining data from the drivers' point of view, investing relatively short time and in an easy and economical way. All the previous studies, that analysed the interaction between motorized vehicles and cyclists on rural roads using a driving simulator, considered only one cyclist riding alone, and simulated scenarios designed by varying the geometric characteristics of the rural road, the position of the cyclist or the oncoming vehicle presence.

None of them studied the effect of groups of cyclists riding on rural roads, and real geometric and traffic scenarios considering cycle traffic and oncoming traffic were not simulated.

The presence of cyclists on two-lane rural roads not only affects safety, but also traffic operation. Moll et al. (2021) performed a study using a traffic micro-simulator to analyse the effect of cycle traffic on traffic operation on narrow two-lane rural roads. Their results showed that cycle traffic presence decreases motorized vehicle average travel speed and increases percent followers and delays. The use of a driving simulator allows to obtain several performance measures to characterize and analyse the affection on both safety and traffic operation.

Previous studies performed by Llopis Castelló et al. (2016, 2019) proposed a methodology for road safety analysis using driving simulators. Following this methodology, the virtual scenario is designed, recreated and loaded into the driving simulator based on geometric characteristics of the road and surroundings.

Then, a set of driving simulator tests is performed by some volunteers. Finally, the results of the simulator are validated by comparison with the real data obtained on field observations. At last, the results obtained from the simulator can be analysed to obtain conclusions. This methodology can be used not only to analyse road safety, but also to characterize traffic operation (Dols et al., 2021).

The present study aims to simulate a real geometric scenario and three traffic scenarios obtained from field observations. Other innovation of this study is that the traffic scenarios simulated include groups of sport cyclists, riding in different configurations. Using the developed driving simulator will be possible to obtain some results which are difficult to obtain through other methodologies, enabling a better analysis of the phenomenon.

2. METHOD

The first step was to create the road physical virtual scenario. The physical recreation used the methodology developed by Dols et al. (2016) that requires to define the road geometric characteristics (alignment, elevation and cross-section), as well as the environment (side margins, vertical signs, road markings, surroundings, etc.). From this information, the virtual scenario can be recreated and loaded into the driving simulator. In the next step, a group of volunteers (who must be representative), will travel through the virtual scenario using the simulator. Fig. 1 shows the methodology used.

This paper is focused on the first stage. The main objective was to incorporate groups of cyclists inside the driving simulator scenario, and to simulate the real road and traffic characteristics in a realistic way. The traffic scenarios implemented corresponded to real scenarios observed in the segment.

Therefore, the results of the simulator can be validated with field data in order to analyse the behaviour of the drivers in the simulator with respect to that observed in the field. In addition, on the second stage, data from driving simulator test can be used to evaluate safety and traffic operation in the road.

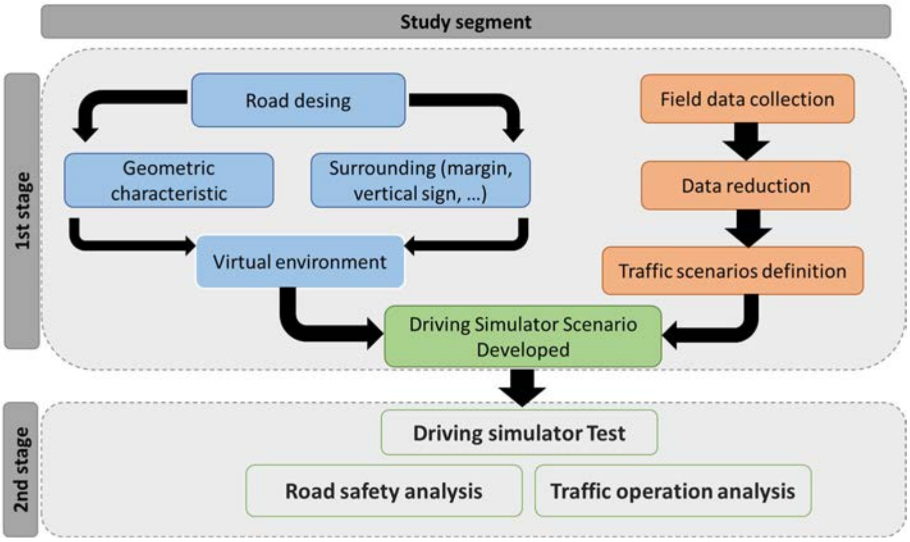


Fig. 1 – Methodology used to develop road segment and cross-section characteristics.

2.1 Study segment description

This study was performed in a segment of two-lane rural road located in the road CV-310, in the region of Valencia (Spain). The study segment is 4,860 meters long, and it has a lane width of 3.2 meters. The road has paved shoulder varying the width between 1.5 and 2 meters. The road has a downward slope of about 7.2% from the beginning to the end of the segment analysed. An important feature of this segment is that the shoulder is coloured in red.

2.2 Field data collection and reduction

Data collection consisted of naturalistic recordings made simultaneously in the extremes of the segment, using small high-definition video cameras. The video cameras were discreetly located so that they could not be noticed by road users. Data reduction beginning with reviewing the videos recorded in the start point of the segment, and the timestamp and the typology of each road user was registered. Finally, the videos recorded at the end point of the segment were reviewed to complete the dataset. This data reduction was realized in both directions of the studied segment. As a result, the time space diagrams considering the trajectories of each road user were obtained and used to select the traffic scenarios with the maximum and the minimum bicycle traffic for the simulations.

2.3 Virtual scenario

The virtual scenario design can be a laborious process. As Dols et al. (2016) indicated, the scenario geometric and traffic characteristics to be modelled will determine the accuracy of the model and therefore the success of the study to be carried out. Modelling the virtual scenario requires a high degree of specialization in many areas (traffic, road design, road safety, among others) as well as graphic simulation techniques and 3D object modelling, to reproduce real-world conditions as good as possible

The present study aims to simulate a real geometric scenario and different traffic scenarios obtained from field observations. To do this, firstly, a physical scenario has to be developed.

The physical scenario has to be similar to the real road segment, so their design is based in real data collected on the road and obtained from computer programs based primarily on satellite imagery. Once the physical scenario has been designed and built, the traffic scenarios have to be designed. The traffic demands considered in each traffic scenario were based on field observations. However, the main challenge is to integrate the groups of cyclists and their observed behaviour in the simulator.

2.3.1 Physical scenario

The physical scenario was designed by the Institute for Design and Manufacturing (IDF) of the Universitat Politècnica de València based on the Multilayer Editing Procedure (Dols et al., 2016, 2021). This methodology implies that the scenario editing procedure of all elements to define the virtual scene are modelled as a multi-layer editing technique in which different data-files are including the types of information needed to model the road and their surrounding virtual scene.

2.3.1.1 Road Design Geometry

The road design was developed using Civil 3D software. Then, the horizontal and vertical alignments, and the cross-section characteristics were provided in an Excel file with the coordinates (x, y, z) of the axis of the road, the edges of the lanes and the platform given at each meter. One of the characteristics of this section is that the width of the shoulder varies between 1.5 m and 2 m, the majority being 1.5 m wide, while the lane width is constant during all the segment To consider the variation in the cross section, the equations of the shoulder width limits were obtained as an input to the physical development of the model for the simulator.

Terrain model of the surrounding area

ASC file with the cartography, downloaded from the website of the National Plan for Aerial Orthophotography (NPAO), and combined with a more precise tachymetry.

Orthophotography of the study area

Also downloaded from the National Plan for Aerial Orthophotography (NPAO) website in Enhanced Compression Wavelet (ECW) format.

Inventory of Elements of the road and the environment

A file in Excel format, with all the elements of the superstructure as vertical signs, road beacons, road markings, lateral safety barriers and lateral walls was completed. Each road and environment element were described and their specific location in the road, referenced to the beginning of the road segment, were registered.

For each observed vertical sign, the location where it appears, referenced to the beginning of the study segment, and the margin where it appears were indicated. In addition, to know the orientation of each of them, the direction of circulation was noted. Fig. 3 show the different vertical signs observed in the study segment, and lately introduced into the virtual physic scenario.

Fig. 2 - Vertical signs observed in the study segment.

In the study segment some road beacons to signalize the curves were observed (Fig. 3). These road beacons were located in the road indications their point location, referenced to the beginning of the segment, and their margin and orientation. The number of signs that formed each beacon (simple or double) was also indicated. The location of them was always out of the road, and of the lateral safety barrier, when it was present. In the study there were also observed a speed radar sign and its corresponding speed radar device (Fig. 3).

(a) (b) (c) (d)

Fig. 3– (a) simple road beacon; (b) double road bacon; (c) speed radar sign; (d) radar box observed in the study segment.

The different types of road markings observed in the study segment are shown in Fig. 5.

The lateral centre lines, which separate the lane and the shoulder, were continuous in all the segment, while the centre line presented the five types shown in Fig. 5. These data were reported considering the points were the lines changed along the segment. In the study segment there are simple and double lateral safety barriers (Fig. 6), most of them are double safety barriers, used to improve the safety for motorcyclists; and there are only two segments with a simple safety barrier.

The locations of the safety barriers were defined indicating the type "Simple" or "Double", and the point of the road and the length where this containment system exists. In addition, it has been differentiated for each of the road margins in an increasing direction of road length, referring to the origin of the study segment. The disposition of the safety barriers will be on the outside of the hard shoulder.

Fig. 4 - Different centre and lateral line types observed in the study segment.

(a) (b)

Fig. 5 - Lateral safety barriers observed in the study segment. (a) simple safety barrier; (b) double safety barrier.

In this section there are several lateral walls whose height, and the initial location and length were provided. The texture and colour of each lateral wall was registered in order to obtain a similar result in the virtual scenario. A CAD file was also generated with the location of environmental elements that cannot be associated with a specific point of the road, such as buildings and vegetation. Two types of trees were defined in the virtual environment, they were orange and pine trees.

2.3.2 Traffic scenarios

As a novelty on driving simulator studies, real traffic scenarios were simulated, considering the same cycle traffic and oncoming traffic than observed on the field. This fact makes the validation process more realistic, so it is possible to validate the simulator results for each traffic scenario simulated in a more exact way. Therefore, the physical appearance of all road users, and their trajectories along the road segment were analysed.

2.3.2.1 Groups of cyclists

The trajectories of the cyclists along the segment depend on the shoulder width at each point. Therefore, the trajectories of the cyclists had to be incorporated in the simulator considering the lane and shoulder width variation. The positions of the bicycles were different considering the direction, as the lane and shoulder widths. The bicycles positions were defined as y_br and y_bl, for the right and left side of the road respectively. Then, for the direction with x positive values, the trajectory of the bicycles, which ride on the right shoulder, was defined by:

While the trajectory of the bicycles in the opposing direction, when they ride in the left shoulder, were defined by:

$$y_{br} = \begin{cases} y_r + \frac{y_{rs}-y_r}{2} & \text{if } y_{rs} - y_r \geq 2.2 \\ y_{rs} - 1.1 & \text{if } 2.2 > y_{rs} - y_r \geq 1 \\ y_r - 0.1 & \text{if } y_{rs} - y_r < 1 \end{cases} \quad (1)$$

$$y_{bl} = \begin{cases} y_l + \frac{y_{ls}-y_l}{2} & \text{if } y_l - y_{ls} \geq 2.2 \\ y_{ls} + 1.1 & \text{if } 2.2 > y_l - y_{ls} \geq 1 \\ y_l + 0.1 & \text{if } y_l - y_{ls} < 1 \end{cases} \quad (2)$$

These trajectories correspond to a single cyclist. When two cyclists ride two-abreast, they are modelled as two bicycles, separated 1 m and centred in the defined positions for one cyclist. To better reproduce the groups of cyclists in the simulator, the different groups were simulated based on a combination of one cyclists and a couple of cyclists riding two-abreast.

The distance considered between cyclists who ride in-line was 1 m. About the speed at which the bicycles ride, there was considered that all the bicycles ride at the same speed, and this speed was considered constant based on the values obtained in filed data.

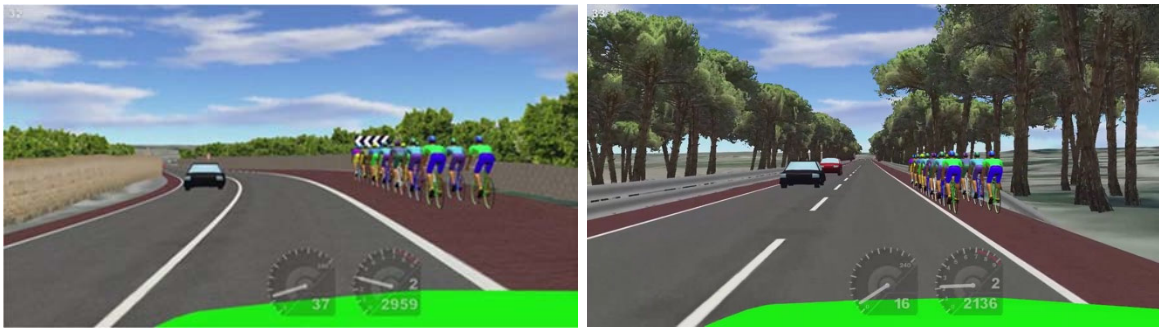
Oncoming motorized vehicles

All the oncoming vehicles were considered to travel at the same constant speed. This speed was obtained from the field data collected in the study segment. Regarding the lateral position, the oncoming motorized vehicles were centred in the lane for both directions, as it was the most common position observed on field.

2.3.2.2 Cyclists and motorized vehicles appearances in the simulator

The vast majority of cyclists who ride on two-lane rural roads are sport cyclist. Therefore, to increase the reality in the simulator experiment, all cyclists introduced in the simulator were equipped by sport cyclist clothes and helmet. To simulate the reality better, different colours and models were considered for the simulation, for both bicycles and motorized vehicles. In that way, the cyclists and the oncoming vehicles that one participant encounters during the test have different appearance selected at random, as it happens in reality. Fig. 7 shows various examples of overtaking manoeuvres of the vehicle driven in a curve or straight lines section of the scene where the traffic of oncoming vehicles appears at the same time.

In the virtual scenario developed, four types of medium-sized vehicles have been reproduced (5-door sedan, 3-door coupe, sports car and van), with dimensions between 3.8 meters to 4.5 meters in length, widths from 1.72 m to 1.91 m and heights from 1.2 m to 1.82 m. The cyclists modelled occupies a length of 1.52 m, width of 0.52 m and height of 1.52 m, where the only difference between the members of the peloton is the clothing colour they wear.



(a) (b)

Fig. 6 – Cyclists and motorized vehicle appearance reproduced in the driving simulator. (a) overtaking manoeuvre of cyclist peloton in a curve; (b) overtaking manoeuvre of cyclist peloton in a tangent segment.

2.3.2.3 Traffic scenarios simulated

Both bicycle and motorized vehicles traffic data were provided for the simulator in an Excel file, which included the direction of the simulation, the Average Travel Speed (ATS) of motorized vehicles and bicycles, and the initial location of each road user when the test starts.

The simulated traffic scenarios were selected from the field dataset. Regarding the time-space diagrams obtained, the vehicle who overtakes a higher number or cyclists had been chosen as the traffic scenario 1. The traffic scenario 2 was selected from the data obtained in the opposing direction, in that way participants changes the direction of travel and so they are less conditioned to the same travel. The traffic scenario 2 was selected considering a vehicle trajectory which encounters a lower cycle traffic. Then, it is possible to compare the effect on the traffic operation considering one scenario with high cyclist demand and another with a lower one. Finally, a third scenario was designed based on the traffic scenario 1 and doubling the cycle traffic. This scenario was not observed on field but can offer results about how a high cyclist demand affect the safety and traffic operation in a rural road. In these scenarios, a similar volume of oncoming vehicles has been considered, in order to compare the condition generated by varying only the cycling volume.

2.4 Driving simulator

The experimental tool used in this study is the SE2RCO driving simulator, designed and developed by the Institute for Design and Manufacturing (IDF) of the Universitat Politècnica de València (Llopis-Castelló et al., 2016). This tool it is based on a fixed-based simulator which provides the capability for implementation different simulation software, data collection and driving assessment in real time. It is composed by simulation computer, three-screen-display monitors with 120 degrees of field of view (FoW) (1.80x0,34 m and Matrox TripleHead2Go graphics card), steering wheel, pedals, and gear-shift lever and adjustable seat based on a Citroen Saxo. It is capable to acquire longitudinal and lateral speed, location and azimuth with a frequency of 10 Hz. It has been instrumented with load cell (brake pedal force), potentiometers to measure displacement in the three pedals, micro-switch to detect gear-lever position, encoder for measuring steering wheel angle and torque sensor for the steering wheel torques.

3. RESULTS AND DISCUSSION

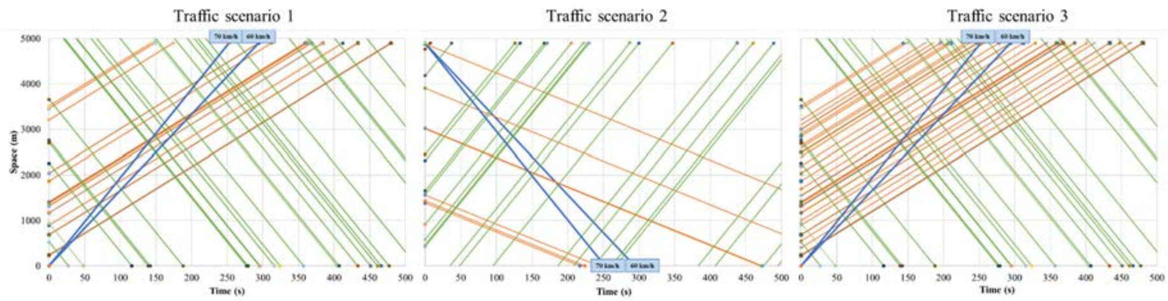
3.1 Field data

The field data collection was carried out on a Saturday morning, since it is when it was expected to see a greater number of groups of cyclists. Table Table 1 shows the main results of the field data collection. According to the results of average travel speeds (ATS) showed in Table 1, the average travel speed of motorized vehicles in both directions for the simulator were considered 70 km/h, while for bicycles a different ATS were stabilized considering the travel direction. Then, for bicycles an ATS of 35 km/h in the direction 1, and of 23 km/h in direction 2 were considered. These average travel speed selected for bicycles in the driving simulator were more realistic than the previous ones considered in other studies which used a driving simulator, since they were obtained from field measurements.

Direction	Initial hour	Duration	Observed bicycles	ATS bicycles (km/h) Mean (SD)	Observed motorized vehicles	ATS motorized vehicles (km/h) Mean (SD)
1	8:20	4:39	287	34.85 (4.72)	777	69.93 (6.78)
2	8:19	4:14	191	22.64 (3.42)	539	68.44 (6.75)

Table 1 – Bicycles and motorized vehicles and their ATS registered during the data collection.

Fig. 7 shows the time-space diagrams for the three traffic scenarios with the trajectories of the bicycles in orange and those of the opposing vehicles in green. The trajectories correspond to straight lines since it was considered that all of them circulated at a constant speed. The trajectories of two hypothetical vehicles that travel the section at constant speed have been represented in blue, one driving at 70 km/h and the other at 60 km/h. It is observed that when a driver travels the section at a higher speed, interactions with more cyclists are produced.



(a) (b) (c)

Fig. 7– Trajectories of bicycles and oncoming vehicles: (a) traffic scenario 1; (b) traffic scenario 2; (c) traffic scenario 3.

3.2 Virtual scenario

According to the scenario design methodology developed by Dols et at. (2021), the total development time of the virtual scenario applied in this study, based on the multi-layer methodology, can be divided into three phases: editing time (obtaining and editing data sources with specific software), programming time (preparation, treatment and adaptation of the data for a specific simulator) and processing time (processing time to generate native files adapted to a specific simulator). Considering that the virtual scenario has been designed for a 4.86 km segment of the road, and according to the hour/km ratios necessary for the implementation of the virtual scenario, the development times results used in each of these three phases have been quantified as follows:

Editing time: 35 hours	Editing time ratio, Rte: 7.2 hours/km
Programming time: 84 hours	Programming time ratio, Rtp: 17.28 hours/km
Processing time: 0.16 hours	Processing time ratio, Rts: 0.034 hours/km

Therefore, the total estimated ratio of development time used in this study is about RT = 24.5 hours/km. This development time can be considered as moderate (between 20 to 35 hours km), compared to other methods of developing scenarios with manual editing, which are usually classified as very high (more than 50 hours / km). The values of the development times of virtual scenarios obtained in this study are consistent with those defined by Dols et al. (2021) in the analysis of virtual scenario development methodologies for the development of road safety audits through the use of driving simulators.

One of the advantages of using this multi-layer scenario design methodology is the fact that it presents the possibility of introducing very rapid changes in the traffic simulation model used. For example, in this work bicycles are moving at a constant speed in each scenario, but if needed, it is possible to modify the behavior model of each independent cyclist, or a peloton as a whole, modifying the specific Excel file with the data required, allowing the analysis to be adapted to more unfavorable or dangerous situations.

In the development of the traffic scenario, the bicycle and vehicle paths have been simulated according to a previously established behavior model. However, the versatility of the method used also allows the introduction of behavior models with variable trajectories for each of the mobile objects on the scene, with only modify the data layer that determines the trajectory of cyclists and vehicles.

One of the limitations of the present study has been the analysis of the physical contacts between vehicles and cyclists. In our work, the modeling of the physics between objects has been carried out without the purpose of studying the effect of the collision between vehicles and cyclists, nor the consequences of the same, since the final objective has been based on determining the behavior of the driver before the appearance of groups of cyclists who have to be overtaken considering oncoming traffic. This current limitation may be the source of future work in which a vehicle-cyclist contact model should be introduced to determine the trajectories and consequences of the collision of cyclists and vehicles circulating on the road. In that case, a contact physics modeling would have to be developed in one of the data layers that allow the generation of the entire virtual scenario.

4. CONCLUSIONS

In this paper the development of a driving simulator integrating cyclists is performed. To recreate the road physical virtual scenario and ensure that it is similar to the real road, naturalistic data was collected by realizing naturalistic observations in the extremes of a two-lane rural road segment. From these recordings, traffic scenarios were obtained, both for motorized vehicles and for bicycles.

Based on field data, both of the road geometry and surroundings and of the traffic, it is possible to recreate the real phenomenon observed on field. Therefore, it is possible to validate the driving simulator results and compared them to field data. Finally, by using the driving simulator it is possible to obtain some results which are difficult to obtain through other methodologies, enabling a better analysis of the phenomenon.

On further research will be possible to analyse the effect of some changes in the safety and traffic operation. These variations can be realized on the geometry of the rural road, as incorporating turnouts, varying the lane or shoulder widths and colours, or varying the speed limit of the road. It is also possible to analyse the effect of variations in the traffic demand.

Future works applying this methodology would allow the analysis of the road safety from both existing roads and others that are in the design phase, by introducing models of traffic behavior of cyclists and vehicles, according to certain cross section configuration or construction, e.g. the introduction of roundabouts, variable widths, slopes, etc.

AKNOWLEDGEMENTS

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ASSESSING SIM RACING SOFTWARE FOR LOW-COST DRIVING SIMULATOR TO ROAD GEOMETRIC RESEARCH

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ABSTRACT

In last years, driving simulators have had an increasing use in researching highway geometric design. However, research simulators have high costs. A possible solution to avoid these costs is using videogame simulators. Videogame racing simulators have achieved high quality with a moderate cost. Some of these games include very detailed models that describe very accurately the performance of the simulated vehicles. In addition, they provide very realistic images of the car, the highway and their surroundings.

With the aim of using them as research tools, several of the most popular games have been analysed. Two of them have been selected: rFactor2 and Assetto Corsa. Also, a 3D model of a section of an actual highway has been made and adapted to be used by the aforementioned games. Some tests have been conducted using a custom computer system, and the modelled highway section, with both game simulators. From these tests results, both sim racing software can be used to build a low cost driving simulator useful for road geometric design research.

1. INTRODUCTION

Driving simulators are designed to reproduce situations that occur in actual vehicle driving. Numerous studies establish the usefulness of driving simulators in research on road geometric design, traffic studies, and driver training.

Driving simulation research has a series of advantages compared to research based on actual driving. One of the most important advantages is the capability to create virtual environments with fully controllable parameters that would be challenging and expensive in actual driving (Olstam et al. 2008).

Another advantage of simulators is the relative ease of collecting data about driving parameters. In addition to the speed and acceleration values, which are not difficult to measure in actual driving, there are other parameters such as the position of the vehicle within the lane, the stopping distance from a stop line, or the fixation point of the driver's gaze, which are relatively easy to measure in a simulator and more difficult to measure in actual driving tests (De Winter *et al.*, 2012).

Driving simulators can be classified according to the type of vehicle they simulate: passenger cars, trucks, motorcycles, machinery and others. A distinction must also be made between simulators intended to be driven by one person or those intended to simulate autonomous vehicles. This paper talks about driving simulators for passenger cars driven by a person, which will be called driving simulators.

The use of driving simulators for research dates back to the second half of the last century (Fox, 1960). Currently, driving simulators use computerized systems. Their use has increased in recent years, favoured by the increase in computers' power and the improvement in the quality of image display systems.

Despite this development, the price of a driving simulation system for research on road geometric design is still too high for many research departments at universities. In the low range, a primary research simulator can cost between 30000 and 100000 euros. The most advanced models have complete systems for reproducing accelerations and require a hangar for their installation. Their cost can reach several million euros (BMW Group, 2020).

Allen *et al.* (1995) studied the characteristics that a simulation system based on a personal computer should have to serve as a low-cost simulator for research. The composition of a simulation system remains the same as when Allen *et al.* analyzed it.

However, some of the necessary components have improved performance and availability. A simulator requires various hardware and software components. Also, it is necessary to establish the characteristics of the simulated vehicle and the information necessary to reproduce the scenario in which the simulation takes place.

The simulator hardware includes the reproduction of the driving cabin, the reproduction systems of the images, sounds and accelerations, and the computers that control the entire system. The cockpit is where the driver sits and includes the controls to operate the simulated vehicle. The most basic controls are those to change the direction and speed of the vehicle.

The computer keyboard can be used for these functions in the most straightforward simulators, although today, it is common to have a steering wheel and pedals for the accelerator, brake, and clutch.

The cabin can include other additional controls, such as the gear lever or the handbrake, for example. Automakers sometimes use simulators to test the ease of use of new controls. Most complex simulators reproduce the interior of the vehicle completely. According to Mecheri *et al*. (2017), the absence of a cockpit in the simulator causes drivers to underestimate the vehicle's distance to the right edge of the road. In curves to the right, drivers move further from the centre of the road. This is not the case when turning to the left.

Leaving aside the possible influence that non-driving factors may have on driving, such as the driver's state of mind, the drivers take their actions based on the perceptions they receive through their senses. Of these senses, the one with the most influence is sight, although hearing and the perception of accelerations are also important.

According to Sivak (1996), most of the information used by drivers is visual. In a driving simulator, the image reproduction system consists of one or more screens that reproduce images with a certain cadence measured in frames per second (fps). The images span a certain width of the field of view (FOV). The FOV presented to the users of the simulator greatly influences their driving performance (Shahar *et al.*, 2010). There may be some additional screen to simulate what the driver would see through the rearview mirrors, for the instrument panels' presentation, to control the simulator software or to display the telemetry parameters. In some cases, virtual reality glasses are used instead of screens.

Some authors have pointed out that virtual reality glasses do not provide significant advantages and, on the other hand, increase dizziness problems in simulator users (Kemeny and Panerai, 2003; De Winter *et al.*, 2007, 2009)

One or more speakers reproduce the sounds that the driver heard while driving. The sounds include the engine's noise, the friction of the wheels with the road, the sound produced by other vehicles, the wind, or others.

In most elemental systems, there is no mechanism available to reproduce accelerations. Current models of steering wheels usually include vibration systems, called force feedback, which reproduce the sensations that the driver perceives through the steering wheel while driving, due to impacts with irregularities in the road, due to collisions, wheel slippage or other reasons. More complete systems may include actuators that move the seat in rhythm with the vehicle's supposed movement.

The simulator software runs on one or more computers. It controls all the hardware. The software is in charge of managing the vehicle's controls, performing the calculations related to the physical dynamics of the movement, generating the images and sounds, and maintaining the general operation of the system.

The simulation uses a virtual scenario containing all the information related to the road, its surroundings, the weather, and the traffic of other vehicles and pedestrians. This virtual scenario, together with the physical parameters that define all the scenario elements, constitutes the simulation's data.

One of the factors that most affect the economic cost and consumption of the simulator's resources is the reproduction's fidelity. Trying to replicate the world in all its details is impossible and inefficient.

Furthermore, it is unnecessary to achieve the research objectives. Modelling involves abstraction. The model must extract the aspects of the world that are important so that the tests' results have the required validity. Some authors claim that it is essential that the operation of the vehicle, the visual representation and the behaviour of the objects in the environment are as realistic as possible (Olstam *et al.*, 2008; Allen *et al.*, 2010). Other authors think that greater fidelity does not always positively affect the result. It depends on the objectives that the simulation wants to achieve (De Winter *et al.*, 2009; Tichon and Wallis, 2010)

The video game industry has become one of the leading entertainment industries. The expression 'sim racing' refers to virtual motor racing competitions based on driving simulation games. This expression highlights the difference with the arcade type driving games, which leave aside the driving simulation aspects a bit to delve into other different objectives. There are two hardware platforms for this software: consoles and personal computers (PC). Consoles offer the advantage of immediacy; it is only necessary to turn on the console and start playing. Computers need more preparations, but they also offer the most significant possibilities in terms of customization and modification of games to adapt them to research objectives. Some of the sim racing games simulate circuit car racing, such as Assetto Corsa, rFactor 2, iRacing, Automobilista, Project Cars 2 and F1 2020. Others simulate rallies, such as Dirt Rally, Collin McRae Rally or Richard Burns Rally. There are also others geared towards truck driving, such as Euro Truck Simulator. Currently, almost all have versions available for consoles and PC. They also usually include the ability to compete with other players over the Internet.

Sim racing has undergone significant development in recent years, leading to championships in which professional motorsports drivers participate. Often such tournaments are even televised and lead to significant cash flows from prizes and advertising. This has led large car manufacturers to develop content for such events, providing realistic models of their vehicles, for example. Currently, the main simulation games reproduce the racing circuits with maximum fidelity, using models extracted using LIDAR techniques that reproduce even the most minor details of the track or its surroundings. All this has resulted in some of the existing games reaching very high standards for the quality of the graphics and the fidelity of the reproduction of the physics of the vehicle movement. The widespread use of sim racing video games has led some researchers to question whether their use by young people may have an influence on how they drive actual vehicles in the future (Ruscio, 2018).

Parallel to the development of the sim racing games industry, an industry of hardware components for such games has been developed, including all the components necessary to reproduce the vehicle's cockpit: seats, steering wheels, pedals, gear stick, motion platforms and others. This development has led to lower prices for these components.

There have been experiences in using Sim Racing games for research. Weinberg and Harsham (2009) built a driving simulator using commercial components for the video game industry to reproduce the cockpit. The simulator seat was equipped with a motion platform that allowed to reproduce the vibrations and inclinations experienced during driving due to potholes, acceleration, braking and others. As software for the simulation they used rFactor software (Studio 397 and Image Space Incorporated, 2005). For the creation of the scenarios they used the program Bob's Track Buider (Pywell, 2007). To obtain the telemetry they used plugins from the rFactor game as well as plugins developed by themselves. The result was a simulator that they claim was comparable to a mid-range research simulator and at significantly lower cost. Tiu et al. (2020) analyzed the possibility of using a sim racing game to analyze the driving ability of people who had suffered a stroke. The authors of the study point out several advantages in using sim racing games compared to research simulators: they have a considerably lower cost, provide a wide range of telemetry values and offer greater realism of the images and the operation of the vehicle. One of the drawbacks noted in the study is the difficulty in reproducing real traffic situations with more than one vehicle.

Using a simulator based on a sim racing game for research has advantages and disadvantages compared to using a simulator specifically designed for research. About the cost of the hardware (computers) and the vehicle cockpit, all things being equal, the cost is the same.

However, the cost of simulation software, as already mentioned, is much higher in research simulators. While a simulation software for research can cost between 30000 and 100000 euros, the software cost to create a simulator based on a sim racing game, including all the additional software necessary for creating scenarios and the management of the telemetry, rounds the 100 euros. Another advantage of sim racing games is the realism of the vehicle physics. In general, the realism achieved in the physics of vehicle operation in the latest versions of sim racing programs is superior to that of commercial research simulators (excluding the specific simulators available to large car manufacturers). The quality of the graphics and the scenarios realism is also generally superior to that of the research simulators. However, research simulators have specific tools that make it easy to incorporate the road geometry. In sim racing games, it is necessary developing specific tools or use more artisanal procedures. The simulation of the traffic of other vehicles and pedestrians is possible and relatively easy to incorporate in the research simulators. In sim racing games, it is not possible, or it is not easy.

In general, simulation software has two critical components in simulation: the graphics engine and the physics engine. The physics engine manages the controls inputs, performs the necessary calculations, updates the vehicle and other objects positions and passes the information to the graphics engine, which is responsible for generating the images that appear on the screens. Both the graphics engine and the physics engine use 3D scene data and vehicle data.

The creation of the 3D model of the scenario in which the simulation is to take place is the most time-consuming task in the tests carried out with a driving simulator (Dols *et al.*, 2016; Dols *et al.*, 2021). The possible components of this scenario are:

- Road:
    1. Geometry: Alignment, profile and cross-section
    2. Pavement: physical and visual characteristics of the road pavement
    3. Traffic sign and road marking
    4. Infrastructure associated with the road: guard-rails, lighting columns and other elements
- Environment:
    1. Area of the terrain that is visible while driving
    2. Constructions, vegetation and other elements whose presence may affect driving
- Traffic: other vehicles, pedestrians or animals that may affect the behaviour of drivers
- Weather: wind, rain, snow, fog or other weather effects
- Sound effects

Depending on the type of experiment and the level of fidelity desired, each element needs greater or lesser detail. The simulation software also needs to know the vehicle characteristics in the simulation to reproduce its behaviour.

2. MATERIALS AND METHODS

The start-up of the simulator consists of the acquisition, assembly and configuration of the hardware and software. Then, for each test, the 3D model of the road and its environment must be created in the appropriate data format for use in the selected simulation software.

With this, it is now possible to test by conducting road trips with different drivers while recording telemetry data. Finally, the data from the routes telemetry is analyzed to conclude the research. Below is the description of these phases as they have been carried out in this research work.

2.1 Hardware

The hardware used during this research has been the following:

- Computer: HP Prpdesk, Intel i7, 64 bits, 3.4 GHz, 8 Gb RAM
- Graphic card: NVIDIA GeForce GT 730 2 Gb RAM

- Screen: HP 2009V
- Steering wheel: Thrustmaster T300 RS – GT Edition
- Pedals: 3 metal pedals (accelerator, brake and clutch)

As gearshift stick, the steering wheel's paddles were used, one of them to upshift and the other to downshift.

2.2 Software selection

The first part of this research work consisted of selecting the sim racing games to assess their suitability for use as support software for a driving simulator applicable to the research. For this, the main sim racing programs has been explored and analyzed their fundamental characteristic. A survey was conducted among regular users of sim racing games to obtain additional information about the reviewed games. The survey asks about the graphics quality, the realism of the physics of the vehicle movement and some other questions. The survey obtained 54 valid responses. Figure 1 shows a graph with the results of the survey.

The horizontal axis indicates the quality of the graphics for each game, and the vertical axis indicates the realism of the vehicle dynamic. The program that got the best rating from users for its physics was Richard Burns (RB) Rally. Top rated for graphics quality were Assetto Corsa and Assetto Corsa Competizione. They both score very highly when it comes to physics.

Not all games allow for incorporating actual roads or for using ordinary tourist vehicles. Programs that do not allow such modifications are not helpful for the type of research intended. It is also needed to extract the telemetry of the tests to analyze speeds, trajectories, and other data.

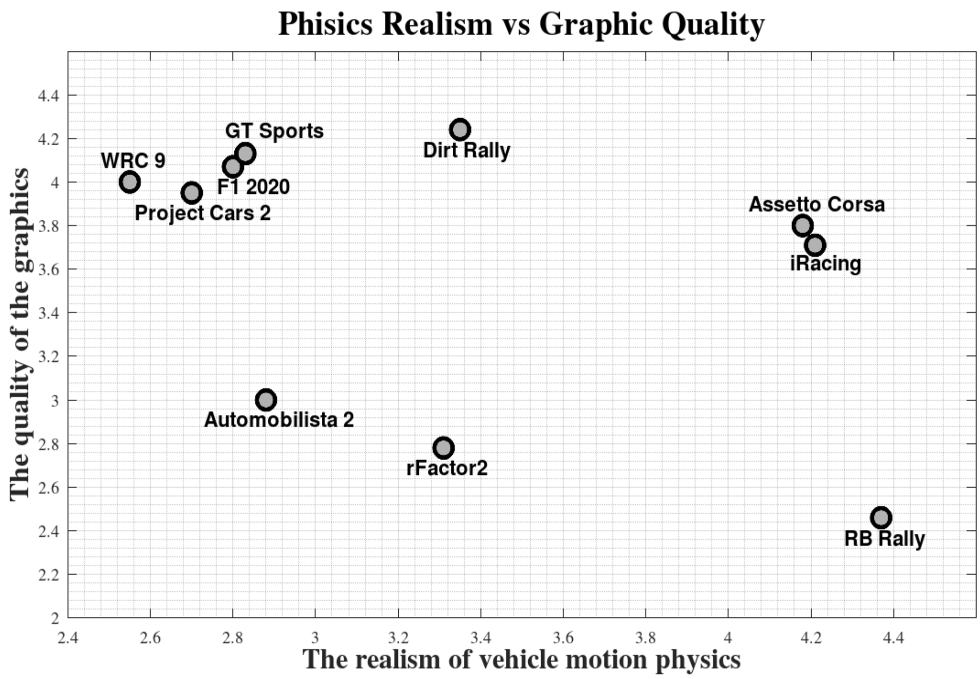

Figure 1 – Summary of survey results about sim racing games: image quality vs physics

Among the sim racing games analyzed, only three meet the conditions to incorporate actual roads, use passenger cars, and allow extracting and analyzing the telemetry: Assetto Corsa, RB Rally and rFactor2. All three have high-quality graphics and very realistic physics. RB Rally is no longer in development, so the decision was to use Assetto Corsa and rFactor2 for research tests (Studio 397 and Image Space Incorporated, 2012; Kunos Simulazioni, 2013).

Sim racing games come with presets adapted to sporty driving. For use in road research, it is convenient to adjust some parameters to increase the realism of driving of a passenger car. One of them is the turning of the steering wheel. In racing cars, a particular turn of the steering wheel produces a more significant turn of the wheels than in passenger cars.

Another parameter that is important to adjust is the driver point of view. The two games selected allow to set the position of the driver seat. The width of the FOV is also essential; an improper setting produces an unrealistic driving feel.

2.3 3D model development

For each road to test, developing a 3D model in the appropriate data format for the chosen simulation software is necessary. 3D modelling software is an adequate tool to create these models. 3DS Max and Blender are examples of this type of software. Modelling software can export their models to the FBX format, but each sim racing game uses its specific format for the 3D model. Some software is needed to convert the 3D model (in FBX format) to the specific format of the sim racing game.

When generating the FBX files, 3D objects and materials need specific parameters to define their characteristics so that later the physics and graphics can be interpreted appropriately by the sim racing game. Each of the games has a different way of defining these parameters.

Hence, it was necessary to develop two different models: one for Assetto Corsa and the other for rFactor2. The Assetto Corsa scenarios use the .kn5 format, which can be obtained from the corresponding FBX file using the KS Editor software (made by Assetto Corsa developers). This format includes the materials and the images of the textures used to display them. However, the rFactor2 scenarios use GMT format files for the geometry of the 3D meshes and the files. It stores the texture images in separate files.

Each of the programs has a set of files where the physics of the materials is defined. Figure 2 shows the workflow used from creating the 3D model for the two sim racing games.

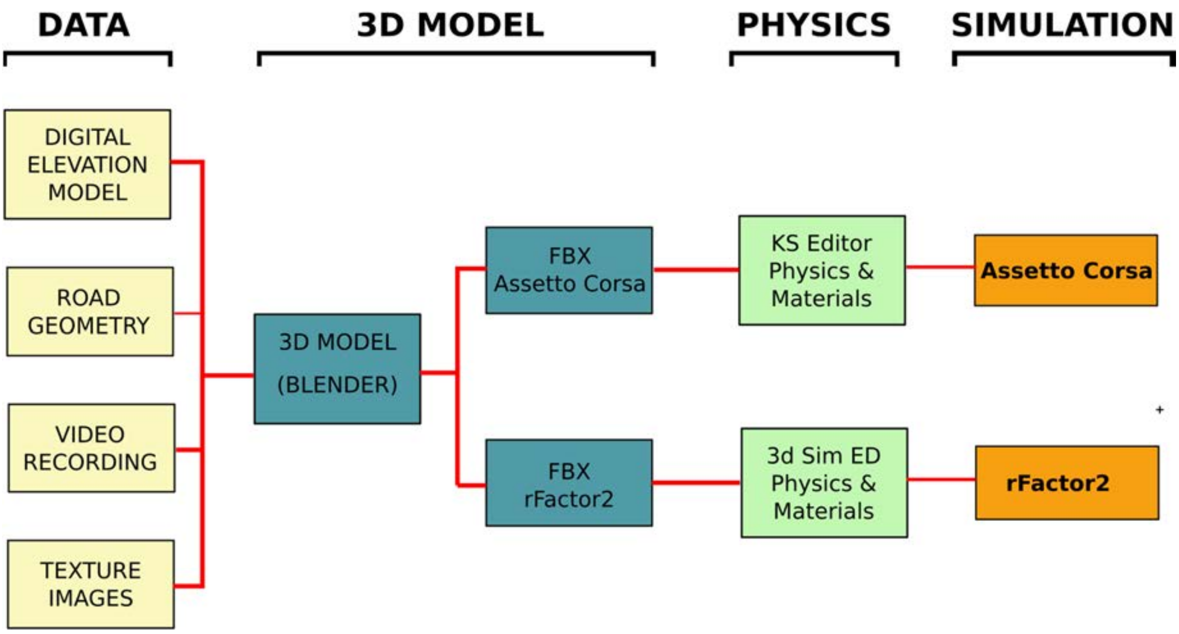

Figure 2 – Workflow for creating simulations using the sim racing games rFactor2 and Assetto Corsa.

This research work studied a 6 km long section of the two-lane rural highway M-607, located between Colmenar Viejo and Cerceda (Madrid). The section chosen is located between stations 36 and 42. The lane width is 3.5 m and the shoulder width is 2.5 m.

Digital elevation model (DEM) from the Spanish *Instituto Geográfico Nacional* (CNIG) was used in GIS format. A 12x3 km rectangle was used, which included the road area. The road centre line geometry was obtained from the definition of its alignments. Using GIS tools and scripts developed for this study, a file was generated with the X, Y, Z coordinates of the centre line points every 10 meters.

For 3D modelling, the Blender v2.91 software with the GIS plugin was used (Blender Foundation 2021, Lyszczarz, 2012). A script developed in Python by the authors was used, allowing reading an XYZ coordinate file and converting it into a 3D Blender curve to incorporate the road centre line in Blender (Higuera de Frutos, 2021). In order to achieve a more realistic 3D model (road markings, traffic signs, etc.) data recorded in the actual highway through RoadRecorder software was used (Higuera de Frutos, 2017). Images with free licenses were used for materials textures (roadway asphalt, shoulders, terrain, vegetation, guard-rails and traffic sign). The final model had 136,156 vertices, 249,947 edges, 118,796 tiles, and 197,039 triangles.

Figure 3 shows two details of the edition of the model with Blender software. The image on the left shows a general view of the scenario: the road mesh and the digital elevation model mesh with the mountains in the background. The image on the right shows a detail of a part of the model.

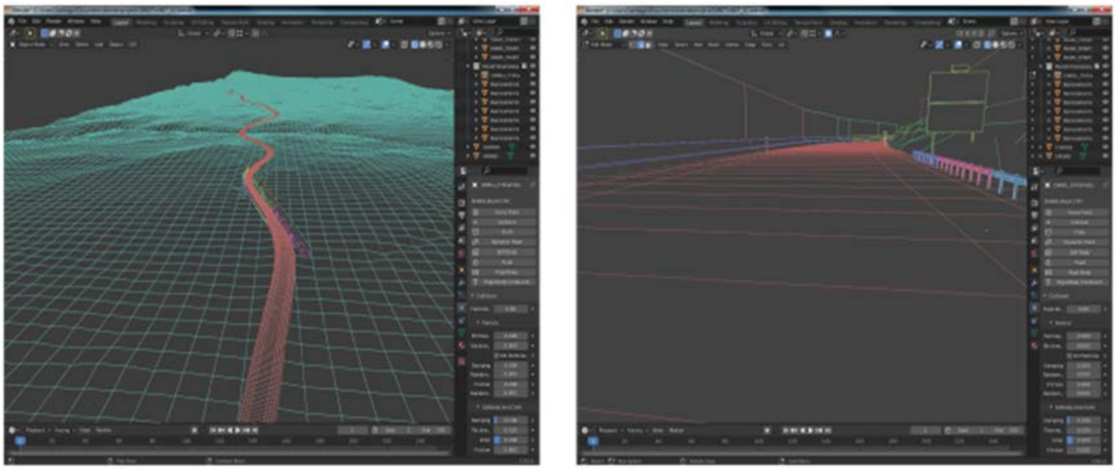

Figure 3 – Edition in Blender. The left image shows DEM and road meshes with mountains on the horizon. The right image shows the mesh detail in some area of the model

2.4 Materials and physics

The 3D model must follow certain conventions regarding the geometries and names of objects and materials. Together with specific parameters defined in the scenarios configuration files, these conventions allow the game engines to correctly interpret the way of visualizing the materials and interpreting the physics. Also, specific objects, called *spawn objects* by Assetto Corsa and *timing objects* by rFactor2, allow games to interpret the position where the simulation begins, the direction of the routes, and what telemetry sections record, among other functions. Each game has its objects and its way of interpreting them.

The lighting characteristics, the properties of the objects materials, and the shaders parameters determine the visual aspect. Each game has its shaders and its collection of parameters to define. Each object, for example, the road surface, uses several superimposed images (several image channels), which, when processed by the shaders, generate the final appearance. It is a complicated process that requires specific knowledge of computer image processing.

Some configuration files define the properties of the objects and their physical behaviour.

The primary interaction is between the vehicle tires and the roadway surface. The gravity force also affects all objects. It is also needed to define if the objects can collide or move in case of impacts. The game engine will interpret the driver actions on the controls and resolve collisions, friction or acceleration of the vehicle.

2.5 Telemetry

The physical parameters of the simulation can be monitored using data acquisition plugins and stored in telemetry files.

The most widely used telemetric data analysis program is Motec (MoTeC Pty Ltd, 2001), a professional system well known in all kinds of actual motorsport competitions. Assetto Corsa and rFactor2 can also use Motec. Each game allows installing a specific plugin to generate data logs that the Motec program can then interpret.

The telemetry files generated offer about one hundred parameters measured while driving every few milliseconds. The parameters include the instantaneous values of position, speeds, accelerations, vehicle inclination angles, engine operation values, parameters about the tires, temperatures, and many more. Also, Motec offers the possibility of generating formulas that, from the existing parameters, allow generating values not contemplated by default.

An interesting feature is generating the track followed by the vehicle from the lateral acceleration values. This option helps analyze the trajectory followed or generate the drawing of the road when the GPS position is not available.

For this study, Motec software was used in order to analyze vehicle telemetry of every test.

3. RESULTS AND DISCUSSION

Creating scenarios was laborious and required knowledge about 3D modelling and image processing, but the results were satisfactory. The generated scenarios can be used, with minor modifications, in either of the two simulators (Assetto Corsa and rFactor2). The imaging of the two simulators was very sophisticated, with highly realistic images. The process of creating scenarios and starting the simulations required a similar workload for both programs. Figure 4 shows the comparison between road actual video frame, the image generated by Blender, and the equivalent frames while driving in each of the simulators.

To carry out the driving tests in the modelled section, five drivers aged between 50 and 60 years collaborate. All drivers had more than 20 years of actual vehicle driving experience.

Each of them did two test runs with each of the simulators on the M-607 road scene. Next, each driver made two tours in each simulator, and the system recorded the corresponding telemetries. Drivers did not found significant differences between the physics of vehicle operation. The driving sensations were realistic with both software.

Figure 4 – Top left: a video recording of the actual road. Top right: image generated by Blender. Bottom left: image from Assetto Corsa. Bottom right: image from rFactor2

Figure 5 shows an example of a report generated by Motec comparing the speed during the same driver trip, once using the rFactor2 simulator and the other time using the Assetto Corsa simulator. The upper part of the graph corresponds to the comparison of the speeds along the route. The black line represents the speeds during the ride with rFactor, and the blue line during the ride with Assetto Corsa. The vehicle speed values are similar. The lower part of the graph corresponds to the road track generated from the geographic coordinate data obtained by rFactor2.

4. CONCLUSIONS

The objective of this study was to analyze the possibility of using sim racing games as driving simulators in research work on road geometry. A comparison has been made between the two existing games that, in the authors' opinion, offer the best features for this purpose: rFactor2 and Assetto Corsa.

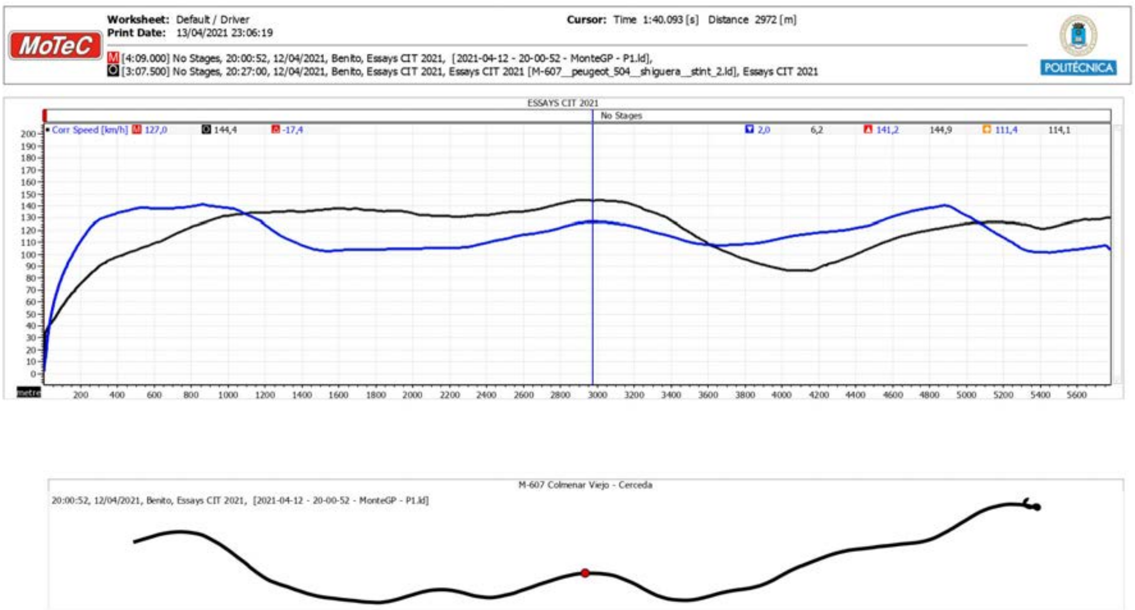

Figure 5 – Motec telemetry report. Comparison between the speed of the same driver in two different simulators ((Assetto Corsa and rFactor2). Up: speed (km/h). Down: road alignment (m)

The use of 3D design software (Blender), GIS information and road geometry to create the 3D scenarios was a time consuming task, but provided results with realistic images. During the driving tests, the drivers found no significant differences between the physics of the vehicles in the two games. Both software offered realistic driving sensations. The telemetries obtained (positions and speeds) had enough information for future research studies on vehicle speeds and road geometry. In next research works, the number of studied roads and the number of drivers will be increased.

In conclusion, both tested software can be used for building a low-cost driving simulator for road geometric research.

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PREDICTION OF CONTAINER FILLING FOR THE SELECTIVE WASTE COLLECTION IN ALGECIRAS (SPAIN)

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ABSTRACT

The aim of this study is to create an intelligent system that improves the efficiency of garbage collection, (cardboard waste, in this particular case). The number of cardboard containers to be collected each day will be determined based on a prediction made on the filled volume recorded in each container. It will be reflected in the cost and fuel savings, reducing emissions and contributing to environmental sustainability. These results will allow planning the sequence of waste removal, which means the optimal collection route considering restrictive parameters such as the type of truck, the location of containers, collection times by zones, and the availability of working staff.

A filling prediction system is proposed based on real historical data provided by the current waste collection company in Algeciras (ARCGISA). To achieve this objective, an intelligent system is designed using predictive analytics and several methods based on machine learning, modelling the collection system as a classification model, comparing the results from a statistical point of view (using sensitivity, specificity, etc.). The results obtained with the best-tested method indicate an improvement average rate of 26% in sensitivity performance index and 67% in specificity performance index.

Currently, waste collection is carried out without predictive analysis. The relevance of an efficient waste collection system is becoming increasingly important. Achieving optimal waste collection will result in improved service to citizens, cost savings for the administration, and significant environmental improvements.

1. INTRODUCTION

This project aims to create a 'smart' system that improves the efficiency of waste collection, in this case, cardboard. This system solves two major problems faced by waste collection companies. On the one hand, to determine which containers should be collected each day according to their filling volume and, on the other hand, to obtain the collection order, i.e. to know which is the optimal route for the collection of the containers. This will save costs and fuel, thereby reducing emissions and contributing to environmental sustainability.

A filling prediction system is proposed based on real data, provided by the company ARCGISA (Agua y Residuos del Campo de Gibraltar, S.A.), from which the optimum collection time will be estimated based on an ideal filling level and the optimum route for collecting the containers will be obtained. A significant reduction in management time, economic savings and an improvement in the quality of the service provided to citizens are expected, increasing urban sustainability. In summary, a dynamic system of container filling predictions is proposed to estimate the optimal filling time and calculate the most favourable route for collection. To achieve these objectives, the project aims to design an intelligent system using predictive analytics and machine learning to improve the planning and efficiency of selective waste collection, based on the use of neural networks.

Each person generates a large amount of waste every day. The life cycle of waste harms the environment. Efficient waste management has become a necessity to preserve available natural resources. For this reason, the objective is to achieve urban sustainability and guarantee the quality of life of citizens. Furthermore, waste treatment offers a business opportunity, since the recycling of products such as cardboard allows them to be reused for the production of new products. The management of this waste for further treatment is a chain that involves the collection, transport, processing, recycling and monitoring of new products.

Increasingly, organisations and companies assume that environmental improvements in their production systems and services are competitive advantages, either by reducing economic costs or by improving the image of the product in the eyes of better informed and aware consumers. To reduce waste generation and improve sustainability, tools and mechanisms such as life cycle analysis (LCA) and eco-design are used.

LCA is a methodology used to assess the potential impact on the environment of a product, process or activity throughout all its stages of existence (extraction of raw materials, production, distribution, use, end of life). At each stage, the energy and resource inputs and potential outputs in the form of emissions, discharges and wastes associated with the system under assessment are quantified.

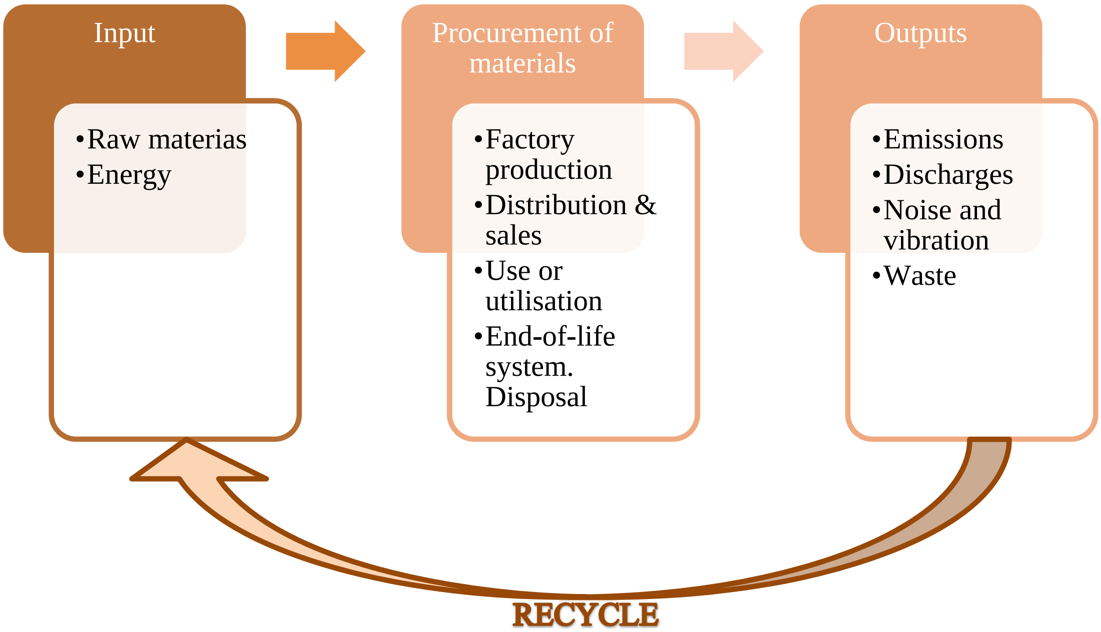

Fig. 1 - The life cycle of a product.

In Spain, around 1.5 million tonnes of domestic plastic, brick, metal and paper/cardboard packaging were recycled in 2019. This figure comes from two main sources of rigorous control to ensure the rigour of the information on waste management; the sources are the municipalities responsible for the selective collection of packaging and the recycling plants responsible for transforming this waste into new raw material. Table 1 shows the recycled packaging waste (in tonnes) by material and area of management (municipal or private) in 2019. The amounts considered have been certified by the local authorities based on the agreements signed by Ecoembes (is a non-profit organization in Spain devoted to sustainable development and recycling).

Quantities recycled (tonnes)	Conventions and Agreements with Public Administrations	Authorised private managers	Total
Plastics	527.949,1	88.786,6	616.735,8
Paper & cardboard	577.319,0	54.364,8	631.683,8
Metals	219.368,2	30.052,0	249.420,1
Wood	0,0	7.821,5	7.821,5
Total	1.324.636,3	181.024,9	1.505.661,2

Table 1 - Amounts recycled in Spain 2019 (source: MITECORD)

Regarding a regional level, Andalusia has 19 light packaging sorting plants and 1,552 Andalusian companies that make the recycling system possible. There are 83,465 yellow and blue containers on public roads, which is 2,046 more than in 2018. In the last five years, the use of the blue bin has increased by an average of 22%. Each citizen deposited 7.5% more paper and cardboard packaging in 2019 compared to the previous year, i.e. each Andalusian citizen deposited 13.2 kg of paper and cardboard per year.

The idea is to predict each container separately, which is more difficult due to the specific characteristics of the state of each container, i.e. its location, the population density of the area in which it is located, the habits of the citizens, etc. And that this prediction serves to subsequently generate optimal collection routes. There are studies to predict waste quantities using time series techniques to predict the quantities of waste generated by an entire city, e.g. Xiamen in China (Xu et al., 2013).

To generate the optimal routing of vehicles, there is still little work directly related to the waste collection problem. There is a study conducted in Portugal, in which collection routes are planned for all days of the month, which are repeated every month and thus minimise the cost of operation. (Teixeira et al.,2004), but it focuses on the routes generated, not on the amount of waste in each container. The objective is to minimise the total distance travelled in the period, which is the sum of the distances travelled by all vehicles on each day.

There is a growing body of literature on the prognosis of the municipal solid waste (MSW) generation. For decades, studies have been conducted using different models, which generally fall into four categories: regression-based models (Daskalopoulos et al., 1998, Sokka et al., 2007, Benitez et al., 2008, Rimaityte et al..., 2012), system dynamics models (Dyson and Chang, 2005, Kollikkathara et al., 2010), computational intelligence models (Jalili and Noori, 2008, Noori et al., 2009, Wang et al., 2010), and time series based models (Chen and Chang, 2000, Navarro-Esbri et al., 2002, Li et al., 2003, Liu and Yu, 2007). Computational intelligence models, such as support vector machines and artificial neural networks, are commonly used due to their high flexibility and non-linear prediction capability. However, these three types of models often use demographic and socio-economic factors that are difficult to identify and quantify (Chen and Chang, 2000; Dyson and Chang, 2005). Time series forecasting models generate future information on MSW generation on a time scale using only historical MSW information.

The authors of this study have previous experience in the use of Artificial Neural Networks (ANNs) in predictive modelling related to transportation engineering and logistics. It is worth highlighting the studies carried out to predict the number of correct inspections at border inspection posts (BIPs). This problem can lead to congestion and bottlenecks within these critical facilities in port or airport systems and can lead to higher costs and delays in the supply chain.

Forecasting of the inspection volume or over freight cargo or maritime traffic can be useful tools to improve the quality of service, operations planning and human resources in ports.

This is also the case of this work where the prediction is about container fill rates and can be useful in the quality of waste collection system (Moscoso-López, J.A et al, 2016; 2020; Ruiz-Aguilar, J.J et al, 2014; 2019; 2020).

Achieving an optimal waste collection will mean an improvement in the service to the citizen, a saving in economic costs for the administration and a significant environmental improvement. The aim is therefore to avoid unnecessary trips to nearly empty containers, as the emissions of pollutants generated by extra trips could harm the environment rather than contribute positively to waste collection.

2. DATA DESCRIPTION

Selective waste management is carried out by the company Aguas y Residuos del Campo de Gibraltar (ARCGISA). It is a public service company owned by the Mancomunidad del Campo de Gibraltar. ARCGISA, as the main company in the agreement for the collection of cardboard, has a limited number of resources to carry out the waste collection. The planning of the current collection system has a wide margin for improvement, as several factors influence in the process, such as the timetables of the staff, the type of vehicle, the type of streets, the situations in the city, the collection timetables, the capacity of the containers themselves, their location, etc. Of the entire collection process, the most important and costly phase of the cycle is the collection procedure, accounting about 70% of the cost associated with waste treatment. This involves the work of many people and vehicles. This project focuses on improving the planning and management of the selective collection of cardboard in the Campo de Gibraltar area.

Campo de Gibraltar consist of seven municipalities, which form one of the three metropolitan areas in the province of Cadiz. In the metropolitan area of the Bay of Algeciras, we find the first industrial pole of Andalusia and the second in Spain and the main port of the national port system in terms of total traffic 5.125.385 TEUS/year . This places the scope of the project at a population of 270,000 inhabitants (INE 2019) and an industrial, commercial and port area of the first national order. It should be noted that Algeciras is the largest municipality in the study area, and is integrated into the National Smart Cities Plan.

In Algeciras, waste collection is currently carried out without predictive analysis. Collection routes are often left to truck drivers. With the growth of cities, the importance of having an efficient waste collection system is increasing. An intelligent waste collection system is therefore proposed to solve the problems faced by the collection services. It will determine which containers need to be collected each day and what is the optimal route for each truck.

The pattern of generation of this waste is fluctuating and does not follow a constant seasonal pattern. This fact makes it difficult to plan the collection, and as mentioned above, it is the operators themselves who manually monitor the filling percentage of the container being collected to estimate when the next collection will take place. This data has to be manually typed in the office, which involves many hours of dedicated staff time. Figure 2 shows the actual annual volume of each container. This is the reason why this project proposes an intelligent system for predicting fill levels based on historical collection data, using predictive analytics and machine learning techniques to estimate which containers are in the optimal range for collection.

3. METHODS

In this work, the objective is to obtain a multiple regression model f:Rn→R for the desired output parameter (the cardboard container volume as a function of the lagged time-series data) using Artificial Neural Networks (ANNs).

3.1 Neural Networks

A Multiple Linear Regression (MLR) model may not be the best fit available. In such cases, a nonlinear regression method like artificial neural networks (ANNs) may provide a better analysis. The most widely used ANN model is the feedforward neural network, based on backpropagation learning procedure (Rumelhart et al., 1986). It models the relationship between X and Y in the form of the equation 1.

$$Y = g\left(\sum_{j=0}^{M} w_{kj} \cdot f\left(\sum_{i=0}^{D} w_{ij} \cdot X_i\right)\right) \tag{1}$$

where *g(x)=x* and *f(x)=tanh(x)*, are proved to be universal approximators (Horni et al, 1988), given the sufficient number of hidden units (M value in the formula). Such networks can, therefore, approximate arbitrarily well any general function, which makes them highly interesting for modelling purposes.

3.2 Experimental Procedure

Thus, the overall system can be viewed as a mapping from a set of input features, to an output variable (the next daily value of cardboard volume in a certain container). The mathematical form of the mapping is determined with the help of the data (training set). Of course, we need to build a system capable of making good predictions on unseen data. In order to measure this generalization capability, crossvalidation using another set of samples (test set) are used.

We adopted crossvalidation to estimate the number of hidden units based on the generalization performance of the model.

We divide available data into 3 distinct groups (training, validation and test sets). Then, we estimate the parameters of each model using one of the groups (the training set). Validation set is used to early stopping and to avoid overfitting. Finally, the test set is then used to test the quality indexes simulating the real performance of the model. This process is repeated 20 times, and the results averaged over these runs. This procedure of resampling simulation has been designed to avoid variation coming from different sources, thus independence and randomness is guaranteed. The different preprocessing methods have been combined with several topologies of backpropagation feedforward neural networks (BPNN) networks.

3.3 Perfomance indexes in classification

To visualise the results obtained with a classification model, the Confusion Matrix (Kohavi and Provost, 1998) is normally used. Each row of the matrix represents the number in actual values for each class and each column represents the number of predictions for each class.

		Prediction	
		Negative	*Positive*
Real	*Negative*	**a**	**b**
	Positive	**c**	**d**

Table 2 - Confusion matrix

True positive and true negative results are a correct classification, while false-negative and false-positive results are two types of errors. It depends on the values:

- **a,** is the correct number of predictions in a negative case.
- **b,** is the number of incorrect predictions in a positive case, i.e. the prediction is positive when the value should be negative.
- **c,** is the number of incorrect predictions that a case is negative, i.e. the prediction is negative when the value really should be positive.
- **d,** is the number of correct predictions that a case is positive.

Some standard indexes are defined: accuracy, precision, true positive rate (TPR), false positive rate (FPR), true negative rate (TNR) and false-negative rate (FNR):

$$\text{Accuracy} = a+d / (a+b+c+d) \quad (2)$$

$$\text{Precision} = d / (b+d) \quad (3)$$

$$\text{Sensitivity} = d / (c+d) \quad (4)$$

$$\text{Specificity} = a / (a+b) \quad (5)$$

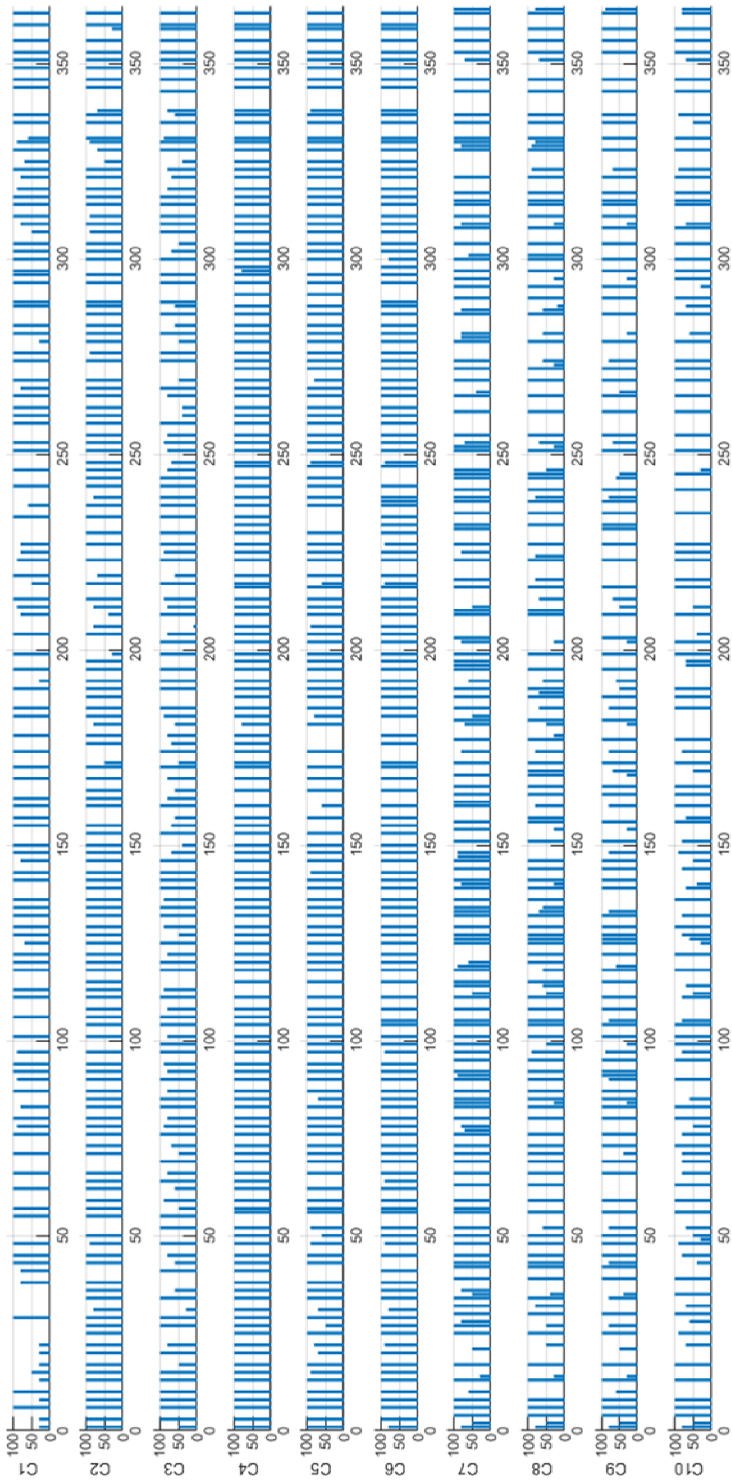

Fig. 2 – Distribution of the actual amount of cardboard collected during the year for each container.

4. RESULTS AND DISCUSSION

This section discusses the most important results obtained in this study. Table 3 shows the real performance of the actual collection system. It is worth mentioning that a lot of inefficiencies were detected. The specificity for each container is really not adequate. This lack of performance means that the actual collection system is very inefficient because there were a lot of times when the truck comes to an empty (or not adequately full) container.

Container	Sensitivity	Specificity	Accuracy	Precision
C1	0,52	0,25	0,4	0,48
C2	0,5	0,05	0,4	0,64
C3	0,61	0,09	0,41	0,53
C4	0,5	0	0,42	0,73
C5	0,51	0,05	0,41	0,65
C6	0,51	0,03	0,42	0,69
C7	0,58	0,16	0,47	0,66
C8	0,57	0,29	0,47	0,59
C9	0,56	0,35	0,47	0,55
C10	0,55	0,33	0,45	0,51

Table 3 - Average performance for each container using the actual collection system.

Table 6 contains the mean correlation coefficients obtained in the random re-sampling experiment with 20 replicates for each container and in function of the number of neurons and the window in the past. The experimental procedure has been applied to a sample of 10 containers of Algeciras, numbered C1-C10. In general, it is worth mentioning that the best performance between the forecasting and the real values were obtained with a certain number of neurons (most of the times, 10 or 20 neurons). This fact indicates that the prediction model is not exactly linear and therefore, methods such as multiple linear regression or ARIMA fails in their predictions. Nevertheless, as Table 6 illustrates, the best results were obtained using a moderate number of neurons and the different number of lags in the past depending on the container. Using too many neurons could improve results in the training stage but can produce overfitting and wrong results in the test phase.

Table 4 compiles the quality indexes of the best models selected in table 6. Especially relevant are the values obtained in sensitivity and specificity because these two indexes indicate how the classifier model works to detect when the cardboard container should be collected (50%-100% of total volume) and also how the truck should not collect a cardboard container (0%-50% of total volume). Both indexes allow us to compare the efficiency of the forecasting model.

There are two cases with two models selected because they have obtained very similar results of forecasting (see Table 4, the case of containers C4 and C8). In these cases, we can adopt two strategies. On the one hand, we can use the Occam’s razor criterium and selecting the simplest model (in this case, with less parameters, i.e. less number of neurons). On the other hand, we can select the model with a lesser distance in the pair (sensitivity, specificity) to the point (1,1). To compare with the actual collection system, we have computed Table 5 reflecting the improvement obtained in each container using the best forecasting model.

Container	Sensitivity	Specificity	Accuracy	Precision	Parameters
C1	0,742	0,910	0,813	0,918	d =3 nhiddens = 10
C2	0,731	0,851	0,760	0,940	d = 4 nhiddens = 10
C3	0,823	0,825	0,824	0,888	d = 2 nhiddens = 10
C4	0,893	0,800	0,877	0,956	d = 5 nhiddens = 5
C4	0,875	0,813	0,864	0,959	d = 5 nhiddens = 10
C5	0,721	0,975	0,780	0,990	d = 1 nhiddens = 50
C 6	0,885	0,800	0,868	0,947	d = 4 nhiddens = 10
C7	0,902	0,514	0,800	0,839	d = 2 nhiddens = 20
C8	0,790	0,825	0,802	0,893	d = 2 nhiddens = 20
C8	0,781	0,842	0,803	0,901	d = 2 nhiddens = 50
C9	0,781	0,845	0,807	0,881	d = 4 nhiddens = 20
C10	0,748	0,914	0,821	0,920	d = 5 nhiddens = 50

Table 4. – Mean ANN best model's parameters for each container.

Container	Sensitivity	Specificity	Accuracy	Precision	Parameters
C1	0,222	0,66	0,413	0,438	d =3 nhiddens = 10
C2	0,231	0,801	0,36	0,3	d = 4 nhiddens = 10
C3	0,213	0,735	0,414	0,358	d = 2 nhiddens = 10
C4	0,393	0,8	0,457	0,226	d = 5 nhiddens = 5
C5	0,211	0,925	0,37	0,34	d = 1 nhiddens = 50
C 6	0,375	0,77	0,448	0,257	d = 4 nhiddens = 10
C7	0,322	0,354	0,33	0,179	d = 2 nhiddens = 20
C8	0,22	0,535	0,332	0,303	d = 2 nhiddens = 20
C9	0,221	0,495	0,337	0,331	d = 4 nhiddens = 20
C10	0,198	0,584	0,371	0,41	d = 5 nhiddens = 50
Mean Total	**0,26**	**0,67**	**0,38**	**0,31**	

Table 5. – Improvements obtained using the best forecasting model for each container.

C1		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,496	0,810	0,824	0,829	0,839
	2	0,352	0,849	0,851	0,856	0,790
	3	0,320	0,820	**0,859**	0,855	0,822
	4	0,320	0,787	0,848	0,855	0,818
	5	0,324	0,803	0,845	0,851	0,774
	6	0,303	0,788	0,850	0,826	0,806
	7	0,242	0,729	0,757	0,851	0,791

C2		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,386	0,844	0,840	0,875	0,877
	2	0,504	0,868	0,875	0,874	0,853
	3	0,561	0,857	0,886	0,871	0,898
	4	0,548	0,869	**0,906**	0,898	0,834
	5	0,457	0,881	0,850	0,881	0,843
	6	0,592	0,879	0,893	0,883	0,834
	7	0,640	0,871	0,890	0,880	0,832

C3		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,413	0,721	0,731	0,807	0,802
	2	0,394	0,786	**0,842**	0,850	0,827
	3	0,362	0,810	0,813	0,808	0,764
	4	0,422	0,820	0,760	0,792	0,763
	5	0,499	0,754	0,810	0,788	0,738
	6	0,457	0,754	0,775	0,786	0,734
	7	0,558	0,748	0,753	0,779	0,756

C4		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,666	0,912	0,912	0,910	0,899
	2	0,614	0,924	0,911	0,914	0,918
	3	0,801	0,902	0,900	0,897	0,903
	4	0,738	0,935	**0,936**	0,903	0,856
	5	0,575	**0,936**	0,907	0,905	0,880
	6	0,680	0,903	0,917	0,931	0,913
	7	0,737	0,927	0,923	0,905	0,919

C5		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,276	0,792	0,869	0,887	**0,901**
	2	0,433	0,858	0,878	0,895	0,837
	3	0,581	0,859	0,868	0,854	0,862
	4	0,506	0,839	0,852	0,868	0,810
	5	0,579	0,856	0,868	0,872	0,753
	6	0,597	0,775	0,866	0,833	0,787
	7	0,557	0,837	0,823	0,861	0,792

C6		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,590	0,862	0,872	0,873	0,875
	2	0,520	0,890	0,891	0,900	0,894
	3	0,599	0,890	0,887	0,889	0,855
	4	0,578	0,876	**0,903**	0,898	0,881
	5	0,719	0,891	0,881	0,898	0,809
	6	0,589	0,855	0,885	0,891	0,815
	7	0,594	0,870	0,892	0,853	0,804

C7		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,208	0,577	0,591	0,619	0,614
	2	0,307	0,571	0,637	**0,667**	0,636
	3	0,207	0,549	0,606	0,650	0,618
	4	0,383	0,611	0,598	0,618	0,559
	5	0,321	0,568	0,624	0,654	0,583
	6	0,303	0,470	0,633	0,577	0,580
	7	0,214	0,422	0,434	0,561	0,586

C8		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,320	0,627	0,645	0,676	0,669
	2	0,321	0,635	0,659	**0,682**	**0,682**
	3	0,290	0,627	0,659	0,621	0,548
	4	0,284	0,588	0,624	0,672	0,624
	5	0,186	0,641	0,666	0,670	0,593
	6	0,234	0,482	0,586	0,639	0,540
	7	0,209	0,581	0,626	0,607	0,507

C9		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,298	0,665	0,674	0,705	0,706
	2	0,307	0,667	0,696	0,715	0,712
	3	0,325	0,668	0,697	0,710	0,661
	4	0,281	0,689	0,671	**0,720**	0,677
	5	0,263	0,699	0,691	0,719	0,649
	6	0,197	0,596	0,687	0,706	0,657
	7	0,242	0,518	0,640	0,617	0,564

C10		nhiddens				
		1	**5**	**10**	**20**	**50**
lags	**1**	0,324	0,646	0,664	0,710	0,707
	2	0,270	0,684	0,691	0,713	**0,729**
	3	0,254	0,630	0,683	0,710	0,678
	4	0,278	0,658	0,671	0,686	0,606
	5	0,134	0,632	0,651	0,681	0,637
	6	0,249	0,507	0,656	0,659	0,590
	7	0,178	0,587	0,623	0,645	0,580

Table 6. - Mean correlation coefficients in the random re-sampling experiment with 20 replicates for each container as a function of the number of neurons and the window in the past.

5. CONCLUSIONS

In summary, with the experiments done, the R correlation coefficient (over test sets in the best models) yields closer estimates to real values of the collected year 2019 time-series. It was clear from our experiments that some of the neural models are much better than others (see Table 4). For example, the R correlation coefficient (average) between BPNN best model (nhiddens = 10, d = 4) is 0.936 in the container C4, better than the rest of models (over test sets).

We have tested the potential of shallow ANNs as a predictive tool in this application. ANNs require no priori assumptions about the model in terms of mathematical relationships or data distribution. We have used multilayer perceptron models (MLPs) with a backpropagation learning rule. The designed procedure of resampling simulation avoid variation, thus independence and randomness is guaranteed. Determination of the model which fits better the prediction of each cardboard container volume time-series can be possible. The improvements in the performance indexes have been quite relevant and the new predictive system should be easily applied to save costs and fuel, thereby reducing emissions and contributing to environmental sustainability.

In summary, this work provides an effective and alternative way to compute predictions with the hypotheses used in the study, obtaining a new forecasting system that allows us to improve efficiency and it should be useful to better garbage collection planning.

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COMPARISON OF MARITIME TRANSPORT INFLUENCE OF SO2 LEVELS IN ALGECIRAS AND ALCORNOCALES PARK (SPAIN)

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ABSTRACT

The main aim of this work was to measure the influence of the volume of shipping over the Sulphur dioxide (SO2) concentration in the air pollution in two monitoring stations located at Algeciras city and Alcornocales Park developing the same analysis in these two locations.

The target is to demonstrate the assumption that Algeciras is more affected by SO2 than Alcornocales Park which is 30 km far away from Algeciras Port. A multiple regression approach has been applied using wind data: wind direction (degrees) and wind speed (km/h) recorded in two weather stations, together with the volume of the gross tonnage per hour (GT/h) of vessels in the Bay of Algeciras to estimate SO2 concentration values in the two stations Algeciras and Alcornocales. The database contains records of hourly samples of these variables during the year 2019. Different artificial neural networks (ANNs) models were compared and the results showed that SO2 in Algeciras station could be better explained than the same pollutant in Alcornocales station. On the other hand, ANNs produced better results than linear models which means that nonlinear models fit best the data. A cross- validation procedure has been applied in order to assure the generalization capabilities of the tested models. The results showed that in Algeciras a more reliable estimation could be done reaching a correlation estimation between the model and the target (real) values of SO2. This fact highlights the major influence of maritime transport in the Bay of Algeciras

1. INTRODUCTION

The importance of cities outdoors in pandemic times has increased substantially since people are doing their lives in streets, parks, and common zones.

It is now, more than ever, when the air surrounding cities becomes essential to develop secure sports activities and their day to day life. This is what motivates this study, in order to gain knowledge about how ports can affect towns. Algeciras city is highly populated with a total of 123,000 inhabitants in 2020, and the Bay of Algeciras is a big exchange site of winds, which makes it interesting analysing this area in concordance with a pollution scenery. For this reason, this study is developed in this location due to its connection with chemical and steelmaking industries, Gibraltar airport, and Algeciras Port, one of the most important ports of goods in Europe, which is a hub of economic activity. Maritime traffic has experienced a massive increase in Europe, and in the whole Globe. The low offer of public transport in the bay makes this zone full of constant private traffic which decreases the air quality. All the transportation sources contribute to a complex pollution scenario, although we focus on Algeciras Port. As one of the main ports in Spain and Europe, the relevance of maritime traffic evinces not only goods movement but also air pollution.

Therefore, the appearance of particulate matter is higher in port zones (González et al., 2011, Viana et al., 2014) often motivated by the ineffective maintenance of vessel engines that makes them unnecessarily consume and waste more fuel (Moreno-Gutiérrez et al., 2015). High rates of the total ships' emissions can be dispersed to 400 km inland (González et al., 2011). Worldwide estimations suggest that vessels are responsible for 15% of NOx and 8% of SO2 emissions all around the Globe, involving 20- 28% of the total emitted gases in the transport sector (Corbett et al., 2007). Besides, other estimations calculated that vessels produce 3% of the total human greenhouse gases, double of aviation (IMO). Not only do navigating ships discharge fumes to the atmosphere but also docked vessels, which can be considerably reduced by switching to lower-sulphur fuel in the ECAs (Emission Control Areas) (Wan et al., 2019). Some pieces of research estimated that 172,000 vessels consumed during voyages about 47 million metric tons of heavy fuel oil and emitted about 2.4 million metric tons of SO2 (Wang et al., 2007). The database provided by Algeciras Port Authority showed that about 29,000 vessels berthed during the year 2019 in the Bay and, while berthing only the auxiliary engine (AE) is functioning to generate electricity onboard what produces lower emissions than cruising (Durán-Grados et al., 2020). Lee et al., (2020) estimated other emissions from several types of ships (general cargo, cruise, container, and tankers vessels) facing the docking process.

Calculations in SOx emissions in the Strait of Gibraltar went from 8.20 ton/km2/year in 2007 (Moreno-Gutiérrez et al., 2015) to 11.60 ton/km2/year in 2017 (Nunes et al., 2020). As a curious fact, Durán- Grados et al., (2020) estimated how Ro-Pax passenger-ships affected the atmosphere in the Strait of Gibraltar during the 90 days of COVID-19 pandemic lockdown while all vessels were berthed in the port of Algeciras taking into account the auxiliary engine and, they obtained a reduction of 12% of emissions. Several studies present an overview of air quality in Europe and port cities (Guerreiro, et al., 2014; Wagner 2019).

Others, the relationship between transport-related air pollutant concentrations to integrate new models for sustainable mobility of vehicles (Catalano, et al., 2016) and the usage of different methods to predict peaks of pollution in critical meteorological situations, particularly in the Bay of Algeciras (Muñoz et al., 2014). Due to huge vessels with engines run on heavy fuel oil (2,700 times higher than road fuel), the shipping emissions are tackled in many manuscripts (Corbett et al., 2007; Liu, et al., 2014; Nunes, et al., 2019; Puig, et al., 2020; Bilgili, et al., 2021; Moreno-Gutiérrez and Durán-Grados (2021)).

Nunes, et al., (2019) evaluated four important ports in Portugal in terms of environmental, social, and economic criteria to evaluate the implementation of policies for in-port emissions. Other authors have studied four types of marine fuels on the environment and human health and concluded that IMO 2020 Sulphur Cap are not at a desirable level yet (Bilgili, et al., 2021). Sanchez et al., (2020) detailed methods to reduce traffic emissions and to implement policy interventions in cities.

In terms of meteorological events that affect pollution, winds seem to be important. Meteorology contribution to pollution events together with forecasting models are faced by Muñoz et al., (2014); Gonzalez-Enrique et al., (2019b); Vellalassery et al., (2021).

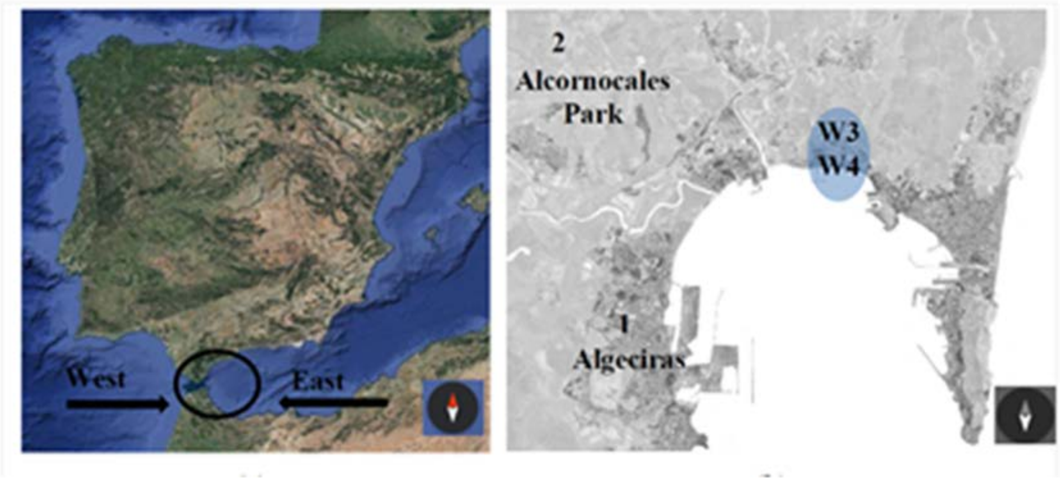
Estimations related to urban areas are tackled in Hu et al., (2021) and in Johnson et al., 2020). The evolution of the interaction between ports and cities is shown in Hesse (2013) adapted from Hoyle (1988). Sustainable cities are related to green transport but Wagner (2019) revealed also multiple factors such as economics, planning development, civil engineering, geography, and of course, transportation.

In this work, the best estimation model of SO2 concentrations in Algeciras and Alcornocales Park is achieved using historical data resolving an input-output fitting problem with feedforward artificial neural network (ANNs). Linear regression models are applied and compared as a benchmark. The rest of this manuscript is organised as follows.

Sect. 2 describes the study case, the database and the methodology. Sect. 3 presents the experimental procedure and the different tested approaches. Sect. 4 discusses the obtained results, and finally, Sect. 5 states the main conclusions.

2. MATERIALS AND METHODS

The Bay of Algeciras is located in the south of Spain, Figure 1(a), and the port of Algeciras is shown in Figure 1(b). The strategic position of the port due to its specific orographic location and the two main directions of wind, East winds (Levante) and West winds (Poniente), affect this area. Figure 1(b) highlights the monitoring stations over the Bay, described in Table 1. Weather stations were denoted using Wn (W3- 4) and listed Algeciras and Alcornocales Park correspond to pollutant monitoring stations



(a) **(b)**

Figure 1 – (a) Bay of Algeciras location and its frequent winds; (b) Monitoring stations (air pollution 1- 2, and meteorological W3- 4)

This study area was chosen due to the importance of maritime transport in this bay. As well, road traffic that moves the goods from this point to the rest of Spain has increased substantially during the last ten years in Algeciras. The two monitoring stations tested, Algeciras and Alcornocales Park are located in Figure 1(a). Alcornocales Park was chosen because it is a remote unspoilt green area where, theoretically, pollution does affect less.

The hypothesis is that Algeciras city is more affected by maritime transport than Alcornocales station. Therefore, a prediction model in Algeciras should be better explained than another in Alcornocales station, due to the effect of maritime transport.

Looking at Figure 1(b), the localization of the Bay of Algeciras is clear and also the different monitoring stations spread over the region. The two dominant winds in the bay are shown in Figure 1(a), Levante (East) and Poniente (West). These peculiar ways in which the wind blows are due to the funnel factor of the bay contained by the Rock of Gibraltar and due to the connection between the Atlantic Ocean and the Mediterranean Sea.

Code	Monitoring/weather station	Latitude	Longitude
1	Algeciras (EPSA)	36º8'11.7" N	5º27'11.44" W
2	Alcornocales	36º13'35" N	5º31'11.44" W
W3	Cepsa (60 m high)	36º11'37.66" N	5º24'1.24" W
W4	Cepsa (15 m high)	36º10'54.7" N	5º25'43.42" W

Table 1 – Location of the meteorological and SO2 monitoring stations

2.1. Materials

Andalusian Government and Algeciras Bay Port Authority (APBA) have provided to the University of Cádiz the recorded values of SO2 concentration, wind, and GT (Gross tonnage) of vessels. The database was recorded hourly for SO2 concentration and wind speed and direction. Then, a new data imputation procedure was performed to complete the missing values. Here, missing data values have been included using a data imputation algorithm considering the measured values in other monitoring stations close to each station, following a proceeding previously used in other works by authors (Turias et al., (2006), Turias et al., (2008), Martín et al., (2008), Moscoso-López et al., (2016), González-Enrique et al., (2019a), Ruiz-Aguilar et al., (2020)). Figure 2(a)(b) shows SO2 concentration time-series and Figure 3(a) shows the wind rose representation of W3 station (Cepsa at 60 m high) and Figure 3(b) the wind rose of W4 station (Cepsa at 15 m high).

The vessel database provided by APBA contains a register for each vessel in the Bay in 2019 (with corresponding timestamps of arrival and departure). The database was transformed into a GT/h (Gross-tons per hour) computing the number of vessels in an hour and the total of Tons of those registered ships. Therefore, each hour a certain number of vessel-tons are located into the Bay, and theoretically affecting the air pollution.

The pollutant data are collected in two monitoring stations in Algeciras and Alcornocales Park, and the weather data are collected in two meteorological stations located in Cepsa refinery at 60 m high (W3) and 15 m high (W4) (see Figure 1b). The SO2 concentration (μg/m3) is recorded in Algeciras city and Alcornocales Park to verify the initial hypotheses (that Algeciras is more affected by SO2 than Alcornocales Park). The weather variables used in this research are the two components of the wind; wind speed (km/h) and wind direction (degrees).

Code	Variables	Measurement	Station
Output1	SO_2	$\mu g/m^3$	Algeciras (EPSA)
Output2	SO_2	$\mu g/m^3$	Alcornocales
Input1	Vessels	GT/h	-
Input2	WS (Wind speed)	Km/h	Cepsa (60 m)
Input3	WS (Wind speed)	Km/h	Cepsa (15 m)
Input4	WD (Wind direction)	Degrees	Cepsa (60 m)
Input5	WD (Wind direction)	Degrees	Cepsa (15 m)

Table 2 – Variables of the study

2.2. Methods

Artificial Neural Networks (ANNs) have been tested in this work together with the use of vessel and wind information in order to predict SO2 concentrations. In this sense, this system could be seen as a virtual sensor SO2 concentrations as a function of maritime transport and wind variables. ANNs require no prior assumptions about the model in terms of mathematical relationships or data distribution. Feedforward ANNs based on a backpropagation learning rule has been used (Rumelhart et al., (1986)). The output was the hourly SO2 concentrations, and the inputs were the gross tons of vessels summed each hour in the Bay of Algeciras, and the wind speed and wind direction in a certain timestamp.

Furthermore, different models were built, some of them using only the pollutant information and the rest considering exogenous variables (vessel and wind information).

The purpose of this modelling approach is to establish a quantitative relationship between a group of predictor variables, X, and a response Y (in this case, the SO2 concentration to be predicted). ANNs have found many applications on air pollution (Jorquera et al., (1998); Nunnari at al., (1998); Gardner et al., (1999); Balaguer, et al., (2002); Perez et al., (2001); Perez et al., (2002); Viotti et al., (2002); Kukkonen et al., (2003); Turias et al., (2003); Turias et al., (2006); Turias et al., (2008); Martín et al., (2008); González-Enrique et al., (2019a)).

For feedforward ANNs, a pattern is formed by inputs together with the pollutant concentration to be forecasted, named real or desired output. There is no way to determine the optimum although Hornik et al., (1989) show the capabilities of backpropagation feedforward networks. An experimental procedure has been used to determine the best ANN configuration.

A standard Multiple Linear Regression (MLR) model has been used as a benchmark in this study.

3. EXPERIMENTAL PROCEDURE

A procedure of resampling simulation was designed to select the model with the best generalization capabilities. First of all, data were selected to create and train the network.

Then its performance was evaluated using mean square error and regression analysis. A feedforward artificial neural network with sigmoid hidden neurons and linear output neurons can fit multi-dimensional mapping problems arbitrarily well, given consistent data and enough neurons in its hidden layer. Authors have successfully used similar procedures in other problems (Ruiz-Aguilar et al., (2014); Moscoso-López et al., (2016); Gonzalez-Enrique et al., (2019b); Ruiz-Aguilar et al., (2020)). Besides, in this problem, the best ANN model using 1000 replications was chosen. ANNs were trained with the Levenberg-Marquardt backpropagation algorithm. Finally, the obtained results were statistically analysed and compared in order to select the model with the best generalisation capabilities.

ANN models with different hidden units were compared to determine the effect of the addition of non-linear processing capabilities on model performance. The resampling procedure was found to reduce test set prediction error and to mitigate the effects of overfitting.

The strategy split randomly the database into three portions (training 70%, validation 15%, and test 15% sets) and the performance results were collected only for the test set in order to estimate the generalization error of each model using unseen data as .

Approach	**Input variables**	**Wind direction**
1	Vessels	Levante (East Wind)
2	Vessels	Poniente (West Wind)
3	Vessels, WS, WD	Levante (East Wind)
4	Vessels, WS, WD	Poniente (West Wind)

Table 3 – List of the tested approaches in the experimental procedure

The approaches 1 and 2 are represented in Equation (1):

$$\hat{SO}_2(t) = f(vessels(t)) \quad (1)$$

The approaches 3 and 4 are represented in Equation (2):

$$\hat{SO}_2(t) = f(vessels(t), wind\ direction(t), wind\ speed(t)) \quad (2)$$

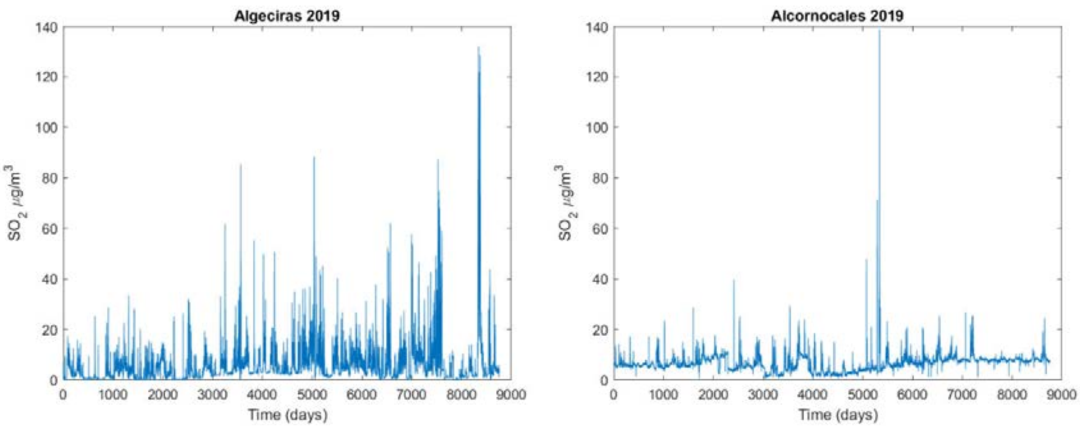
where vessels(t) are the hourly sum of the gross freight in tonnes of all the vessels in the Bay.

The output in each approach is the concentration of SO2 recorded in every station (Algeciras or Alcornocales Park). The models have been subdivided into three submodels: the first one for wind patterns of "Levante" (East wind), the second one for wind patterns of "Poniente" (West wind), and the last one for the rest of the examples in the database. Figure 3(a)(b) shows the winds of roses where these two main wind scenarios can be seen

4. RESULTS AND DISCUSSION

The Bay of Algeciras supports a mean of tons of vessels of one million tons per day as we can see in Figure 4. Moreover, Figure 2(a) shows the large variability of SO2 concentrations in Algeciras and higher concentration values. In contrast, Figure 2(b) indicates a low variability in Alcornocales Park and lower data.
The simulations were run in MATLAB environment. A complete experiment using shallow.

ANNs was developed to prove the efficiency and reliability of SO2 concentration estimation in two monitoring stations in the Bay of Algeciras (Spain) as a function of the total gross tons each hour. Levenberg-Marquardt was used as optimization algorithm and early stopping to avoid overfitting.



(a) (b)

Figure 2 – Hourly SO2 data from stations in 2019 (a) Algeciras; (b) Alcornocales Park

Figure 2 shows a considerable number of concentration peaks of SO2 pollutant in Algeciras than in Alcornocales Park monitoring station, also these values in Algeciras station fluctuate considerably more and in Alcornocales Park the values are significantly more stable. Table 4 shows their means and standard deviation.

Station	Mean Value	Standard deviation
Algeciras	5.8168	8.5573
Alcornocales Park	6.7610	3.6223

Table 4 – Descriptive statistics of SO_2 monitoring stations

Characteristic winds in the Bay of Algeciras are drawn in the wind roses in Figure 3(a)(b). Both clearly show pure East winds 90º (Levante) and pure West winds 270º (Poniente), although in the Bay the West encompasses an angular range of 270º ± 30º approximately.

Most of the winds are normally lower than 54 km/h (15 m/s) and only a few episodes a year are higher than 70 km/h (20 m/s).

Figure 4, shows the 2019 vessel database provided by APBA. This data contains a register for each vessel in the Bay in 2019 (with corresponding timestamps of arrival and departure). In order to check if this data leverage SO2 concentrations, the database was transformed into a GT/h (Gross-tons per hour) calculating the number of vessels in an hour and the total of tons of those registered ships. Thus, a certain number of vessel-tons are located into the Bay each hour. In Figure 4(b), a data histogram is shown. The most frequent data is about 1E+06 GT/h. This amount of vessels produces emissions that can affect a certain area of influence

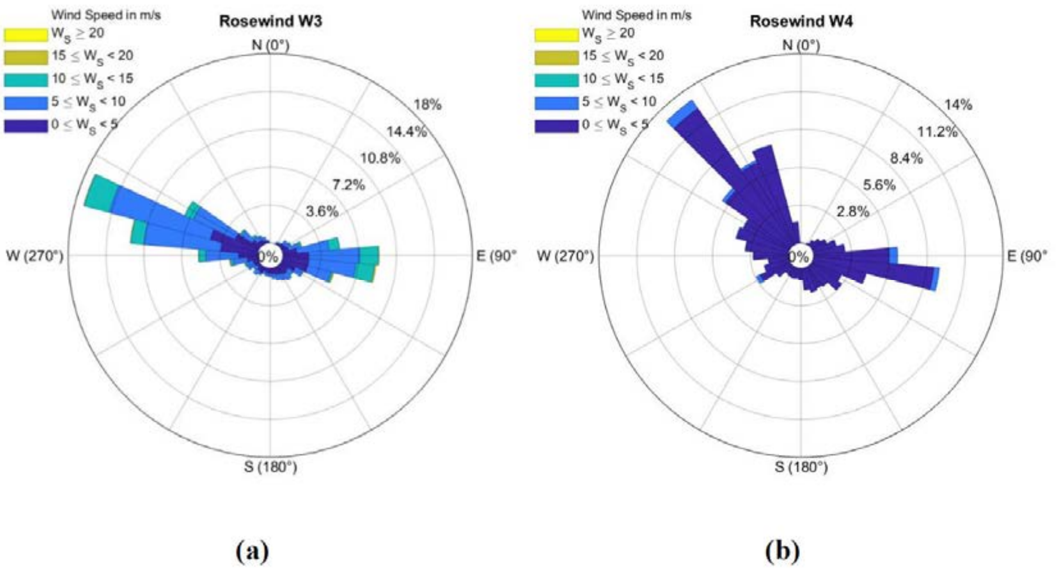


Figure 3 – Wind roses year 2019 (a) station W3 at 60 m high; (b) station W4 at 15 m high

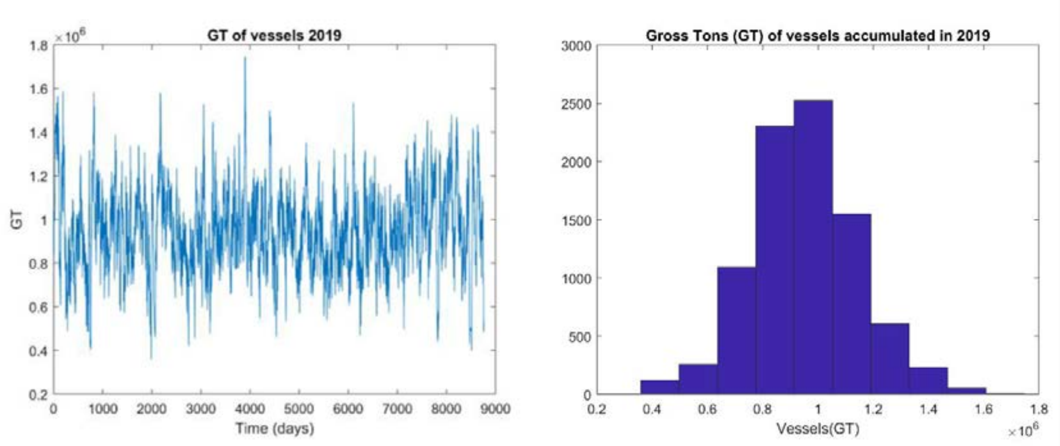


Figure 4 – Hourly vessel data 2019 in Gross Tons recorded in the port of Algeciras

In Tables 5-6 the results of linear regression models are exhibited for every approach. The highest regression coefficient (r = 0.4499) using the linear model is obtained in Algeciras for approach 4 (vessels + West wind) compared to r = 0.2432 in Alcornocales, which indicates a better explanation of the linear model in Algeciras. Analysing Table 6, approaches 1 and 2, it is observed that if we consider only the vessels as input, the model seems to show more leverage in Alcornocales in the case of East wind conditions. In the case of Algeciras, the linear model produces better results when Poniente conditions are registered. This fact could be explained due to in these specific conditions the SO2 concentration values show lower values in Algeciras and they are easier to model linearly.

Approaches 3 and 4 get better results than approaches 1 and 2, which means that input variables affect more strongly if interactions are considered.

Tables 7-8 show the results of ANN models. It is worth mentioning that ANN models fit better the database than MLR models. This fact is explained due to nonlinear behavior of the pollutant dispersion around the study area. One more time, the best results were found when approaches 3 and 4 were used. In the case of Alcornocales, better estimation results were obtained in Levante conditions, and the case of Algeciras, the best estimation model was found in Poniente conditions. The highest result is obtained in Algeciras with 20 hidden neurons (r = 0.7810) compared to the highest coefficient (r = 0.6356) in Alcornocales for approach 4 and only 1 hidden neuron.

Globally, the results show a poor linear relation amongst variables which means that, in comparison to ANNs models in Tables 7-8 with better regression coefficients, the inputs do not follow linear relations. ANNs models work better in general when exist non-linear behaviors and this fact is observed in the obtained results.

Besides, better results were obtained when wind variables are also used. Furthermore, a differentiation between Poniente models and Levante models improves the obtained results as we can see in Tables 5-8.

Weather station W3	Approach	r (MLR model)
Alcornocales	1	0.0853
	2	0.1727
	3	**0.2432**
	4	0.0854

Table 5 – Highest comparison results in Alcornocales Park station using RML

Weather station W4	Approach	r (MLR model)
Algeciras	1	0.1229
	2	0.0583
	3	0.2596
	4	**0.4499**

Table 6 – Highest comparison r results in Algeciras station using RML

Weather station W3	Approach	Neurons (ANNs model)				
		1	**5**	**10**	**20**	**50**
Alcornocales	1	0.3693	**0.3951**	0.3781	0.3744	0.3594
	2	0.4183	0.4264	0.4457	**0.4549**	0.4472
	3	**0.6356**	0.5665	0.6062	0.5608	0.5878
	4	0.4835	0.4968	**0.5552**	0.4646	0.5420

Table 7 – Highest comparison r results in Alcornocales Park station using ANNs

Weather station W4	Approach	Neurons (ANNs model)				
		1	**5**	**10**	**20**	**50**
Algeciras	1	0.4272	0.4559	0.4301	0.4607	**0.5012**
	2	0.3179	0.3167	0.3021	0.4122	**0.4259**
	3	**0.5740**	0.5567	0.5508	0.5623	0.4978
	4	0.7287	0.7586	0.6965	**0.7810**	0.7055

Table 8 – Highest comparison r results in Algeciras station using ANNs

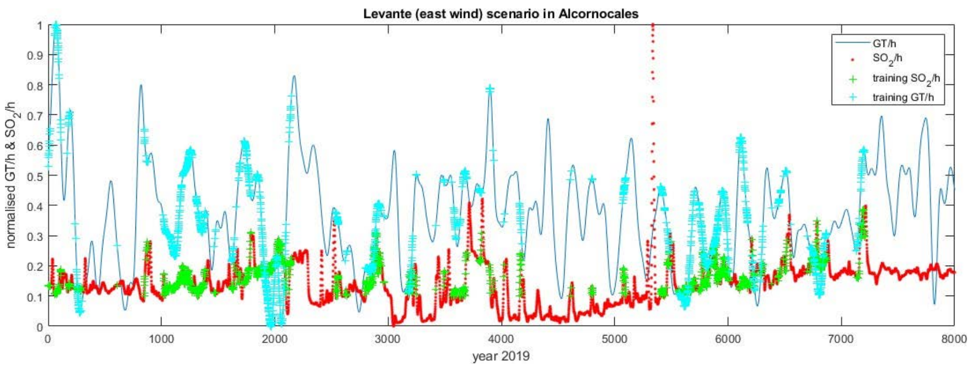


Figure 5 – Levante scenario in Alcornocales Park in the year 2019

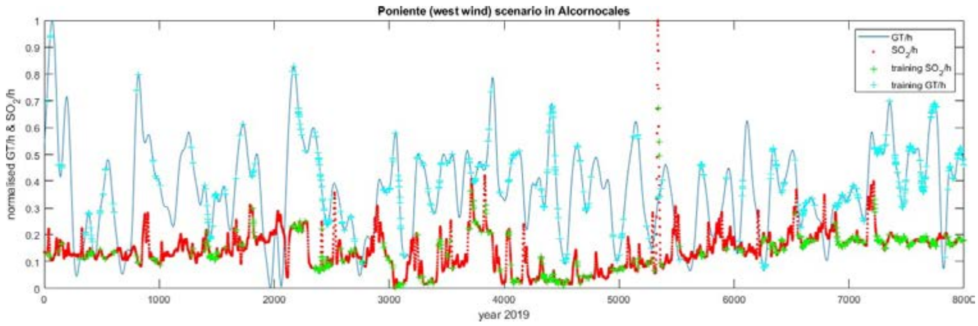


Figure 6 – Poniente scenario in Alcornocales Park in the year 2019

Figures 5-8 show the different variables used and also show the training examples in order to analyse how in each case, different conditions appear. Figures 5-8 show data after applying normalisation. The training examples of SO_2 are shown in green evidencing

Poniente and Levante events in both monitoring stations, Algeciras and Alcornocales Park. Ingeneral, West winds (Poniente) produce lower SO_2 situations and the reverse occurs with East winds (Levante). In both stations, West winds (Poniente) events models produce a better fitting in training data for SO_2 (green crosses) than in East wind due to the fluctuating nature of the SO_2 time-series in Levante conditions. Generally, in Poniente conditions, SO_2 data are more stable.

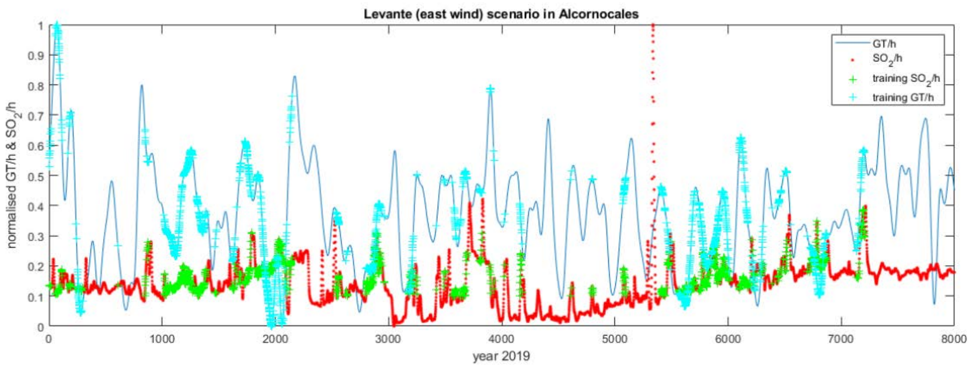


Figure 7 – Levante scenario in Algeciras city in the year 2019 (W4)

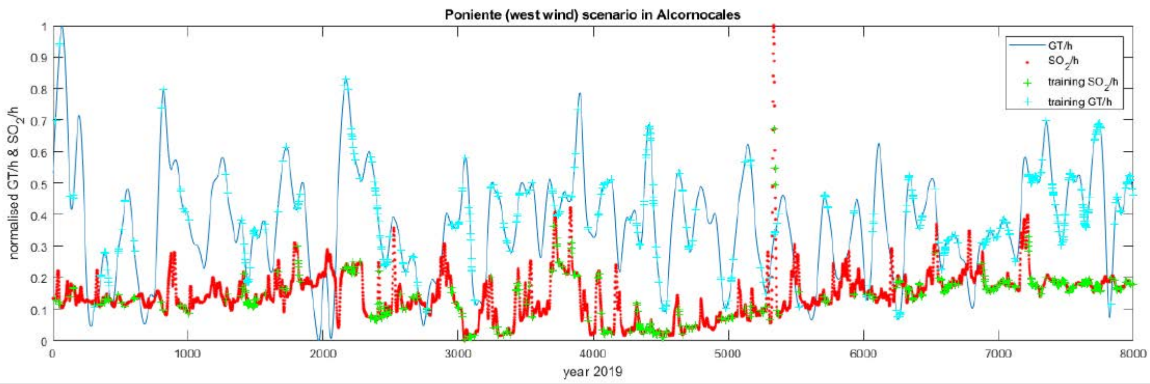


Figure 8 – Poniente scenario in Algeciras city in the year 2019 (W4)

5. CONCLUSIONS

The SO2 database is better suited to non-linear models as we can see from the results in Tables 5-8. ANNs models show better results than linear models, going from 0.7810 with 20 hidden neurons to 0.4499 in linear models in Algeciras. Although East winds are supposed to fit better the data in Algeciras, the results show that West winds produce a better fitting training data for SO2 due to the stability of SO2 data in Poniente conditions.

Once the study is developed, several conclusions can be extracted:

ANNs models deeply improve results of MLR revealing a strong non-linear behavior.
The usage of separated models for the two dominant winds (Poniente events and Levante events) also enhances the results of an individual model.

Future researches will focus on the usage of non-supervised clustering algorithms such as Kohonen's self-organising (SOMs) maps to produce patterns to which separate models can be applied and also deep learning approaches.

The analysis presents promising results to be used afterward in SO2 forecasting models . together with historical data of the time-series of SO2. In this research, the SO2 data were only used as outputs. Therefore, using a wind separation stage (Levante and Poniente), a robust estimation was developed and the obtained results have allowed us to confirm that this approach can serve as a support decision tool to citizens and/or institutions.

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UNCERTAINTY ANALYSIS METHODS TO SELECT THE OPTIMAL ALTERNATIVE IN THE DESIGN OF PARKING FACILITIES

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ABSTRACT

The selection of the preferred alternative in a parking facility project is usually made in a state of uncertainty. Decision-making methods are a useful tool to systematically arrive at a final decision between different alternatives and reduce subjectivity in decision making by creating a series of filters. However, the selection of the appropriate variables to be considered in the analysis may be problematic as well. Performing sensitivity analyses on entry variables is a key feature to ensure that the final choice is stable when initial conditions experience changes. This paper suggests a methodology to select the best alternative when considering parking facilities. The methodology compares the results from two different sensitivity analyses techniques. The changes in preference experienced as the applied weights change through the process are analyzed and the most critical criteria are identified.

1. INTRODUCTION

Urban mobility planning is a fundamental aspect of sustainable development. Sustainable mobility is thus understood as a transport system that allows the movement of people and goods in better conditions of functional quality (travel time, punctuality, comfort, safety, etc.), with more rational use of resources (energy, space, etc.) and a lower environmental impact (reduction of emissions derived from these consumptions. Parking facilities planning is a very significant element of urban transport system planning and sustainable city development, both at local and strategic levels.

A parking facilities policy can be an appropriate strategy to address congestion problems (Ibeas et al., 2014). In general, proper parking management will result in less search traffic and a better use of available parking space (European Union, 2005). On average, a car can spend up to 23 hours a day parked and uses several parking spaces each week (Litman, 2016). Problems related to parking planning are among the most common problems faced by designers, planners, operators and public sponsors. These problems often materialize as a lack of supply (few spaces are available, more need to be built) or deficient management (available facilities are used inefficiently and need to be better managed). Also, parking facilities come at a high cost to society, (Litman, 2016). Therefore, proper planning of parking facilities is necessary and new alternatives need to be studied taking into account all the variables that determine their efficiency and sustainable development.

Multicriteria decision-making (MCDM) methods are tools used regularly for the selection of infrastructure alternatives. The main advantage of MCDM is the simplicity of application and the versatility it offers to solve any problem where there is a known limited number of alternatives. The construction of the decision matrix itself helps to analyse the problem and synthesise the possible solutions, as well as the relative importance of the different requirements (Mullur et al., 2003). However, they have some drawbacks that need to be highlighted: Firstly, potentially optimal alternatives may be discarded because they never receive the highest total score, yet they are the alternatives that best meet the main requirements; Secondly, depending on the method used for weighting criteria, this process has a subjective component and is influenced by the preferences of the decision-maker.

Furthermore, the usefulness of any model depends on the accuracy and reliability of its results. Therefore, it is highly desirable to develop MCDM methods that are less sensitive to the relative importance of the criteria (weighting), or to build strategies that help to assess the sensitivity of the model and the uncertainty of the outcome, (Maliene et al., 2018).

In this research, the results provided by a MCDM for the selection of alternatives in parking facilities projects are analysed by comparing results from the application of two different methods, that are based on sensitivity analysis. For this purpose, the changes in the ranking of alternatives by varying the weights in the selection criteria are analysed and the most critical criterion is determined.

2. LITERATURE REVIEW

MCDM methods are tools that have been extensively used for the selection of infrastructure alternatives. Practitioners often rely on simple decision methods such as the weighted sum method or the Pattern method (Sigford and Parvin, 2013), (Suarez Galarza, 2015).

These methods are characterized by a direct assignment of weighting criteria, which is very subjective. Similarly, sensitivity analysis is limited to changing the weighting of criteria to determine how the ranking of alternatives changes, without analysing the critical criteria or threshold values that determine changes in the ranking.

In the academic literature, there is a broad body of knowledge focused on the selection of alternatives in infrastructure projects in different fields. MCDM methods are applied with different objectives: to assess the sustainability of the different alternatives (Penadés-Plà et al., 2016), (Sierra et al., 2018), (Zavadskas et al., 2018); to take into account the correlation between input variables, (Mardani et al., 2015); to obtain a ranking of suitable alternatives to optimise and/or prioritise investments in early stages of infrastructure planning; (Belošević et al., 2018); to assess risks, (Mohsen and Fereshteh, 2017); to determine the optimal location, (Wu et al., 2019).

MCDM methods have many advantages because they allow complex problems to be solved systematically and simply. Nevertheless, the results of the different decision methods are affected by a certain degree of uncertainty. It is therefore important to identify and understand the different sources of uncertainty and to quantify, as far as possible, the uncertainty and its influence on the results of the decision method. However, recognising and quantifying uncertainty is a complex and multifaceted issue, (Azzini et al., 2020). The uncertainty in the data, procedures and approaches used for its resolution justify making a study of the behaviour of the decision-making process as complete as possible, (Moreno-Jiménez et al., 1998). In this sense, the analysis of the behaviour should be carried out at three levels that respond, respectively, to the effectiveness, efficacy and efficiency of the decision process: (1) the approximation (validity); (2) the modelling (robustness); and (3) the solution (stability), (Moreno-Jiménez et al., 1998).

Sometimes the concepts of uncertainty analysis, sensitivity analysis and robustness analysis of the decision method are confused due to their similarity. All these concepts target the quality of the decision method, but there are differences between them, (Azzini et al., 2020), (Song and Chung, 2016). Uncertainty analysis aims to quantify the uncertainty in the solution provided by the decision method due to the uncertainty in the inputs (criteria and alternatives) of the method, (Azzini et al., 2020). To determine the robustness of the methods, an analysis of the behaviour of the solution is usually performed, assessing the possibility of change in rank between alternatives when relevant aspects (alternatives, criteria, dependencies, etc.) are added or removed, (Moreno-Jiménez et al., 1998). Finally, sensitivity analysis measures the stability or behaviour of the solution to small changes in preferences that occur during the resolution process, or to small changes in the values of the parameters. Thus, sensitivity analysis is a process of investigating the behaviour of an uncertain system, process or method, (Medeiros et al., 2017).

Different types of sensitivity analyses can be grouped into three main categories: mathematical, probabilistic and graphical (Frey and Patil, 2002). Among the sensitivity analyses applied, two stand out: weight variation of the criteria in a given interval and the most critical criterion method. The first method allows to determine independently the effect of each criterion on the solution. For this, the weight of each criterion is modified (increasing and decreasing) by a small percentage - for example, 5%- and by a large percentage – for instance 50%-, while maintain the weight of the rest of the criteria. In this way, the relative sensitivity coefficients of each criterion can be calculated as the number of changes in the ranking of alternatives due to these changes, (Davies et al., 2012). The most critical criterion method is a sensitivity analysis method to assess the impact of uncertainty on the determination of the most critical criterion and on the results, (Triantaphyllou and Sánchez, 1997). In addition to these two sensitivity analysis methods, there are other methods based on uncertainty analysis by optimising the distance metric, (Hyde and Maier, 2004).

3. MATERIALS AND METHODS.

3.1 MCDM methods.

First of all, it should be noted that not all MCDM are perfect for all decision problems. MCDM can be classified into the following groups, (Penadés-Plà et al., 2016), (Hajkowicz and Collins, 2007), (de Brito and Evers, 2016):

- Methods based on a utility/value function or Multi-attribute Utility Theory (MAUT). The objective of these methods is to find an expression through which the decision-maker's preferences are reflected by using a utility/value function.
- Paired comparison methods. These methods allow different alternatives to be assessed according to qualitative criteria by comparing them two by two. They can also be used to establish the relative importance and weighting of criteria, by paired comparisons of the criteria, i.e. the question of how much more important criterion A is compared to criterion B.
- Methods based on the concept of distance. These methods determine a classification of the alternatives according to their distance from an ideal solution. An ideal solution is the hypothetical alternative that is obtained from the combination of the different alternatives, choosing the variables that "behave" best concerning each criterion.
- Outranking methods. This term includes all those MCDM that revolve around the theoretical concept of overcoming relationships.

3.1.1 SAW Method

The Simple Additive Weighting (SAW) method, also known as the weighted sum method, is the simplest and most widely applied method, (Kittur, 2015). For ech alternative, it obtains the weighted sum of the performance ratings for all criteria, (Br Sembiring et al., 2019), (Wira Trise Putra and Agustian Punggara, 2018).

The overall performance rating of each alternative, P_i, is given by the expression:

$$P_i = \sum_{j=1}^{n} w_j * x_{ij} \tag{1}$$

Being w_j the weight of each decision criterion, C_j, and x_{ij} the normalized value of the evaluation of alternative A_i concerning criterion C_j, i.e. the element a_{ij} of the decision matrix after normalization. The alternative that obtains the highest value of P_i is considered the best alternative.

Normalization of the decision matrix's elements is necessary to evaluate the different alternatives concerning decision criteria that have different units of measurement. In this way, normalization converts the elements of the decision matrix into dimensionless values.

In the SAW method, the normalized values are obtained by summing the values of each row of the transposed decision matrix and then dividing each element of that row by that sum, (Ginevičius, 2008). For the normalization of the elements of the decision matrix it is necessary to take into account whether the criterion is a beneficial criterion or a cost criterion, so that the normalized values are obtained according to the following expressions:

$$x_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}, if\ C_j\ is\ a\ beneficial\ criterion \quad (2)$$

$$x_{ij} = \frac{1/a_{ij}}{\sum_{i=1}^{m} 1/a_{ij}}, if\ C_j\ is\ a\ cost\ criterion \quad (3)$$

Being m is the number of alternatives of the decision problem.

3.1.2 AHP Method

The Analytic Hierarchy Process (AHP), was developed by the mathematician Thomas Saaty in the late 1970s, (Saaty, 1990). It is a MCDM based on paired comparisons that allows the decision-maker to express his or her preferences for weighting the different criteria. To do this, the Saaty scale (Saaty, 1990) is applied and the criteria are compared two by two. The differences between these two elements are established verbally and these descriptive preferences are represented by numerical values. In this way, when two elements are equally preferred or important to the decision-maker, the pair of elements will be assigned a "1"; a "3" when there is moderate importance of one element over another; a "5" indicates strong importance of one element over another; a "7" indicates very strong importance of one element over another; and finally a "9" indicates extremely preferred or importance of one element over another. Even numbers are used to express intermediate situations, (Saaty, 1990).

The weight eigenvector is calculated for the criteria that determines which is the most ideal solution. This is done by making a paired comparison of them for each project (Martínez Rodríguez, 2007), (Yepes et al., 2015). It must be taken into account that the weight eigenvector is not the same for each project, since certain criteria may have bigger importance in comparison to the others, depending on the characteristics of the project. It is necessary to remember that AHP measures the global inconsistency of the views by the Consistency Proportion, calculated by dividing the Consistency Index and the Random Index, and it should be less than 10%. The Consistency Index measures the consistency of the comparison matrix, (Saaty, 1990):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

Being λ_{max} the biggest value of the paired transposed comparison matrix, and n the matrix range. The Random Index is an index that measures a random matrix, whose values are given in Table 1.

Matrix range	2	3	4	5	6	7	8	9	10
Random Index	0,00	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

Table 1 – Random Index, AHP method.

Therefore, this allows for an acceptable level of confidence that the decision process has been carried out correctly. On the other hand, through AHP we can establish the ‘behaviour’ of each alternative for each of the qualitative criteria that are part of the decision making processes, to obtain a quantitative assessment for qualitative criteria.

3.2 Sensitivity analysis

The two main methods of uncertainty analysis in which decisions are made are the weights variation of criteria in a given interval and the most critical criterion method. In the first method, the objective is to independently determine the effect of each criterion on the results of the MCDM. For this purpose, the weight of each criterion is increased or decreased by 5% (small change), 50% (large change) and 95% (very large change). The weights of the remaining criteria are similarly increased or decreased to ensure that the sum of the weights of all criteria remains equal to 1. This results in relative sensitivity coefficients calculated as the number of changes in the ranking of alternatives due to changes in the criteria weights.

In the most critical criterion method, the impact of uncertainty is assessed by determining the criterion whose effect produces the greatest changes in the results, (Triantaphyllou and Sánchez, 1997). To do this, it calculates the minimum change (δ) to the weight of a criterion (w_k), to reverse the ranking of the alternatives. It is calculated for each pair of alternatives A_i and A_j for each criterion C_k, as follows:

$$\delta_{k,i,j} = \frac{P_j - P_i}{x_{jk} - x_{ik}} \quad (5)$$

Being P_j and P_i the positions occupied by alternatives A_j and A_i in the ranking and x_{jk} and x_{ik} the normalized ratings of each alternative concerning criterion C_k. The condition $\delta_{k,i,j} \leq w_k$ must be satisfied for the change in the ranking of the alternatives by changing the weights of the criteria to be feasible. Sometimes, it may be impossible to reverse the existing ranking by changing the weights of the current criteria. However, when the conditions are met, the modified criterion weight, w_k^*, can be calculated from the following equation:

$$w_k^* = w_k - \delta_{k,i,j} \quad (6)$$

The percentage change of the criteria weights can be calculated as:

$$\%w_k^* = \frac{w_k^*}{w_k} * 100 \quad (7)$$

The criticality degree of each criterion C_k, D_k, is defined as the minimum absolute value of $\%w_k^*$. From here, the sensitivity coefficient of each criterion, $sens_k$, can be defined as a measure of the sensitivity to the change in the weighting of the criterion C_k as follows:

$$sens_k = \frac{1}{D_k} \quad (8)$$

So the most critical criterion will be the one with the highest sensitivity coefficient.

3.3 Data collection

In this paper, a case study is developed applying to the construction of parking facility in Cordoba City’s centre the two sensitivity analyses previously described. The problem of parking in the historic centre and its periphery was outlined in the Advance of the Sustainable Mobility Plan for the city of Cordoba, drafted in April 2011, (Cordoba City Council, 2011).

In the historic centre there are different types of parking for different usages: private parking for residents, blue zone parking for visitors and loading and unloading parking for good delivery.

On Cordoba’s periphery the implementation of regulated or blue zones is insufficient for the proper management of parking, making it is necessary to limit traffic and better manage mobility.

Three alternatives for a new parking facility are evaluated, (Vimcorsa, 2010):

- Alternative 1: Parking on Gran Vía Parque Ave. on the corner of Manolete Ave. The parking consists of one floor above ground level, uncovered and landscaped, and two floors below ground level.

- Alternative 2: Surface parking in Gran Vía Parque Ave. on the corner of Manolete Ave. in the same location and conditions as alternative 1, but building only the surface level, surface parking.
- Alternative 3: Surface parking in the street Pintor Racionero. Due to the limitations to underground works due to the existence of important archaeological remains, the installation has only the surface parking level.

Ten selection criteria have been considered for the evaluation of the alternatives: C1, Number of parking spaces; C2, Utility value to the user (relationship between users' willingness to pay to save time looking for a parking place and the tariff parking); C3, Number of current parking spaces in the target area; C4, Ratio of inhabitants to existing residential parking spaces in the area; C5, Intermodality; C6, Cost of parking (construction cost and maintenance cost); C7, Environmental impact; C8, Population; C9, Proximity to commercial areas, C10, Proximity to administration areas and offices.

Table 2 includes the evaluations of each alternative concerning each selection criterion, and table 3 shows the normalized decision matrix, according to equations (2) and (3).

Criteria	Alternative 1	Alternative 2	Alternative 3
C1	508	218	246
C2	0.618	0.618	0.653
C3	527	527	688
C4	6.18	6.18	3.82
C5	1005	1005	1970
C6	8525.57	2709.3	2485.16
C7	0.6753	0.0817	0.2431
C8	15275	15275	7540
C9	97532	97532	27139
C10	30150	30150	6797

Table 2 – Evaluations of each alternative concerning each selection criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	0.055	0.067	0.023	0.013	0.019	0.017	0.017	0.063	0.012	0.008
A2	0.024	0.067	0.023	0.013	0.019	0.054	0.146	0.063	0.012	0.008
A3	0.027	0.070	0.018	0.008	0.010	0.059	0.049	0.031	0.003	0.002

Table 3 – Normalized decision matrix.

The vector of weights is determined according to the AHP method as described in section 3.1.2. The weight vector obtained is $w = (0.1056, 0.2037, 0.0638, 0.0350, 0.0475, 0.1310, 0.2124, 0.1559, 0.0270, 0.0181)$. It is important to remember that the consistency of the comparison matrix must be identified. After determining the consistency following equation (4), we obtain CI = 0.0953. Since the Consistency Proportion is under 0.1 the assessments made can be considered as consistent.

To determine the best solution, the SAW method is applied as previously described, resulting in alternative 2 as the best ranked alternative, followed by alternative 1, and finally alternative 3.

4. RESULTS AND DISCUSSION.

To determine the stability of the solutions obtained by the MCDM, a sensitivity analysis is performed as described above. First, the most critical criterion is determined using equations (5) to (8). For this purpose, the alternatives are compared in a pairwise manner, obtaining the degree of criticality of each criterion and the corresponding sensitivity coefficients (Figure 1).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1-2	-424.50	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F
1-3	61.83	-466.29	N/F	N/F	N/F	-41.88	-56.13	55.59	N/F	N/F
2-3	-4975.18	-2496.73	N/F	N/F	N/F	-3084.47	N/F	N/F	N/F	N/F

Table 4 – Criticality degree of each criterion (minimal values). N/F: no feasible change

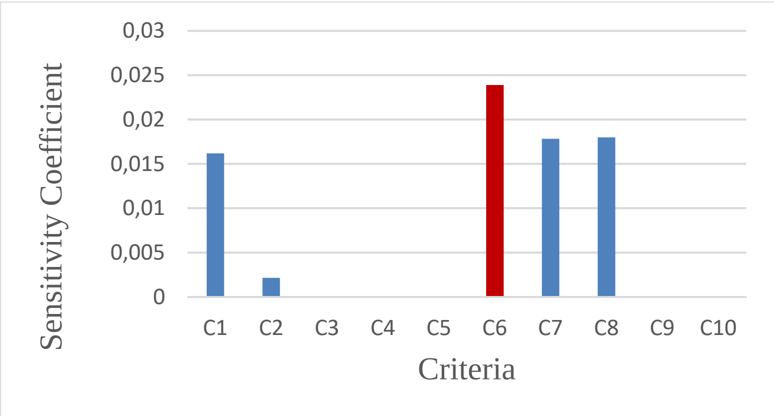

Fig. 1 – Sensitivity Coefficient of each criterion

The results obtained are shown in Table 4. It can be determined that alternative 2 remains the best alternative in almost all cases. Alternative 2 could only be surpassed by alternative 1 if the weight of criterion C1 is increased by 424.50%, and by alternative 3 if the weights of criteria C1, C2 and C6 were increased by 4975.18%, 2496.73% or 3084.47% respectively. However, the most likely changes in the ranking of alternatives 1 and 3.

Relatively small changes in the weights of the criteria can produce changes in the second best alternative. Moreover, it can be deduced that criterion 6 is the most critical criterion, followed by criterion 8, because for the smallest change in the weight of this criterion (41.88%) a change in the ranking of alternatives occurs, which is also reflected in Figure 1.

Next, independent changes in the weight of each criterion are introduced (5%, 50% and 95%). The relative sensitivity coefficients are obtained, that is, the number of changes that occur in the ranking of alternatives due to these changes. The results obtained are included in Table 5.

	Increase (%)			**Decrease (%)**		
	5%	**50%**	**95%**	**5%**	**50%**	**95%**
C1	0	0	0	0	0	1
C2	0	0	1	0	0	0
C3	0	0	0	0	0	0
C4	0	0	0	0	0	0
C5	0	0	0	0	0	0
C6	0	1	1	0	0	0
C7	0	1	1	0	0	0
C8	0	0	0	0	0	0
C9	0	0	0	0	0	0
C10	0	0	0	0	0	0

Table 5 – Relative sensitivity coefficients calculated as a number of changes in the alternative ranking due to change of criteria weights.

The results obtained confirm that changes only occur in one position of the ranking of alternatives. Alternative 2 remains for these weights the best alternative. It is also confirmed that for relatively small changes in the weight of criterion 6 the largest changes in the ranking occur, together with criterion 7. However, criterion 7, according to the analysis of the most critical criterion, has a lower sensitivity coefficient value than criterion 8, which has the second-highest sensitivity coefficient value after the most critical criterion. Given these results, it can be stated that the uncertainty and stability analysis of the solutions of the MCDM must be performed with two different techniques to verify the results because there may be small discrepancies depending on the method used.

5. CONCLUSIONS

MCDM are a very useful tool for the selection of alternatives in a simple way. The decision process however takes place in an environment of uncertainty, because the input variables may vary. Moreover, the results obtained depend on the nature of the selection criteria and, especially, on the weights assigned to these criteria. In most cases, the assignment of weights to the criteria is done by experts, so there is a subjective component and the results may change depending on these weights. Therefore, it is necessary to analyse how the variation in the relative importance of the decision criteria influences the solution of the MCDM. In this paper, we have analysed how changes in the weighting of the selection criteria can influence the solution of the MCDM by using two different sensitivity analysis and comparing the results. It is proposed that whenever possible these sensitivity analyses are carried out to confirm the results and to study the effect of the weights of the criteria on the selection of alternatives. Although the sensitivity analyses carried out have some limitations since they study each criterion independently and do not apply to all MCDM, they are a simple first approximation that allows determining the robustness of the solution obtained and can be the basis for a more exhaustive study of those criteria.

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MOVILIDAD
MOBILITY

ACCESIBILIDAD A CENTROS HISTÓRICOS, EL CASO DE MAJADAHONDA

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RESUMEN

En la actualidad, en todo el mundo la tendencia está concentrada en lograr Ciudades Accesibles usando un patrón de movilidad basado en un transporte masivo sostenible y accesible para personas con movilidad reducida, con las respectivas implicaciones de tener que adecuar el contexto urbano y de tener que integrar movilidad peatonal y transporte público, en una sinergia que tiene el objetivo principal de devolver los espacios públicos a los ciudadanos.

Del PMUS de Majadahonda se sabe que el reparto modal de todos los viajes diarios en la ciudad, alrededor del 20% son viajes no mecanizados, la gran mayoría a pie. La cuota de reparto modal que tienen los desplazamientos a pie en Majadahonda se sitúa por debajo de las ciudades españolas que suele rondar el 30%.

En esta comunicación se presentan los resultados del Plan de Accesibilidad Peatonal realizado por los autores en la ciudad como consecuencia de una iniciativa del equipo municipal. Incluye:

- Análisis y diagnóstico
- Propuestas

Las propuestas son de tres tipos y van más allá de las comunes de accesibilidad, teniéndosetambién en consideración otros aspectos:

- Creación de Itinerarios Accesibles: Prever actuaciones en calles que generen itinerarios accesibles.
- Zonas de calmado de tráfico: El estudio de accesibilidad tiene en cuenta los problemas que existen actualmente en relación con la seguridad de los peatones en la vía pública y los problemas que surgen como consecuencia de la excesiva

velocidad de los vehículos a motor, por lo tanto, se deben proponer medidas o soluciones a estos problemas, para ello se propondrán calles, zonas o actuaciones decalmado de tráfico.

- Urbanismo táctico: Se proponen medidas de urbanismo táctico, estas medidas son económicas y a corto plazo, de manera que la ciudadanía pueda ver el cambio en su ciudad casi desde los inicios de la implantación del estudio de accesibilidad.

1. ENFOQUE

La ciudad es el espacio en el que los individuos adquieren la condición de ciudadanos, estoes, la condición de ser personas titulares de derechos políticos, sociales y culturales. Tal virtud comporta permitir el acceso a las personas a múltiples servicios y equipamientos, posibilitar el contacto con otros y favorecer la libertad de elección; y todo ello en igualdad de condiciones.

Una ciudad debe ser capaz de dar a sus habitantes la capacidad de realizar todas las actividades que en la misma se desarrollan del modo más independiente y autónomo posible.

El espacio público urbano es un elemento dinamizador y fundamental en la sociabilización de las personas, donde se generan espacios de interacción entre los habitantes de la ciudad.El espacio público tiene una clara incidencia y contribución a la calidad de vida social y material en la ciudad, particularmente de los sectores de la población en riesgo de exclusión.

Majadahonda, por su configuración física, sus condiciones climáticas y las previsiones de planeamiento, se presta a la movilidad peatonal para que esta constituya un pilar básico en la construcción de un nuevo modelo urbano. Casi la totalidad del municipio (exceptuando las urbanizaciones situadas más al sur) se sitúa a una distancia de 2,5 kilómetros del centro urbano, una distancia que puede fácilmente ser cubierta andando en unos 30 minutos. Del PMUS se sabe que el reparto modal de Majadahonda indica que, de todos los viajes diarios en Majadahonda, alrededor del 20% son viajes no mecanizados, su gran mayoría son viajesa pie. La cuota de reparto modal que tienen los desplazamientos a pie en Majadahonda se sitúa por debajo de las ciudades españolas.

Existen una serie de factores o de problemas que frenan el avance de la movilidad peatonal y casi todos se engloban en una causa común: lafalta de accesibilidad universal. Por este motivo el Ayuntamiento decidió elaborar el Plan de Accesibilidad Peatonal del casco urbano de Majadahonda:

"*Un Plan de Accesibilidad es un plan de actuación, cuyo objetivo es hacer accesible gradualmente el entorno existente, con el objetivo de que TODAS LAS PERSONAS lo pueden utilizar libre y autónomamente*" Real Patronato de prevención y de atención a personas con minusvalía.

Por lo tanto, un plan de accesibilidad:

- Es un modelo sistemático que se realiza en un entorno concreto con el objeto de encauzar las acciones a acometer: Dirige y organiza
- Es un instrumento dinámico y sujeto a modificaciones: Carácter abierto.
- Las propuestas se definen en estrategias que se estructuran en acciones y proyectos a desarrollar con posterioridad: Precisa de un desarrollo posterior.

2. METODOLOGÍA

La **metodología** aplicada se estructura en tres fases: análisis, diagnóstico y propuestas, quese desarrollan a continuación:

FASE 1 Análisis	Interno	Visitas técnicas
		Toma de datos
		Participación pública
	Externo	Normativa de aplicación
		Benchmarkig
FASE 2 Diagnóstico	Causas	Problemas estructurales
		Problemas de diseño urbano
		Problemas de mantenimiento y conservación
		Problemas de control y concienciación
FASE 3 Propuestas	Tipo, Específicas y Complementarias	Presupuesto
		Priorización

3. ANÁLISIS Y DIAGNÓSTICO

A partir de la información disponible, las visitas técnicas, la toma de datos y la participación ciudadana, se ha realizado el análisis de la situación actual que se estructura en tres bloquesfundamentalmente:

- Análisis funcional: Estudio funcional de las diferentes áreas de actividad en los itinerarios peatonales. Las tres acciones principales (transitar, descansar y cruzar) seestructuran en los siguientes bloques:
    - Vías de tránsito
    - Zonas estanciales

- Puntos de cruceAnálisis tipológico: Este segundo análisis aborda los diferentes elementos urbanos de forma individual, describiendo sus tipologías y características desde la perspectivade la accesibilidad.
- Análisis sectorial: Un estudio por áreas globales del entorno urbano, abordando la realidad concreta de ese ámbito con la complejidad que motiva la superposición de itinerarios puntuales

El diagnóstico de la accesibilidad en Majadahonda recoge una reflexión, una síntesis y una clasificación de todos los elementos que se han analizado y que se han detectado en la tomade datos realizada previamente, de manera que se puedan valorar y establecer las prioridadesde actuación.

Se ha realizado un **diagnóstico en función de las causas**, ya que diferentes causas provocandiferentes barreras urbanísticas y esto da lugar a diferentes soluciones:

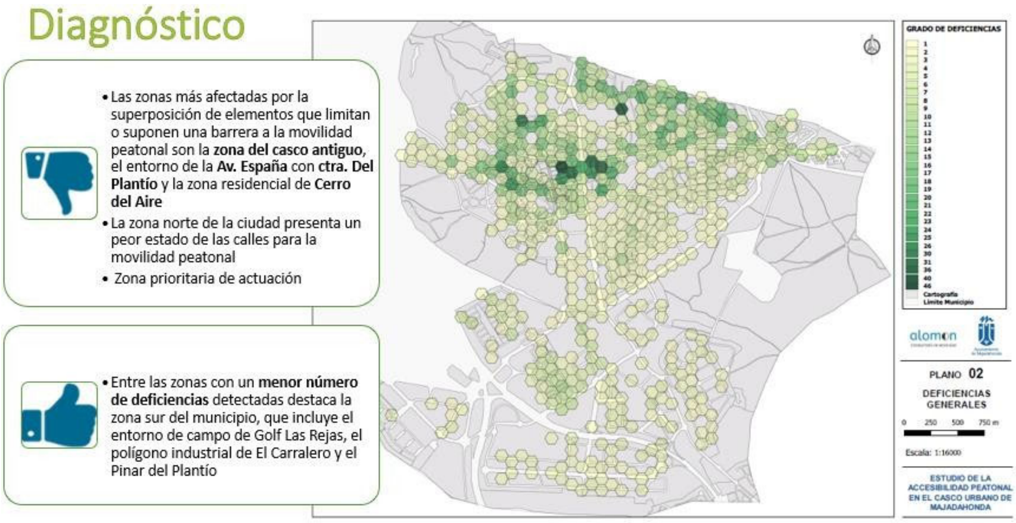
De esta forma, el diagnóstico se ha estructurado en problemas de cuatro tipos diferentes:

- Problemas estructurales: Son problemas que no se pueden cambiar, pero podemos convivir con ellos y ofrecer recursos para que la accesibilidad se mejore, el más destacable es la topografía en la zona histórica y la barrera que supone la M-503.
- Problemas de diseño urbano: Son consecuencia de errores de diseño o de ejecución. En este aspecto destaca la falta de accesibilidad de los itinerarios principales del municipio (acerados insuficientes), la discontinuidad de los mismos debido a los puntos de cruce no adaptados, los elementos urbanos mal

localizados (alumbrado y arbolado interrumpe el paso) y las plazas de aparcamiento reservadas a PMR con un diseño incorrecto.

- Problemas de mantenimiento y conservación: Son derivados de la falta de mantenimiento, conservación y limpieza del espacio urbano. Lo más llamativo es el pavimento en mal estado en algunas aceras.
- Problemas de control y concienciación: Derivados de malas conductas por parte de algunos ciudadanos y que precisan del control por parte de las autoridades competentes. Destacan los elementos comerciales invadiendo la acera, en especial las terrazas de bares y restaurantes y los vehículos mal estacionados.

La siguiente ilustración muestra **diagnóstico global de la accesibilidad** según el número deincidencias detectadas:



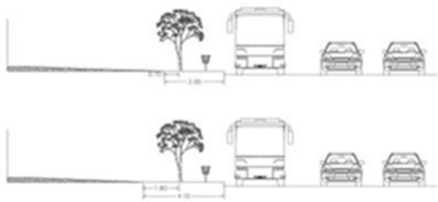
4. PROPUESTAS

En función del tipo de problemática detectada en el diagnóstico de la situación actual de la movilidad peatonal se han considerado **dos tipos de mejoras**:

- Las **propuestas de mejora tipo** se desarrollan para aspectos o problemáticas que sehan detectado de una forma generalizada en el municipio:
-
    - Red de itinerarios peatonales accesibles.
    - Pasos peatonales accesibles.
    - Estacionamientos reservados para PMR.
    - Mobiliario urbano.
    - Escaleras y rampas.
    - Vados vehiculares.
    - Conexión a paradas de autobús.

- Sin embargo, hay muchas otras deficiencias de accesibilidad detectadas que son concretos en determinadas calles y que requieren de un análisis pormenorizado, en estos casos se realizan las propuestas de soluciones específicas.

En ambos casos, se incluyen fichas resumen de las actuaciones necesarias que incluye un breve diagnóstico, las características de la actuación planteada, una estimación del coste deejecución de las mismas, el diseño correcto en base a la normativa de aplicación y la priorización de las actuaciones. Se muestra una ficha de actuación específica a modo de ejemplo:

Avenida de España-1		
Itinerario peatonal no accesible		
El tramo de la Avenida de España comprendido entre la Av. Rey Juan Carlos I y la Calle Mare Nostrum, tiene un ancho de acera que no cumple con la normativa, debido a la existencia de alcorques en el itinerario peatonal. Con esta actuación se plantea el disponer de 1.80 metros de acera desde el alcorque, eliminando la superficie de jardín que sea necesaria para garantizar la accesibilidad del itinerario. En este ámbito se han registrado un **alto índice de siniestralidad vial**	 	
Diseño de propuesta 	**Presupuesto estimativo:** 1. **Demolición y movimiento de tierras:** - m3 de desbroce de tierra vegetal. - m2 de demolición de solera de hormigón y pavimento hidráulico. 2. **Pavimentación:** - ml de suministro y colocación de bordillo de hormigón. - m2 de suministro y colocación de solera de hormigón y pavimento hidráulico.	
	Total: 4.000 €	**Grado de prioridad:** Alta

Una vez creada una red de itinerarios peatonales accesibles es necesario impulsar la movilidad peatonal en el municipio a través de medidas informativas y de concienciación: Elaboración de un plano "Metrominuto" de itinerarios peatonales accesibles y campaña informativa, Medidas de vigilancia y sanción para el estacionamiento ilegal, Medidas de vigilancia y control de terrazas, Elaboración de un estudio de iluminación en el ámbito de los itinerarios peatonales accesibles, Elaboración de un proyecto piloto de mejora del acceso al CEIP El Tejar con medidas de urbanismo táctico.

5. CONCLUSIONES

En la actualidad, hay una clara tendencia, en todo el mundo, a lograr ciudades más amables, más sostenibles y más inclusivas. Ha llegado el momento de modificar la estructura urbanística, edificatoria y del transporte en nuestras ciudades y pueblos, potenciando las medidas que facilitan la información, orientación y comunicación para todos los colectivos, suprimiendo las barreras arquitectónicas existentes y buscando la accesibilidad universal; contribuyendo con ello a que todas las personas disfruten de un confort y una calidad de los servicios ofrecidos, y facilitando el desplazamiento y la integración de las personas con discapacidad, al conseguir una mejora de sus propias cualidades y posibilidades, evitando el aislamiento y la marginación a que se ven sometidos hoy en día.

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WALKING, DRIVING AND WELLBEING DURING THE COVID-19 PANDEMIC LOCKDOWN IN SPAIN

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ABSTRACT

The objective of this paper is to present a detailed descriptive analysis of the influence of the mobility restrictions during the COVID-19 pandemic lockdown in Spain on the wellbeing of people. In this paper, we focus on the wellbeing of walkers and drivers during that period.

The dataset used for this study was collected through a web-based survey during April of 2020, in which 1870 valid responses were obtained. In this study a subpart of the survey is used, including data related to travel characteristics during the lockdown and information collected regarding several wellbeing metrics.

The total mobility of people was reduced more than half during the lockdown, and modal share was also altered substantially. Women increased walking by 44% and men by 48%.

The use of car was reduced by 24% in the case of men, and by 11% in the case of women.

Younger and older people are those who walked more during lockdown. Although walking was the predominant travel mode during the lockdown, those who walked more are related to lower values of wellbeing.

Implications for the development of transport policies to improve the wellbeing of people are derived from the results of this study.

1. INTRODUCTION

The lockdown of Spring 2020 to reduce the spread of the Covid-19 pandemic reduced the economic activity and restricted the mobility of people dramatically all over the world. Using phone data, it was estimated a reduction of weekday mobility between 50% and 60% of vehicles-km in Spain (MITMA, 2020). This reduction was high as 80% during weekends.

Travels between 0.5 and 2 km decreased between 40% and 50%, and those trips longer than 10km decreased between 70% and 80%. According to that study, personal mobility during the lockdown period reduced more than half. The limitation of mobility particularly impacted on public transport. Reductions of 90% of riders were registered in all public transport modes during the lockdown.

Among the negative effects of the limitation of mobility during the lockdown, we are interested in its influence on the wellbeing of people. Staying at home for long periods of time, the need for tele-working and attending classes on-line, and the prohibition of carrying out any out-door activity (except walking the dog), could possibly led people to experience negative feelings. Who was more affected? How (limited) walking and driving influenced wellbeing? What transport planning measures can be implemented to alleviate a lockdown impact on the wellbeing of people? The objective of this study is to answer these questions.

2. WELLBEING AND TRAVEL

Human beings seek to maximize their pleasure experiences, which is achieved through the satisfaction of preferences and minimization of pain with the aim of upgrading gratification in terms of happiness. This is the hedonic or subjective approach of wellbeing (Nordbakke & Schwanen, 2014).

On the other hand, wellbeing can also be achieved recognizing that living consistently with the true self is what inspires and gives meaning to one's life. This eudaimonic, objective or psychological wellbeing occur when the individual lives in congruence with his own value system, and eudaimonic discomfort will occur in the opposite case (Vázquez, Hervás, Rahona & Gómez, 2009).

How the use of each travel mode influence SWB has been extensively studied. For example, a literature review carried out by Ettema et al. (2016) indicates that using active travel modes results in higher travel satisfaction than using the car and in particular public transport. In this line, Morris and Guerra (2015) found that bicyclists present higher values of positive affect, followed by car passengers and car drivers. They also found that users of bus and train experience the most negative emotions.

Singleton et al (2019) found that walking/bicycling is associated with high values of health, confidence, and positive affect. Cycling commuters scored higher on distress, fear, and lower on security. On the contrary, results from the study of Zhu et al. (2019) indicate that the SWB of residents who commute walking or cycling was lower than that of those who commute by other travel modes. Respondents in this study lived in rural areas and cities with low urbanization, which could partially explain these results.

They also found that the longer the commute time, the lower the SWB, which is in line with results from Stutzer and Frey (2008), who found that people with longer commuting time report systematically lower SWB among public transport users. Lunke (2020) has also found that train commuters present highest levels of SWB.

During the Covid-19 pandemic only general studies of wellbeing have been carried out (Cheng et al., 2020; Zacher and Rudolph, 2020; Foa et al., 2020; Kimhi et al., 2020; Sibley et al., 2020; Anglim and Horwood, 2020; Suso-Ribera and Martin-Brufau, 2020). This study aims to fill this gap.

3. SURVEY DESCRIPTION AND DATA COLLECTION

The dataset used for this research was collected by a web-based survey that was designed ad-hoc for this study. The main aim of the survey was to gather information regarding the characteristics of out-of-home activities and the associated mobility during the lockdown in Spain, PWB indicators and positive and negative affect of people. The survey started on April 10, 2020 and ended on April 26, 2020. Respondent recruitment was done using two e-mailing lists including professional and personal contacts of the researchers, and senior students of the Universitat Politècnica de València. Besides, the web-survey was disseminated through personal and institutional on-line social media. Participants live in the Valencian Region of Spain.

The survey was divided in three parts. In the first part of the survey, respondents were asked to estimate their daily, weekly or monthly number of times they left home to perform each of the following out-of-home activities: working, grocery shopping, caring tasks, walking the dog, visiting the doctor, other shopping, and other activities (e.g., bank business). The usual travel mode associated to each activity, average time spent traveling and carrying out each activity per week were also collected. The second part of the survey includes questions to characterize PWB and positive and negative affect. Sociodemographic information is collected in the third part of the survey.

The variables included in the analyses are presented in Table 1. Continuous variables are used to measure walking and car use during the lockdown.

Variables	Description	Type
Sociodemographic		
Age	Age of the respondent	Continuous
Gender	0= male; 1 = female	Categorical
Education	1=none; 2=Primary; 3=Vocational; 4=Secondary; 5=Baccalaureate; 6=Non-university; 7=University	Categorical
Household size of respondents	Number of members in the house, including the respondent	Continuous
Household members > 70	People over 70 in respondent's household	Continuous
Household members < 6	People under 6 in respondent's household	Continuous
6 <= HH members < 12	People between 6 and 12 in respondent's household	Continuous
12 <= HH members < 18	People between 12 and 18 in respondent's household	Continuous
Household disable members	People with functional limitations in respondents' household.	Continuous
Type of housing	1=Apartment; 2=Detached or semi-detached house without garden nor private open-air space; 3= Detached or semi-detached house with garden and private open-air space; 4=Other	Categorical
Occupation	1=Student; 2=Employed, 3=Self-employed; 4=Student and employed; 5=Unemployed; 6=Retired; 7=Homemaker; 8=Other	Categorical
Changes on Internet use	1= I do not use it; 2= Less than before; 3=Same as before; 4= More than before; 5=Much more than before	Categorical
Working at home before the lockdown	1=Yes; 2=No	Categorical
Working at home during the lockdown (different from housekeeping)	1=Yes; 2=No	Categorical

Degree of work organization at home	Likert scale: 1=Very bad; 5=Very good	
Home location	1=Center of a big city (>100.000 inhab.); 2=Suburbs of a big city; 3=Mid size city (10.000-100.000 inhab.); 4=Small town (2.000-10.000 inhab.); 5=Village (<2.000 inhab.); 6=Low density city area; Other	
Net monthly income	1=None; 2=Less than 1.000 Euro; 3=1.000-2.000 Euro; 4=2.000-3.000 Euro, 5=3.000-4.000 Euro; 6=More than 4.000 Euro	
Mobility during the lockdown		
TRIPS	Number of times living home per week	Continuous
P_WALK	Percentage of walking when exit from home per week	Continuous
P_CAR	Percentage of car use when exit from home per week	Continuous
TIME_TRAVEL	Time traveling per week (minutes)	Continuous

Table 1. Definition of sociodemographic and mobility variables

Satisfaction and frustration of the three basic psychological needs were collected using the Spanish version for adults of the general Basic Psychological Need Satisfaction and Frustration Scale (BPNSNF) (Chen et al., 2015). This scale includes six four-item subscales to measure autonomy satisfaction (e.g. “I feel a sense of choice and freedom in the things I undertake”), autonomy frustration (e.g. “Most of the things I do feel like I have to”), relatedness satisfaction (e.g. “I feel that the people I care about also care about me”), relatedness frustration (e.g. “I feel excluded from the group I want to belong to”), competence satisfaction (e.g. “I feel confident that I can do things well”) and competence frustration (e.g. “I have serious doubts about whether I can do things well”). Respondents were asked to use a five-point Likert scale to declare if they totally disagree (1) or totally agree (5) with each statement.

Information regarding positive and negative affect were collected using the Positive and Negative Affect Scale (PANAS) (Watson et al., 1988) translated to Spanish by the authors of this research. PANAS includes 20-item self-report measure of positive and negative affect. High negative affect represents subjective distress and unpleasurable engagement, and low negative affect represents the absence of these feelings.

On the other hand, positive affect symbolizes the extent to which and individual experiences pleasurable engagement with the environment. For example, emotions such as enthusiasm and alertness are related to high positive affect, whilst lethargy and sadness characterize low positive affect. A five-point Likert scale was used in this scale as well.

4. SAMPLE CHARACTERISTICS

1,827 respondents provided valid data to all parts of the survey after validations and cleaning. The distribution of the sample according to gender is reasonable balance (Table 2). However, those whose age is between 45 and 64 are overrepresented in the sample. Similarly, those who are working (employed, self-employed and students that also work), are overrepresented in the sample as well.

One third of respondents belong to households that share with only another person (household size = 2) (Table 3). Respondent's household size equal to three are 24.7% of the sample, slightly higher than those equal to four (23.1%). Those who live alone are 12.1% of the sample. And those who live in households of five or more people are 7.3% of the sample.

Respondents living in apartments are most of the sample (78.8%). Those living in attached or semi-detached with garden and private open-air space are 16.0% of the sample.
Those living in big cities (100.000 or more inhabitants) are overrepresented in the sample; they are 60.3% of the sample. Respondents living in mid-size cities (10.000-100.000 inhabitants) are 20% of the sample.

	Respondents	**Percentage**
Gender		
Male	908	49,7%
Female	919	50,3%
Age		
18-25	265	14,5%
26-35	319	17,5%
36-45	301	16,5%
46-55	372	20,4%
56-65	378	20,7%
>65	192	10,5%
Occupation		
Employed	924	50,6%
Retired	293	16,0%
Student	223	12,2%
Student and employed	130	7,1%
Self-employed	115	6,3%
Unemployed	67	3,7%
Other	54	3,0%
Homemaker	21	1,1%

Table 2. Sample sociodemographic characteristics

	Respondents	**Percentage**
Household size		
1	221	12,1%
2	600	32,8%
3	451	24,7%
4	422	23,1%
5+	133	7,3%
Type of housing		
Attached or semi-detached with garden and private open-air space	293	16,0%
Attached or semi-detached without garden nor private open-air space	38	2,1%
Other	71	3,9%
Apartment	1425	78,0%
Home location		
Low density city area	109	6,0%
Center of a big city (>100.000 inhab.)	690	37,8%
Small town (2.000-10.000 inhab.);	151	8,3%
Mid-size city (10.000-100.000 inhab.);	366	20,0%
Other	20	1,1%
Suburbs of a big city	412	22,6%
Village (<2.000 inhab.);	79	4,3%

Table 3. Sample residence characteristics

5. MOBILITY DURING THE LOCKDOWN

The average number of times respondents left home to carry out any of the allowed activities during the lockdown was 4.9 per week, and the median value is 2.25.

Considering that the sample is overrepresented in those with age between 45 and 64, and those employed, the real value of mobility during the lockdown will be somehow lower. In any case, that value contrasts with the estimated mobility before the Covid-19 pandemic in the Valencian Region of Spain: average of 2.5 daily trips per person (Generalitat Valenciana, 2018). Therefore, the mobility during the lockdown was approximately half than before. This is in line with the study carried out by Ministerio de Transportes in Spain using cellphone data (MITMA, 2020), who reported reductions between 40% and 53% of vehxkm on the weekdays of the second half of March 2020.

Mobility during the lockdown was a slightly higher for men than for women and increased with age. Men left home a median value of 2.5 times per week, and women 2.25 times per week. On the other hand, those with age less than 26 presented the lowest mobility, leaving home only 1.5 times per week. Respondents between 26 and 45 years old left home 2.25 times per week. The highest mobility during the lockdown were performed by those between 46 and 65 years old, who left home 3.0 times per week. And the older respondents presented a mobility during lockdown of 2.0 exits from home per week.

The median value of time spent traveling per week during the lockdown was only 20 minutes for those younger than 26. This value increased to 33 minutes for respondents between 26 and 35 years old, and the value is a slightly higher for those between 26 and 45 years old. Participants between 46 and 55 years old spent the maximum time per week traveling: 58.7 minutes. Those between 56 and 65 years old spent a median value of 55 minutes traveling per week. And those older than 65 spent 38.1 minutes per week during the lockdown.

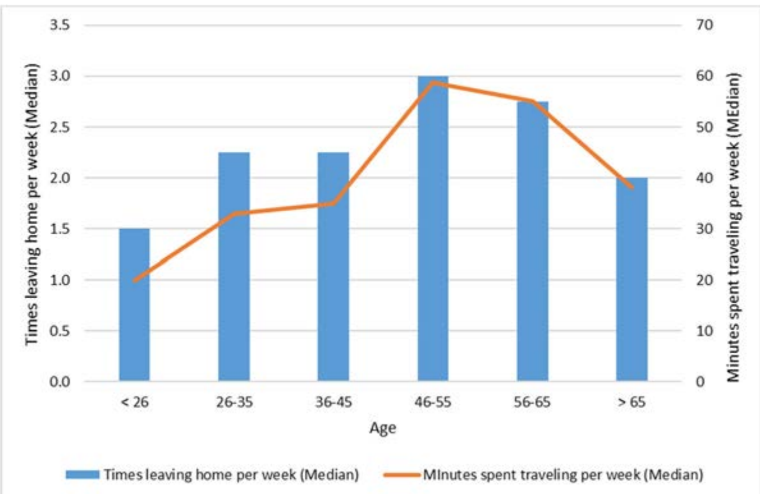

Fig. 1. Degree of mobility during the lockdown by age

The mobility was relatively high for self-employed respondents, who left home a median value of 3,25 times per week. Employed respondents left home 2,5 times per week. Students who also work left home 2 times per week, and students only left home 1,5 times per week. Those who do not work, nor study left home 2 times per week during the lockdown.

Self-employed participants in the study spent the maximum time traveling per week during the lockdown: a media value of 90 minutes. Employed respondents spent a much lower amount of time traveling per week: 45 minutes. Those who studied and were employed part-time spent 25 minutes per week traveling. Students spent the minimum amount of time traveling per week during the lockdown: a median value of 24.3 minutes.

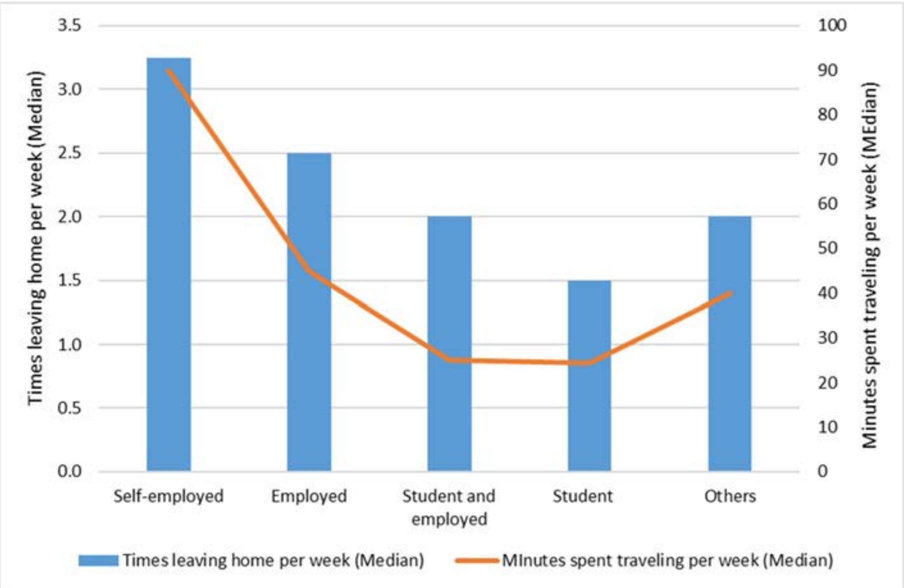

Fig. 2. Mobility during the lockdown by occupation

The travel mode most used when the participants of the study exit from home during the lockdown was walking: the percentage of walking was 77.5%. The second travel mode more used was car, but with only 18.9% of all times respondents left home. The rest of travel modes was hardly used: public transport (2.0%), Bicycle (0.8%), Others (0.8%). It is important to note that almost half of the individuals 849.2%) in the sample only walked when exit from home during the lockdown. In the case of those who used car, 29.7% did not used other travel mode.

Women walked a little bit more than men when leaving home during the lockdown (FIG 4). They also used less the car. Public transport was used by 3% of males, but only by 1% of females.

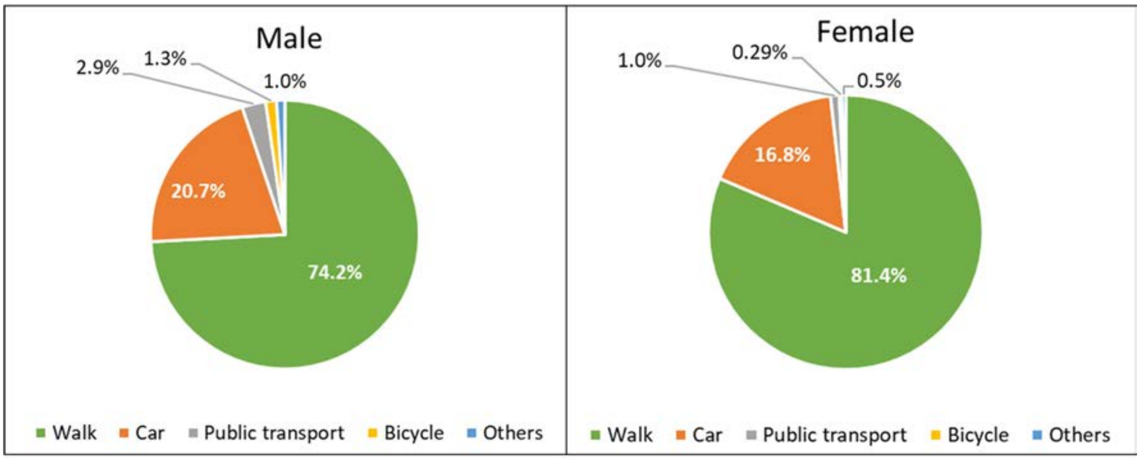

Fig. 3. Travel mode used by gender

The high percentage of walking is due to the consideration of home exits for walking the dog, an out-door activity allowed during the lockdown: more half of the number of times respondents left home walking was to take their dog for a walk (53.3%). The second most important motive for exit home walking is grocery shopping (26.7%). On the other hand, when respondents left home using the car during the lockdown was mainly for going to work (46.6%). Grocery shopping (32.3%) and caring others (14.4%) are the following motives to exit home using car in order of importance.

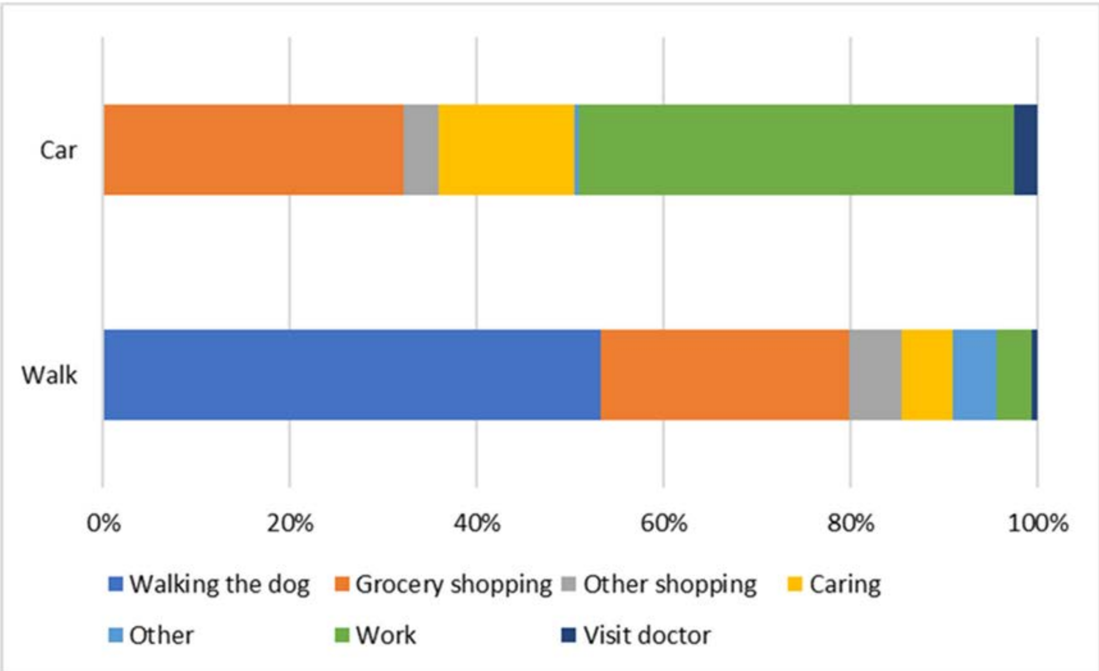

Fig. 4. Motives for leaving home by car and walking during the lockdown

When leaving home during the lockdown, the youngest respondents were those who walk the most (87.9%). In contrast, the walk share of those between 36- and 45-years is 69.8%.

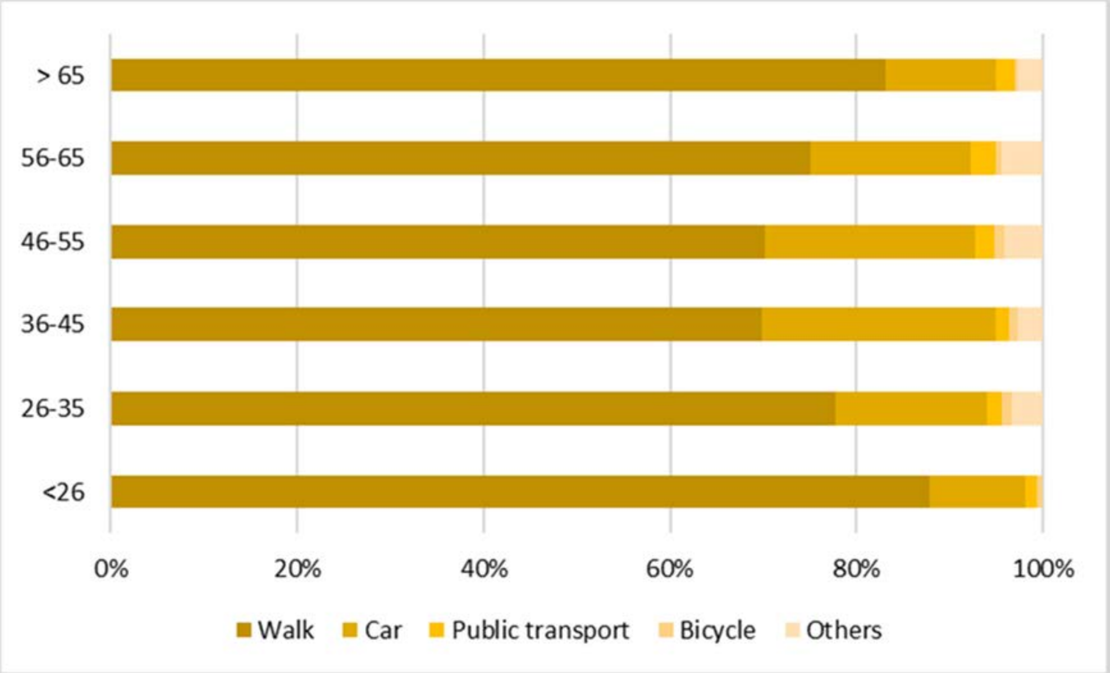

Fig. 5. Travel mode used by age

Mann-Whitney tests are used to find statistically significant differences among median values of PWB variables and Positive and Negative affect according to the characteristics of mobility during the lockdown.

Those who had a low degree of mobility during the lockdown (a median value of times leaving home per week lower than 1.25), and a percentage of walking higher than 66%, present statistically significant higher values of Positive affect (Z=-1.998, Sig=0.046) and lower values of Negative affect (Z=-2.139, Sig=0.032) than those with a percentage of walking between 33% and 66%.

On the other hand, participants who had a high degree of mobility during the lockdown (a median value of times leaving home per week between 2.25 and 6.00) and a low percentage of walking, present statistically significant higher values of Competence satisfaction (Z=-2.523, Sig=0.012) and lower values of Competence frustration (Z=-1.990, Sig=0.047) than those with a percentage of walking higher than 66%.

Similarly, respondents who had a very high degree of mobility during the lockdown (a median value of times leaving home per week higher than 6.0) and a percentage of walking between 33% and 66%, present statistically significant higher values of Positive affect (Z=-2.353, Sig=0.019) than those with a percentage of walking higher than 66%.

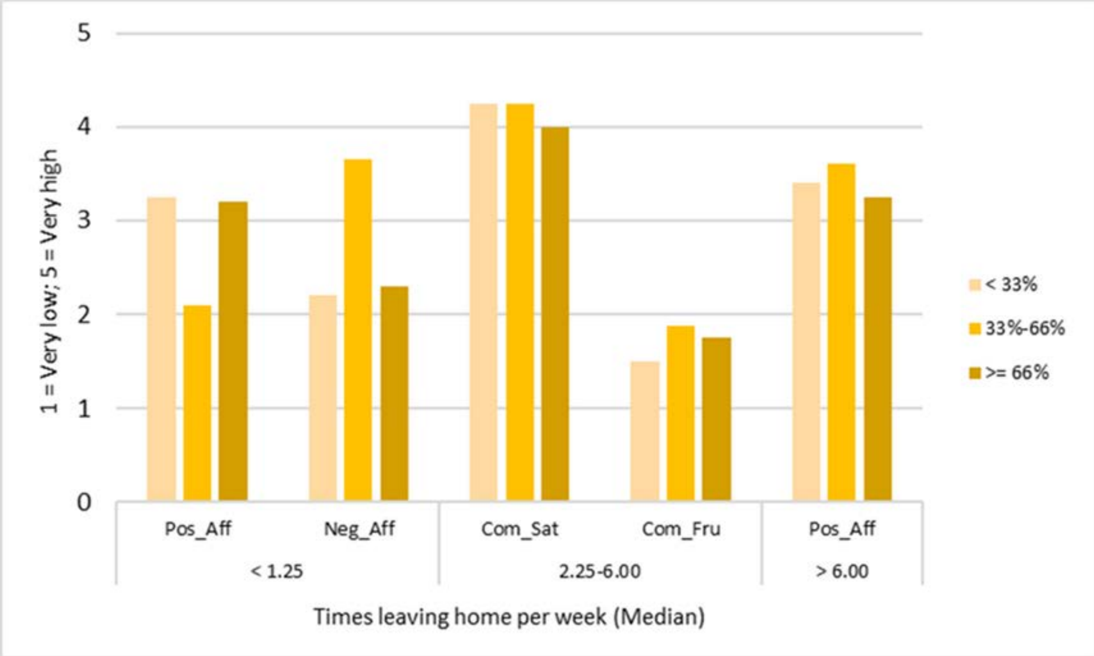

Fig 6. Significant differences of PWB indicators and Positive affect by degree of mobility and % of walking during the lockdown

Those who had a high degree of mobility during the lockdown and a low percentage of car use, present statistically significant lower values of Competence satisfaction (Z=-2.257, Sig=0.024) and Positive affect (Z=-2.289, Sig=0.022) than those with the higher percentage of car use.

Respondents who had a very high degree of mobility during the lockdown and a low percentage of car use, present a statistically significant lower values of Competence satisfaction (Z=-2.616, Sig=0.009) and Positive affect (Z=-3.961, Sig=0.000) than those who use the car between 33% and 66% when leaving home. They also have statistically significant higher values of Negative affect (Z=-2.206, Sig=0.027) than those with higher percentage of car use.

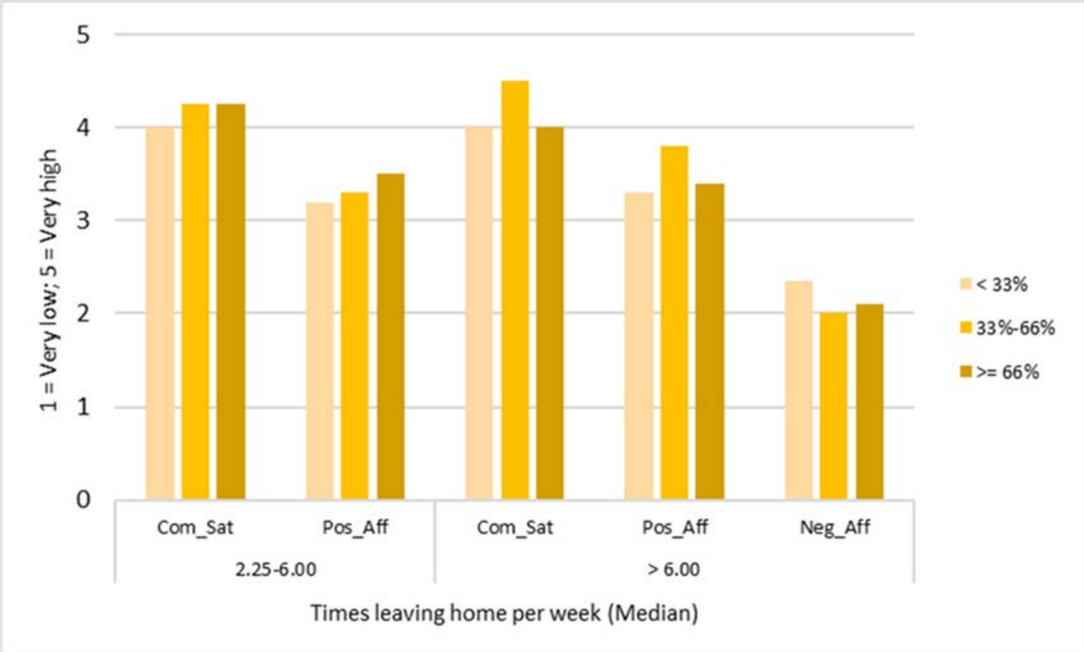

Fig 7. Significant differences of PWB indicators and Positive and Negative affect by degree of mobility and % of car use during the lockdown

Respondents who only walked when leaving home during the lockdown (n=899) present statistically significant lower values of Competence satisfaction (Z=-3.201, Sig=0.001) and Positive affect (Z=-2.215, Sig=0.027) than those who only used car (n=208). They also present statistically significant higher values of Competence frustration (Z=-2.817, Sig=0.005).

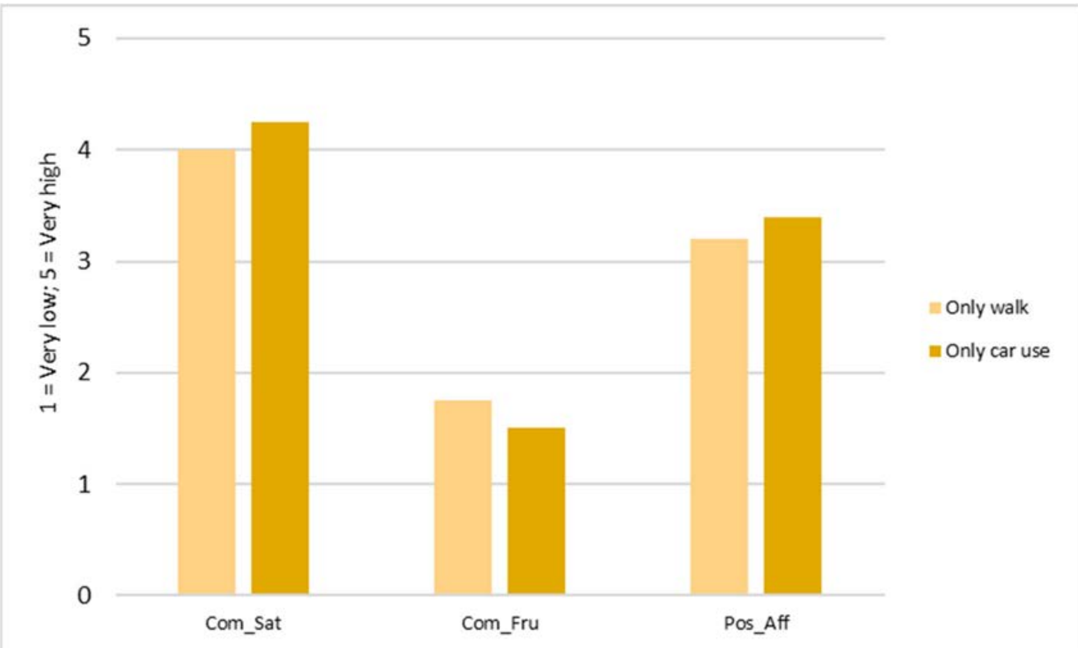

Fig 8. Significant differences of PWB indicators and Positive affect by only walkers versus only car users during the lockdown

Male respondents who only walked when leaving home during the lockdown (n=399) present a statistically significant lower competence satisfaction (Z=-2.506, Sig=0.012) than those who only used the car (n=199). Coherently, male only-walkers present higher competence frustration (Z=-2.995, Sig=0.003) than male only-car users.

Those between 25 and 44 years of age and only walked when leaving home during the lockdown (n=476) present a statistically significant higher competence frustration (Z=-2.672, Sig=0.008) than those who only used the car (n=83). On the other hand, respondents with 65 years old or more who only walked (n=476) present a lower relatedness frustration (Z=-2.272, Sig=0.023) than those who only used the car (n=83).

Self-employed respondents who only walked (n=40) present a higher competence frustration (Z=-2.190, Sig=0.028) and lower positive affect (Z=-2.177, Sig=0.029) than their only car users' counterparts.

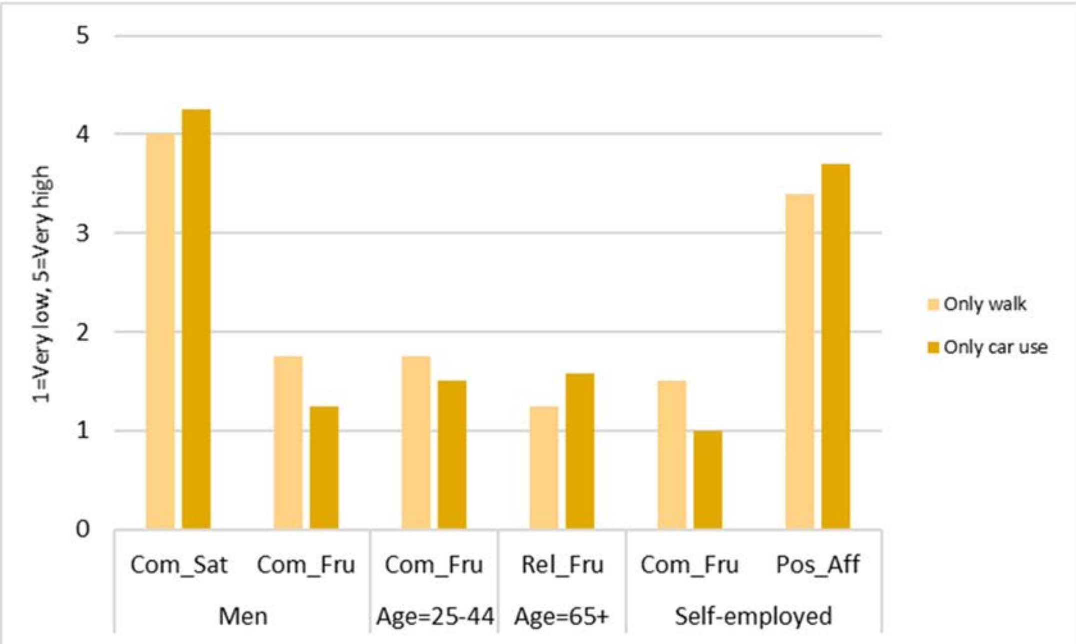

Fig 9. Significant differences of PWB indicators and positive affect of only walkers versus only car users during the lockdown by sociodemographics

Those living in an apartment who only walked when leaving home during the lockdown (n=769) present a statistically significant lower competence satisfaction (Z=-2.520, Sig=.012), and higher competence frustration (Z=-2.468, Sig=0.014) than those who only used the car (n=98).

Similarly, respondents who lived in attached or semi-detached houses with garden and private open-air space and only walked (n=70) present lower competence satisfaction (Z=-2.278, Sig=0.023) and higher competence frustration (Z=-2.780, Sig=0.005) than those who only used the car (n=88).

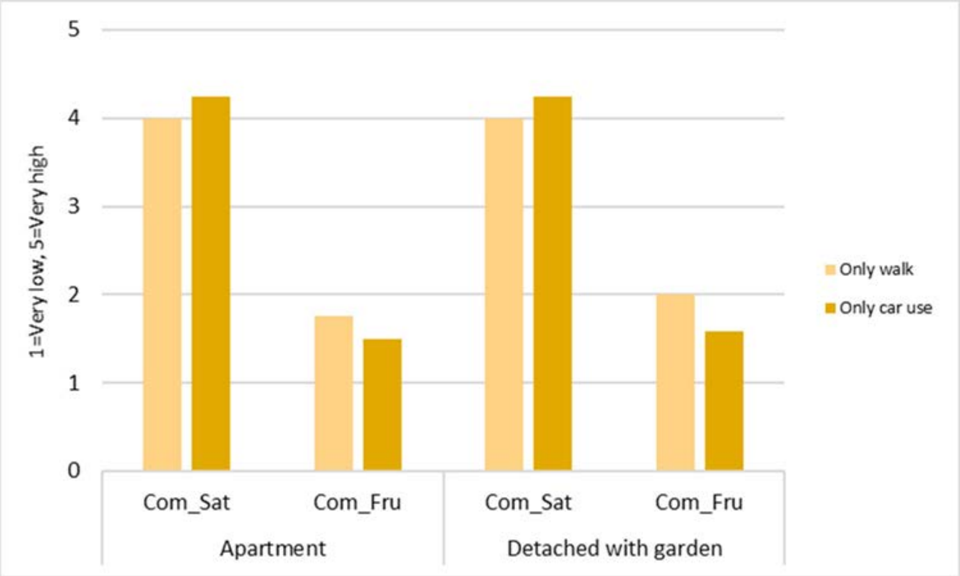

Fig 10. Significant differences of PWB indicators and positive affect of only walkers versus only car users during the lockdown by type of housing

Respondents living in 2-member households who only walked when leaving home during the lockdown (n=314) present a statistically significant a higher competence frustration (Z=-2.201, Sig=0.028) than those who only used the car. Logically, those living in 4-member households who only walked (n=173) present a lower competence satisfaction (Z=-2.448, Sig=0.014) than those who only used the car. And those living in 5+-member households who only walked (n=57) present a lower relatedness satisfaction (Z=-2.075, Sig=0.038) than those who only used the car.

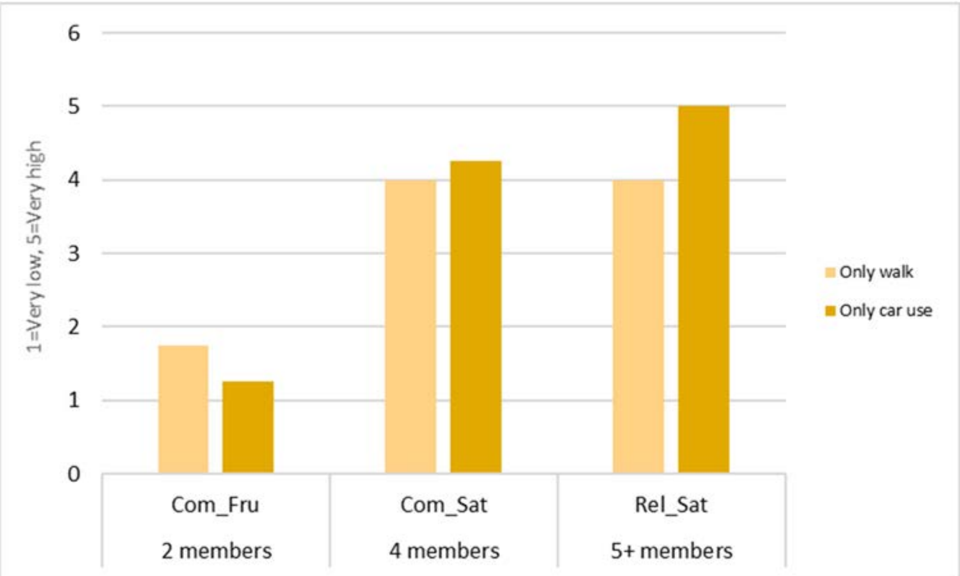

Fig 11. Significant differences of PWB indicators and positive affect of only walkers versus only car users during the lockdown by household size

Those living in the suburbs of a big city who only walked when leaving home during the lockdown (n=219) present a statistically significant lower competence satisfaction (Z=-2.070, Sig=0.038) and higher competence frustration (Z=-2.803, Sig=0.005) than those who only used the car. Respondents living in mid-size cities and only walked (n=161) present a higher competence frustration (Z=-2.490, Sig=0.013) than those who only used the car.

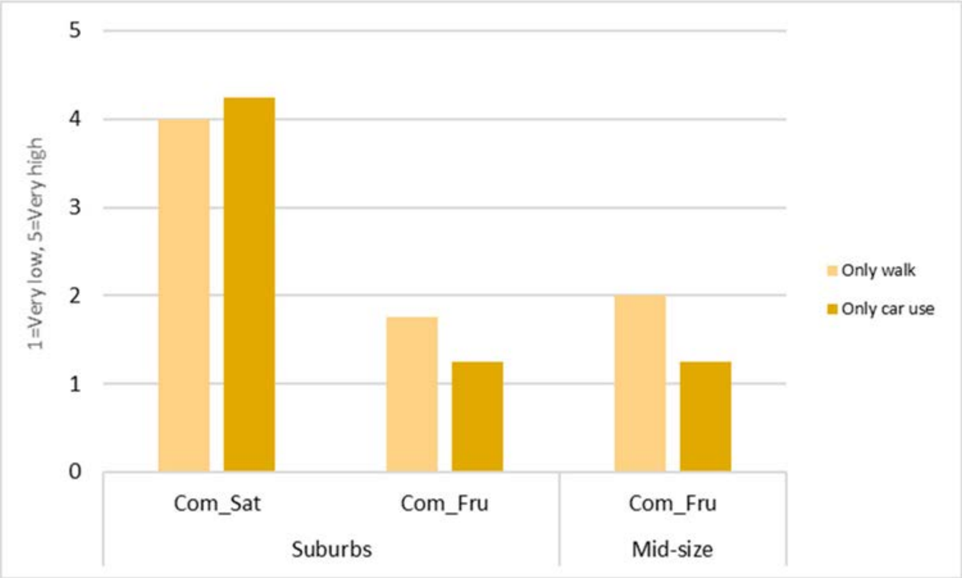

Fig 12. Significant differences of PWB indicators and positive affect of only walkers versus only car users during the lockdown by home location

6. CONCLUSIONS

This paper presents a study of wellbeing of people during the lockdown of March and April 2020 cause by the Covid-19 pandemic in the Valencian Region of Spain. Descriptive and confirmatory analyses are used to study the influence of sociodemographic characteristics of the participants in the research and their mobility attributes on their satisfaction and frustration of basic psychological needs and positive and negative affect.

Mobility was characterized by the percentage of walking and car use when leaving home during the lockdown. For those with a higher the percentage of walking present a lower competence satisfaction and a higher the competence frustration. Moreover, those with the highest degree of mobility during the lockdown and a percentage of walking between 33% and 66% present statistically significant higher values of positive affect than those with a percentage of walking higher than 66%. Only those with a low degree of mobility during the lockdown present statistically significant higher values of positive affect and lower values of negative affect when walking more. These results contrast with the findings related to walking and SWB elsewhere.

During the lockdown people felt more insecure when walking because of the possibility of contagion, which was amplified in urban areas with insufficient pedestrian infrastructure. Besides, walking along complete empty streets increase the sense of insecure (Ferrer et al., 2015).

Some statistically significant differences are found when considering the percentage of car use. Results from the Mann-Whitney test reveal that the more car use, the better the feel in terms of competence satisfaction and positive affect, and present lower values of negative affect. Using car during the lockdown was perceived by people as more secure. During the first weeks of the lockdown, authorities recommended to use private vehicles to those that had to leave home. This fact emphasized the sense of security associated with car, but deteriorated the health security perception of public transport, which persist until today.

Using a subsample of those who only walked or only used car when leaving home during the lockdown, Mann-Whitney tests confirm previous findings: those who only walked felt somewhat worse than those who only used car in terms of competence satisfaction, positive affect and relatedness satisfaction. In particular, men, those living in apartments and attached or semi-detached houses with gardens, those living in 4-member households and those living in the suburbs of big cities, present lower competence satisfaction and higher competence frustration if they only walked. Those self-employed who only walked present lower positive affect. And those living in 5+-member households who only walked present lower relatedness satisfaction. Many people who only walked when leaving home during the lockdown were not used to do it, and they had to walk threaten by the pandemic.

On the other hand, most of those who only drove just kept doing the same thing than before but with the sense of being safer from contagion.

Despite the participants in the research walked a lot during the lockdown, results of this study indicate that those who walked more and those who only walked when leaving home felt somewhat worse compared with those who only used car. There is a need to improve pedestrian infrastructures to provide enough space for people to walk, considering not only the level of service but also health security, which is a factor that should be considered in all transportation planning studies from now on.

ACKNOWLEDGMENTS

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ANALYSIS OF UNIVERSAL ACCESSIBILITY AT PUBLIC TRANSPORT STOPS IN THE CITY OF CÁCERES

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ABSTRACT

When dealing with the problems of urban transport, in many cases only the supply and demand, number of users and urban design are analysed, i.e. aspects that influence the operational functioning of the concession of this public service.

The study proposed in this article aims to analyse the situation of public transport stops in the city of Cáceres following the criteria required by current legislation on universal accessibility, trying to identify the architectural barriers encountered by users of the service who have some physical limitation.

Once the existing regulations have been evaluated and the technical requirements to be met have been defined, a critical study of compliance with the legislation in force at the existing bus stops is carried out. Subsequently, solutions are provided in the event of non-compliance in order to solve the adaptation of urban transport in terms of accessibility and the proposal of specific solutions for improvement in various areas under study is formulated. In addition, the main operational problems detected in the accessibility infrastructures for this means of transport are indicated.

After analysing the problems presented by the network of public urban transport stops, it could be pointed out that most of them are the result of a lack of coordination between the general urban development plan and the mobility plan, which prevents the adequate provision of public services.

1. INTRODUCTION AND OBJECTIVES

The city of Cáceres is a medium-sized municipality with deep-rooted habits, one of which is the use of private vehicles for daily commuting and also for mobility from the outskirts to the city centre, which until now has allowed free surface parking, unintentionally facilitating an increase in the use of private vehicles. According to the Infrastructure Plan for Sustainable Urban Mobility (PIMUS) of Cáceres approved in 2014, 55% of the overall mobility of the municipality is carried out by private vehicle.

In this sense, in comparison with other Spanish cities of similar average size, the use of soft modes of transport is low, which can be attributed mainly to two aspects: 1) the topographical conditions of the city and 2) the behaviour of the user who opts for motorised mobility as an indicator of their quality of life.

In relation to public transport, which represents a small percentage of the total number of journeys made by residents in Cáceres (around 9%), the Local Administration is working to increase its share of daily mobility. In order to make the use of public transport more attractive, awareness campaigns are being carried out to promote public transport to the detriment of private transport within the concept of sustainable urban mobility.

The degree of satisfaction shown with the quality of the urban public transport service by users leads to the conclusion that a service is being provided that is adjusted to the particular needs of the city, promoting sustainable mobility and adapting to the economic resources allocated to the financing of this service (Jiménez-Espada, 2016).

A drawback of the current planning and development model of the city of Cáceres is the lack of reserved lanes for public transport, as well as the lack of bans at bus stops, issues that delay the frequency of bus stops, making the use of public transport less attractive and reducing the number of users.

Numerous actions and initiatives have been carried out in the field of universal accessibility, which have been recognised with the following awards: Queen Sofia Accessibility Award 2012 (a distinction that recognises those city councils that stand out for their ongoing work in the field of universal accessibility for people with disabilities) and the Best Accessible Tourism Destination Award 2014 in Spain (promoted by the company ThyssenKrupp, which recognises the efforts of institutions to eliminate architectural barriers and the fight for equality for people with disabilities). To date, there is still much work to be done in Cáceres to achieve universal accessibility for people with reduced mobility.

In (Fernández-Nicolás, 2019), the current urban accessibility in the intramural area of the historic centre of the city of Cáceres is addressed, setting out actions carried out and proposals for future interventions presented to the competent bodies for approval, applying a model for the promotion of urban accessibility to try to achieve tangible universal accessibility for all types of users, sometimes very limited by the existing conditions but which, even without reaching regulatory compliance, could undoubtedly improve the critical points detected.

In urban transport, accessibility depends on the distance and ease of travel from the home to the interchange point and from there to the final destination, including access on the way up and down, as well as the planning of the overall route.

Making public bus transport more attractive and increasing the quality of the service in terms of accessibility can have a positive effect on the main actors involved:

1) For disabled people and people with reduced mobility, who will directly benefit from the improved accessibility of buses. Accessible public transport offers a greater degree of safety for these users.
2) For the service concessionaires, who, by increasing the number of potential users, will improve their bottom line; an adapted bus with accessibility systems (ramp, low floor, etc.) will give security and confidence to people with disabilities, enabling them to shorten boarding and alighting times. In general, there will be greater efficiency in the management of services, which will benefit the companies' objectives.
3) For society as a whole, which will see a general improvement in public transport; this will attract a greater number of users who, in many cases, will abandon the car, helping to increase the environmental quality of the city by reducing pollution, traffic congestion and accidents. Accessible transport ensures safe and comfortable access for all passengers (Vega, 2006).

Transport will be accessible when it allows people to meet their travel needs independently. To achieve this, stations or stops must have the appropriate characteristics to enable all people with disabilities, both physical and sensory, to travel. In addition, vehicles must have the necessary design conditions and technical solutions to allow communication between all persons.

The idea of accessibility and the way it has been promoted by the different public administrations over the last two decades has come to be best expressed in the form of new concepts and approaches such as Design for All or Universal Design and Integrated Accessibility (Alonso, 2002).

The aim of the study proposed in this article is to analyse the situation of public transport stops in the city of Cáceres in accordance with the criteria required by current legislation on universal accessibility and to offer solutions to the existing problems in the event of non-compliance in order to solve the problem of adapting urban transport in terms of accessibility.

2. ACCESSIBILITY IN PUBLIC TRANSPORT

2.1 The bus network in the city of Cáceres

The city of Cáceres has a population of 96,126 inhabitants, according to the latest data consulted at the National Statistics Institute (INE). The municipality has three districts: Rincón de Ballesteros, Valdesalor and Estación Arroyo-Malpartida, which are also served by the city bus. The company SUBUS (belonging to the VECTALIA group), is the concessionaire of the public passenger transport service in the city. It currently has a fleet of 37 vehicles (29 conventional 12-metre buses, 6 articulated 18-metre buses and 2 minibuses). All buses have a low floor, kneeling system (kneeling) and manual ramp. In addition, two thirds of the bus fleet has a double electric ramp, which is backed up by a manual ramp in the event of a breakdown.

The current bus service in the city of Cáceres has a total of 218 bus stops, distributed around 12 regular lines and 2 occasional lines. Of the 218 existing public transport stops, only 138 of them have a bus shelter.

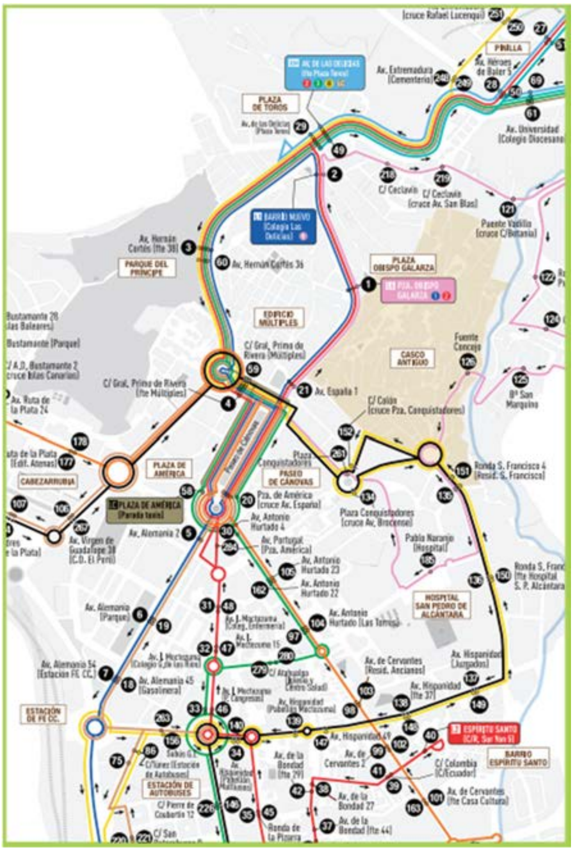

Fig. 1 – Network of bus lines in the city centre (SUBUS, 2020)

With regard to the number of users of this service, it should be noted that in recent years there has been an overall increase in passengers on the lines, which may be due, among other factors, to the management carried out by the representatives of the local administration, who have made a firm commitment to campaigns to publicise the benefits of public transport and have worked in coordination with the concessionary company to implement improvements to the service.

In this regard, efforts have been directed towards modernising and upgrading the urban transport service by contemplating the following measures:

1) Implementation of operating aid systems (SAE) to know the waiting time, mobile applications, recharging of vouchers via internet, installation of USB connections for charging mobile devices on board.
2) Increase in the number of vehicles in the fleet and their integral renovation, as well as the restructuring of lines and the construction of a new city bus station in the city centre.
3) Modification of fares and creation of new types of transport tickets (combined ticket, vouchers for large families, IMAS (Municipal Institute of Social Affairs) social vouchers).

Figure 2 shows the evolution of urban transport passengers over the last 6 years in the city, showing a gradual increase of users using the bus from 2015 to 2019, gaining 355,115 passengers, an increase of just over 8% in 5 years. However, in 2020, ridership plummeted due to the COVID-19 pandemic, with a decrease in ridership of almost 40% compared to 2020.

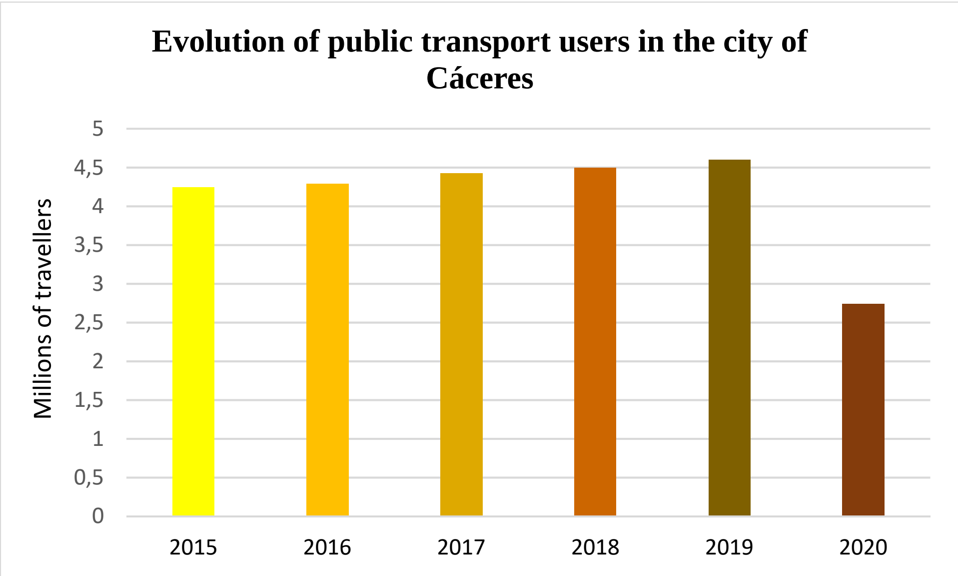

Fig. 2 – Bus passenger registration in Cáceres

2.2 Accessibility issues

According to the Green Paper (Alonso, 2002), the main accessibility problems in urban buses are: the relationship between the pavement and the vehicle, as well as the availability of easy and comfortable boarding systems for all types of users. In addition, other aspects are mentioned such as: space, layout and anchorages for wheelchairs or pushchairs in the vehicles. As basic accessibility indicators, the number of low-floor buses and their proportion of the total are used, and as support indicators, the number of vehicles with ramps and kneeling systems in use and their proportion of the total. In addition, in (Alonso, 2003) White Paper, a series of social and institutional aspects are included, such as: driver training, child buggy access rules and traffic discipline.

The key factors of universal accessibility in transport are usually considered around 4 lines of work: infrastructure, rolling stock, the link between the two and the provision of the service. The guarantee of accessible mobility through public transport is based on the achievement of and compliance with the accessibility conditions set for each of the spaces and moments in the passenger mobility chain. In order to facilitate universal accessibility in rolling stock, (Álvarez, 2011) proposes buses with a low floor and tilting systems for the vehicle that, together with the deployment of small mobile ramps, make it possible to overcome the almost inevitable differences in level with the environment. Buses depend both on the human factor (drivers) and on external factors such as improper parking of vehicles in the vicinity of stops, which make it difficult for the vehicle to get as close to the stop as possible.

Urban transport systems have specific accessibility needs that are determined by the characteristics of these modes of transport, in which there is a large influx of passengers and a frequency that determines the stopping time. These services meet the mobility needs of a population centre and have pre-established routes, subject to specific timetables. They are characterised by seating and standing room and frequent stops. Stops and bus shelters must be accessible to people with reduced mobility and have accessible equipment and furniture (Díaz, 2018). In addition, it is necessary to ensure access to the vehicle by means of low floors, platform lifts, drop-down ramps and kneeling systems. The driving of the vehicle is also important when it comes to guaranteeing the safety of users, who must drive at the appropriate speed for each type of road and avoid driving abruptly. Inside the vehicle there must be spaces reserved for wheelchair users with their corresponding anchorages and safety belts. Likewise, spaces must be reserved for people with reduced mobility.

As indicated in (Alonso, 2010), bus shelters must have information corresponding to the identification, name and route diagram of the lines, as well as a screen that informs users of the location and incidents of the buses on the lines corresponding to that stop.

In Europe, since the early 1990s, the use of low-floor buses on urban transport routes has become widespread (Dols and Vázquez, 2016). According to the information provided in the latest report of the Metropolitan Mobility Observatory (Monzón et al., 2019), it can be said that all of the 14 urban public transport lines in the city of Cáceres have a fleet of buses fully accessible for people with reduced mobility (PRM), the bus being the most accessible means of urban transport for this group, with 100% coverage in operating assistance systems (SAE) and e-ticketing and 10 stops with real-time information panels.

However, public transport stops should be equipped with shelters and perfectly delimited, which in practice is not the case in the vast majority of cases. This fact leads to the appearance of badly parked vehicles that prevent the bus from approaching the bus properly for the boarding and alighting of passengers with reduced mobility and the deployment of the access ramp.

In order to assess the degree of accessibility at public transport stops in the city of Cáceres, the considerations of Royal Decree 1544/2007 are used, whose scope of application in urban buses extends to: stops and rolling stock (vehicles for collective urban transport and with a capacity of more than nine seats, including the driver).

This regulation states that public transport stops and waiting shelters shall be connected to the accessible pedestrian route (IPA) and shall not encroach on it, establishing basic conditions for accessibility in urban transport.

3. RESULTS AND DISCUSSION

The aim of the study proposed in this article is to improve universal accessibility at regular public transport bus stops in the city of Cáceres. In this chapter, taking as a reference the existing regulations that define the technical requirements to be met, a critical study of compliance with the legislation in force (Royal Decree 1544/2007) of all existing bus stops is carried out. Subsequently, solutions are provided in case of non-compliance in order to solve the adequacy of urban transport in terms of accessibility and the proposal of specific solutions for improvement in various areas under study is formulated. In addition, the main operational problems detected in the access infrastructures to this means of transport will be pointed out.

3.1 Bus stops with operational problems

Taking as a reference the regulatory development of RD 1544/2007, of the 218 bus stops currently in service in the city of Cáceres, problems have been detected in 91 of them in terms of universal accessibility, and an inventory has been drawn up, in which the deficiencies are defined on the basis of a series of criteria that help to detect and recognise them.

In the 91 public transport stops analysed, the main errors detected were summarised according to the source of the problem. Thus, the main difficulties were as follows:

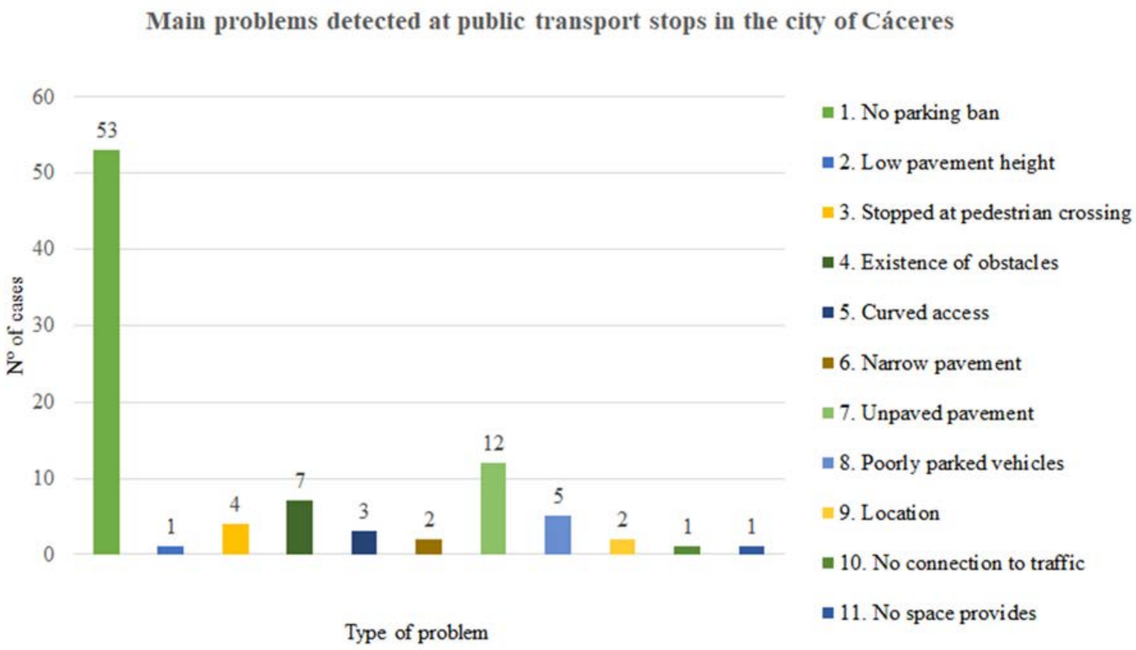

Fig. 3 – Type of problem

The most frequently repeated problem is the lack of parking bans (58% of cases) or, if they exist, they are not correctly signposted. The study shows that a large part of the non-compliances found are due to a lack of planning, as a result of the successive extensions of the network itself in order to solve the problems that have arisen over time in each neighbourhood.

3.2 Proposals for change to improve bus accessibility for people with disabilities

Next, corrective measures are proposed for some specific stops with operational problems of the kind described above, in an attempt to provide standard solutions that can make these stops viable from the accessibility point of view.

By resolving each type of difficulty, the door is opened to propose standard solutions, with the aim of improving journey times and line frequencies, quantitatively reducing the boarding and alighting times of users, thus improving the quality of the service offered to these potential passengers with accessibility problems.

Fig. 4 – Problems type 1, 2, 3

The picture above shows problem typologies 1, 2 and 3. The photograph on the left shows a stop on the university campus with no parking ban for private vehicles, which means that this space is not usually available for buses to approach. It is proposed that the corresponding vertical and horizontal signage be installed to identify the space reserved for public transport. The central image shows a common problem in many cities: the pavement is not high enough for the bus to kneel down. In this case, it is proposed to increase the height of the pavement to 20 cm by means of an anti-slip pavement. The photograph on the right (at 54 Bondad Avenue) shows an undesirable image, the bus stop is located in the middle of a pedestrian crossing. It is felt that it would be appropriate to dispense with the two adjacent parking spaces, widening the pavement in that area and moving the bus shelter away from the zebra crossing and allowing pedestrians to move freely.

Fig. 5 – Problems type 4, 5, 6

The previous figure on the left shows the impossibility of approaching urban transport to the pavement, which is not accessible to people with reduced mobility. The problem is solved by raising the raised kerb to the edge of the road, gaining the necessary area for the location of the stop, which is connected to the pedestrian route by means of a small ramp.

The central image shows that the public transport access is curved. In order to allow the correct approach of the bus, parking is prohibited in the adjacent area, which provides extra space for the vehicle's turning manoeuvre. In the upper right image, a pavement is evaluated that does not comply with the regulations (it is less than 120 cm wide) and does not have a connection for people with reduced mobility. The proposed redefinition of the stop consists of widening the pavement by building a much wider cantilevered platform that connects to the lower level by means of an accessible ramp.

Fig. 6 – Problems type 7, 8, 9

The top left image shows a green area between the pavement and the road, making it impossible for a person with reduced mobility to access the bus. To solve the problem, the pavement should be extended to the edge of the road, thus creating a platform that would allow guaranteed access to urban transport. The central image shows a common inconvenience at bus stops, the indiscipline of the private vehicle driver. The construction of a raised reserved area extending from the pavement to the road would solve the problem. On the other hand, the upper right image shows an example of a poor location of a bus stop immediately after a curve and without a pedestrian crossing nearby, the solution to which is to move it just before the curve (in a straight area), allowing the construction of a bus shelter before a pedestrian crossing.


Fig. 7 – Problems type 10, 11

Figure 7, left-hand side, shows a disconnection with traffic, which could be solved by completing the pavement in the stop area and moving the bus shelter to the centre of this area. On the right-hand side of the image there is no space specifically designated for public transport stops. A rearrangement of the area is proposed, defining an entrance area where the minibus providing the service can stop and turn around by means of a semi-curve. In this way, the bus will not stop in the middle of the street and there will be an area for pedestrians from which the bus can be properly accessed.

Incorrect parking at zebra crossings or bus stops is reduced when there are accessibility features such as low thresholds or platforms. Therefore, it is of particular importance to carry out all those adaptation works at public transport stops that improve accessibility in compliance with the guidelines of RD1544/007.

There are people with reduced mobility who decide to buy non-approved electric scooters to be able to use public transport and who subsequently find that their mobility is reduced because they are unable to use this type of vehicle on the bus. It would be advisable to carry out public information campaigns on accessibility systems on buses.

4. CONCLUSIONS

For the correct development of this work, regular urban passenger transport in the city of Cáceres has been analysed and, specifically, the situation regarding the accessibility of the bus stop network.
Firstly, the conditions of access to public transport stops have been assessed, a service that currently has a total of 218 stops.

Based on the universal accessibility regulations applicable to urban passenger transport (RD 1544/2007), 91 stops have been identified as having accessibility problems for people with reduced mobility and an inventory of these has been carried out, identifying 11 common problems.

Subsequently, corrective measures have been provided for some specific stops that have been adopted as examples and that presented different problems in order to make them accessible.

Having analysed the problems with the network of urban public transport stops in the city of Cáceres, it could be said that most of them are the result of a lack of foresight of new needs, and that they could have been avoided by planning the network in parallel with the development of the new neighbourhoods that have generated these needs.

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¿A QUIÉN AFECTA MADRID CENTRAL?
ANÁLISIS DE LOS CAMBIOS EN EL TRÁFICO TRAS UN AÑO DESDE SU IMPLANTACIÓN.

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RESUMEN

En noviembre de 2018, se puso en marcha Madrid Central, una zona de bajas emisiones en la ciudad que tiene como objetivo favorecer al peatón, la bicicleta y el transporte público, limitando el acceso de una gran parte del parque de vehículos privados, en una superficie de 472 ha. La medida ha resultado ser de gran relevancia para la opinión pública y se espera que haya modificado de manera sustancial los patrones de movilidad en el centro de Madrid y sus alrededores.

El objetivo de este trabajo es estudiar los cambios producidos en el tráfico por la implantación de Madrid Central, tanto dentro del perímetro de la zona de bajas emisiones como en su área de influencia, y analizar si existen tendencias que correlacionen con variables socioeconómicas de la ciudad o tendencias espaciotemporales. Para lograr este objetivo, se analizan datos públicos de tráfico del Ayuntamiento de Madrid (Sistema Integral de Control de Tráfico de Madrid, SICTRAM).

En concreto, se analiza la intensidad de tráfico, el número de vehículos por hora que circulan por las calles. Se han descargado datos desde enero de 2018 hasta diciembre de 2019, lo que permite realizar un análisis de su evolución temporal y espacial, tanto en el área de bajas emisiones como en los distritos colindantes, y relacionarla con la implantación de Madrid Central.

Asimismo, se analizan variables socioeconómicas de la población directamente afectada por la medida (población y renta anual neta). Este análisis se realiza de manera gráfica, visualizando los resultados espacialmente y temporalmente. Los resultados del análisis muestran una disminución general en el tráfico de la ciudad, aunque esta no se distribuye homogéneamente.

1. INTRODUCCIÓN

Disminuir la contaminación atmosférica en las ciudades es una de los mayores retos ambientales actuales, ya que allí es donde encontramos las mayores densidades de población (Gakidou, 2017; Santiago et al., 2021). La contaminación perjudica seriamente la salud de las personas, aumentando los riesgos de enfermedades respiratorias y cardiovasculares, (Chiusolo et al., 2011; Medina-Ramón, 2006; Santurtún et al., 2017) o el riesgo de cáncer (Vineis et al., 2006). Diferentes ciudades europeas han iniciado acciones para reducir los efectos negativos de la contaminación en los últimos años, como: Berlín, Paris, Viena, *etc*. (Viana et al. 2020). El municipio de Madrid es la ciudad más poblada y con mayor tráfico de España. Existe actualmente una importante preocupación en relación a la calidad del aire y la mejora de la configuración urbana. Con el objetivo de mejorar esta situación, desde el ayuntamiento se han estado poniendo en práctica diferentes medidas de gestión del tráfico. En el año 2004, se comenzaron a implantar en Madrid un nuevo conjunto de restricciones al tráfico para limitar la circulación por diferentes zonas, denominadas Área de Prioridad Residencial (APR), siendo la primera en el Barrio de las Letras (Ayuntamiento de Madrid, 2007). Este proceso de delimitar el tráfico en el centro de la ciudad ha ido incluyendo nuevas zonas hasta culminar con la creación de la zona cero de emisiones de Madrid central el 30 de noviembre de 2018, y siendo el 15 de marzo de 2019 cuando se hizo realmente efectiva, al comenzar las sanciones por incumplir las restricciones impuestas. Las medidas impulsadas buscan priorizar el movimiento peatonal, el uso de la bicicleta, el transporte público y los vehículos eléctricos o de bajas emisiones.

Esta área permanente cumple con los criterios que autores como Laña et al. (2016) proponen como solución para la ciudad de Madrid por sus características. El área limitada coincide aproximadamente con los límites del distrito centro de Madrid (Figura 1).

Entre los objetivos que planteaba el Ayuntamiento de Madrid en el Plan A de Calidad del Aire (Ayuntamiento de Madrid, 2017), se pueden destacar los siguientes: (i) mejorar los niveles de calidad del aire para partículas en suspensión (PM) según las recomendaciones de la OMS (Organización Mundial de la Salud); y (ii) cumplir el compromiso de reducción del 50% de las emisiones causadas por la movilidad urbana en 2030 con respecto a 2012.

Estos objetivos se pueden relacionar directamente con la cantidad de tráfico en la ciudad.

Actualmente, el Plan A de Calidad del Aire, ha sido sustituido por la Estrategia de Calidad Ambiental Madrid 360 (Ayuntamiento de Madrid, 2019a), que amplía en un 15% sus objetivos de reducir las emisiones y añade otras medidas como el servicio de varias líneas de autobús gratuitas.

El impacto de la medida de Madrid Central ha sido estudiado previamente. Salas et al. (2021) se centraron en el análisis de indicadores de los niveles de contaminación: la evolución de las emisiones de NO_2 entre 2015 y 2019); Izquierdo et al. (2020) estudiaron el aumento entre 2012 y 2020 del NO2, PM2.5 y O3, y su correlación con la disminución de muertes relacionadas con la contaminación); y Santiago et al. (2021) investigaron la incidencia de la contaminación en puntos clave de la ciudad, obteniendo unos resultados que relacionan de manera positiva las medidas tomadas con una reducción de la contaminación. Este trabajo complementa estos resultados previos, aportando un enfoque diferente, centrado en la evolución del tráfico el año previo a la implantación del Madrid Central y el año posterior, como se ha realizado previamente en otros trabajos (Vidal, 1990; Gutiérrez y García, 2005).

Fig. 1 – Límite de la zona de cero emisiones de Madrid Central (Elaboración propia a partir de los datos del MTN50)

2. MATERIAL Y MÉTODOS

El Ayuntamiento de Madrid dispone de un dispositivo de muestreo del tráfico (Sistema Integral de Control de Tráfico de Madrid, SICTRAM) donde se recogen los datos de intensidad, carga y ocupación del tráfico, cada 15 minutos desde el año 2013. Se trata de un dispositivo móvil donde las estaciones pueden variar a lo largo de los meses.

Aproximadamente se toman datos en 4500 estaciones de forma mensual.

Para evaluar el impacto de la medida implantada, el análisis se ha centrado en la intensidad de tráfico (vehículos/hora) al ser la variable más relacionada con la calidad del aire y la contaminación acústica de las disponibles en las estaciones de medición del tráfico. En total, se han seleccionado un total de 3561 estaciones de medición, incluidas dentro de la zonificación definida y con datos a lo largo de todo el alcance temporal establecido (Figura 2)

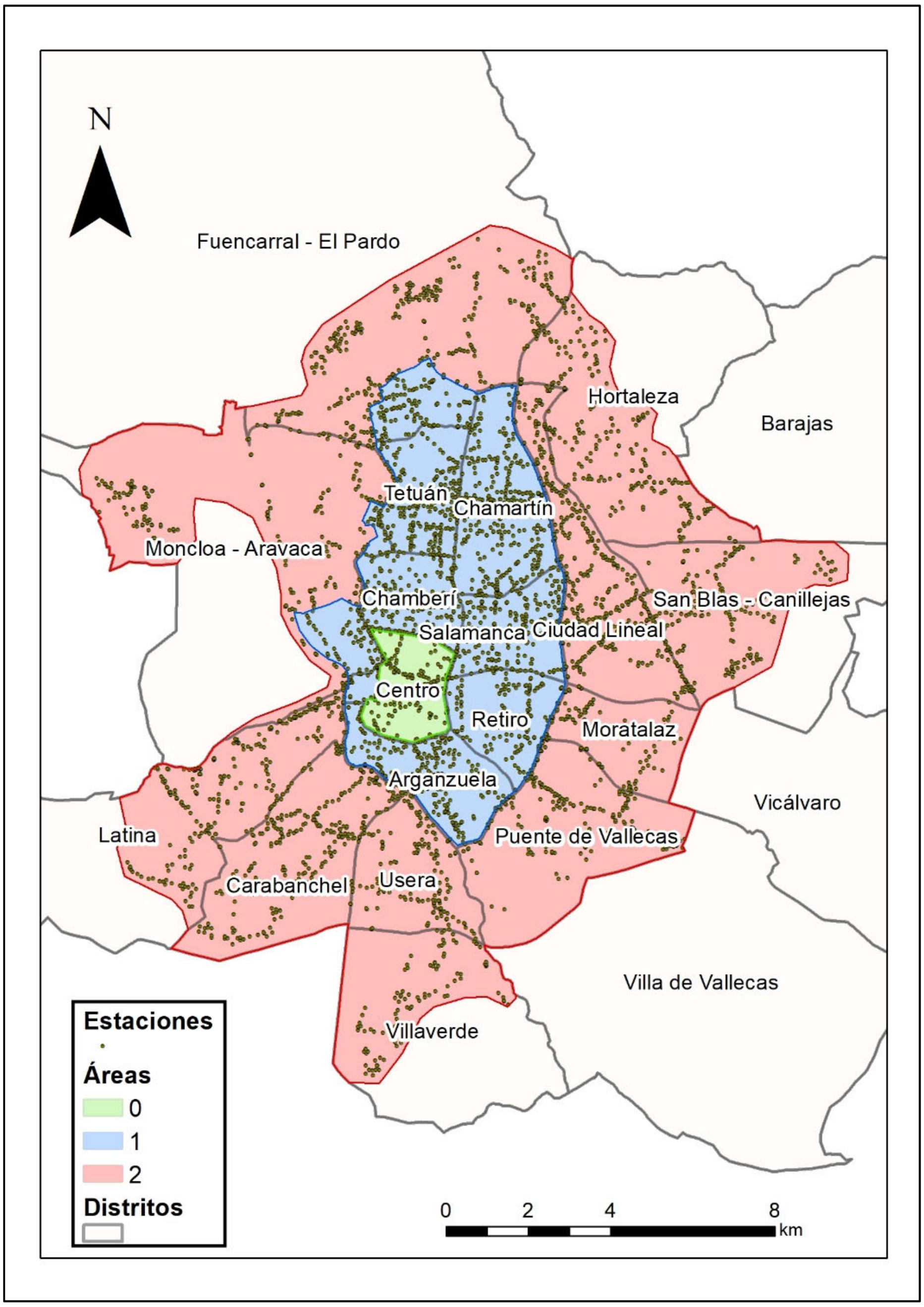

Fig. 2 – Áreas de estudio delimitadas y estaciones de medición del tráfico del SICTRAM seleccionadas en la ciudad de Madrid

2.1 Análisis espaciotemporal de la intensidad de tráfico

Los datos de intensidad de tráfico se han clasificado en función de la posición espacial de las estaciones de medición y la fecha y hora en las que el dato de intensidad se ha tomado. Los datos de intensidad de tráfico han sido promediados de manera conjunta para: cada mes, cada área de estudio, cada distrito y cada franja horaria. Este análisis de datos se ha realizado utilizando un programa desarrollado en los lenguajes de programación de C++ y R.

2.1.1 Análisis espacial

Para visualizar la distribución espacial del impacto de la medida, se han establecido dos divisiones geográficas. Una primera división en tres zonas concéntricas al centro de la ciudad, para estudiar el impacto de la medida por proximidad a la zona cero de emisiones, y una segunda división siguiendo los límites administrativos de los distritos de la ciudad de Madrid.

Las zonas concéntricas elegidas están ilustradas en la Figura 2, y son:

· Área 0, que se corresponde con el lugar de implantación de la zona cero de emisiones de Madrid Central, dónde se han excluido las calles del perímetro exterior, al no existir restricciones para su circulación.

· Área 1, que coincide con el actual servicio de estacionamiento regulado (SER), conocida también como almendra central, excluyendo su perímetro exterior que incluiría gran parte de la M-30.

· Área 2, correspondiente con la zona más periférica de la ciudad, hasta donde se disponía de un mínimo de datos de tráfico. Por este motivo, los distritos de Villa de Vallecas, Vicálvaro y Barajas han sido excluidos totalmente, y otros distritos como Fuencarral - El Pardo, Hortaleza, Villaverde, Latina o Moncloa – Aravaca se incluyen parcialmente.

2.1.2 Análisis temporal

A nivel temporal, se ha considerado que los datos de intensidad de tráfico tienen un carácter estacional anual, por lo cual, se ha decidido comparar los datos de las estaciones entre el año previo a su implantación y el año posterior (2018 y 2019). La capacidad de análisis y la falta de información de los siguientes años no ha permitido ampliar el horizonte temporal.

Para comparar entre ambos años, se ha agregado la información de los datos obtenidos de intensidad de tráfico en cada una de las estaciones de manera mensual.

Por otro lado, también se ha considerado que los datos de intensidad de tráfico también tienen un carácter estacional horario (Monzón et al., 1999), por lo que se ha agrupado los datos de intensidad de tráfico, de cada una de las estaciones, en cuatro franjas horarias: a lo largo de todo el día (00:00 – 24:00), por la mañana (7:00 – 19:00), por la tarde (19:00 – 23:00) y por la noche (23:00 – 7:00); siguiendo la misma clasificación establecida por el Ayuntamiento de Madrid para la evaluación del ruido.

2.2 Datos socioeconómicos

Para abordar el análisis socioeconómico, se ha usado la división administrativa de los distritos de Madrid. Para evaluar el impacto de la medida, se ha correlacionado la variación en la intensidad de tráfico media mensual en cada distrito con (i) los datos de población, como indicador de cuánta gente se ve afectada por la medida, y (ii) la renta anual media, como indicador de la distribución social del impacto. Ajustando una primera regresión lineal a la variación en la intensidad con la población y una segunda regresión lineal con la renta anual media. Los datos se han tomado del año 2019, en el portal web de estadística del Ayuntamiento de Madrid (2020).

3. RESULTADOS

En este apartado, se incluyen los resultados obtenidos del análisis de tráfico de forma general y agregados en las diferentes categorías espaciotemporales establecidas. Después se incluye la relación observada entre la variación en la intensidad de tráfico y los datos socioeconómicos.

3.1 Intensidad de tráfico

Los datos medios anuales de intensidad de tráfico muestran un impacto positivo de la medida en la disminución del tráfico. En cada una de las zonas concéntricas de estudio (Tabla 1), se observa que hay una tendencia radial, siendo el área con una mayor disminución el Área 0, después el Área 1 y por último el Área 2, siendo notable la diferencia entre el Área 0 con las demás. En cuanto a las diferencias por franja horaria (Tabla 2), la disminución es muy similar por la mañana y por la tarde, equiparable a la media de todo el día. El impacto de la medida ha sido menor en el tráfico nocturno.

Área de estudio	**Variación en la intensidad de tráfico media anual (2018 a 2019)**
Área 0	-6,95%
Área 1	-2,49%
Área 2	-1,82%

Tabla 1 – Variación de la intensidad de tráfico media anual entre 2018 y 2019 en las tres áreas de estudio concéntricas establecidas en todo el día (00:00 – 24:00).

Horario	**Variación en la intensidad de tráfico media anual (2018 a 2019)**
Día (00:00 -24:00)	-2,10%
Mañana (7:00 - 19:00)	-2,15%
Tarde (19:00 - 23:00)	-2,07%
Noche (23:00 - 7:00)	-0,54%

Tabla 2 – Variación de la intensidad de tráfico media anual entre 2018 y 2019 en las cuatro franjas horarias establecidas en toda la zona de estudio.

3.1.1 Diferencias espaciales 2018 - 2019

Las tres zonas establecidas para el análisis de la intensidad de tráfico muestran una tendencia en los valores a lo largo del año 2018 y 2019, dándoselos mayores datos de intensidad de tráfico en ambos años el Área 2, seguidos del Área 1 y significativamente más bajos en el Área 0 (Figura 3).

Las disminuciones las diferencias observadas en las medias anuales (Tabla 1) se mantienen al valorarlas de manera mensual, observándose mayores disminuciones en el Área 0 y luego en el Área 1 y el Área 2, las cuales tienen un comportamiento más parecido a lo largo del año. La variación de la intensidad en diciembre es superior en el Área 2 respecto al Área 1, lo cual rompe la tendencia general observa en el resto del año.

Al analizarlo de forma mensual y por zonas concéntricas (Figura 3), se aprecia que solo el Área 0 presenta una disminución de la intensidad de tráfico en el mes de marzo y sin embargo en el mes de julio solo en el Área 0 se produce un aumento del tráfico entre 2018 y 2019.

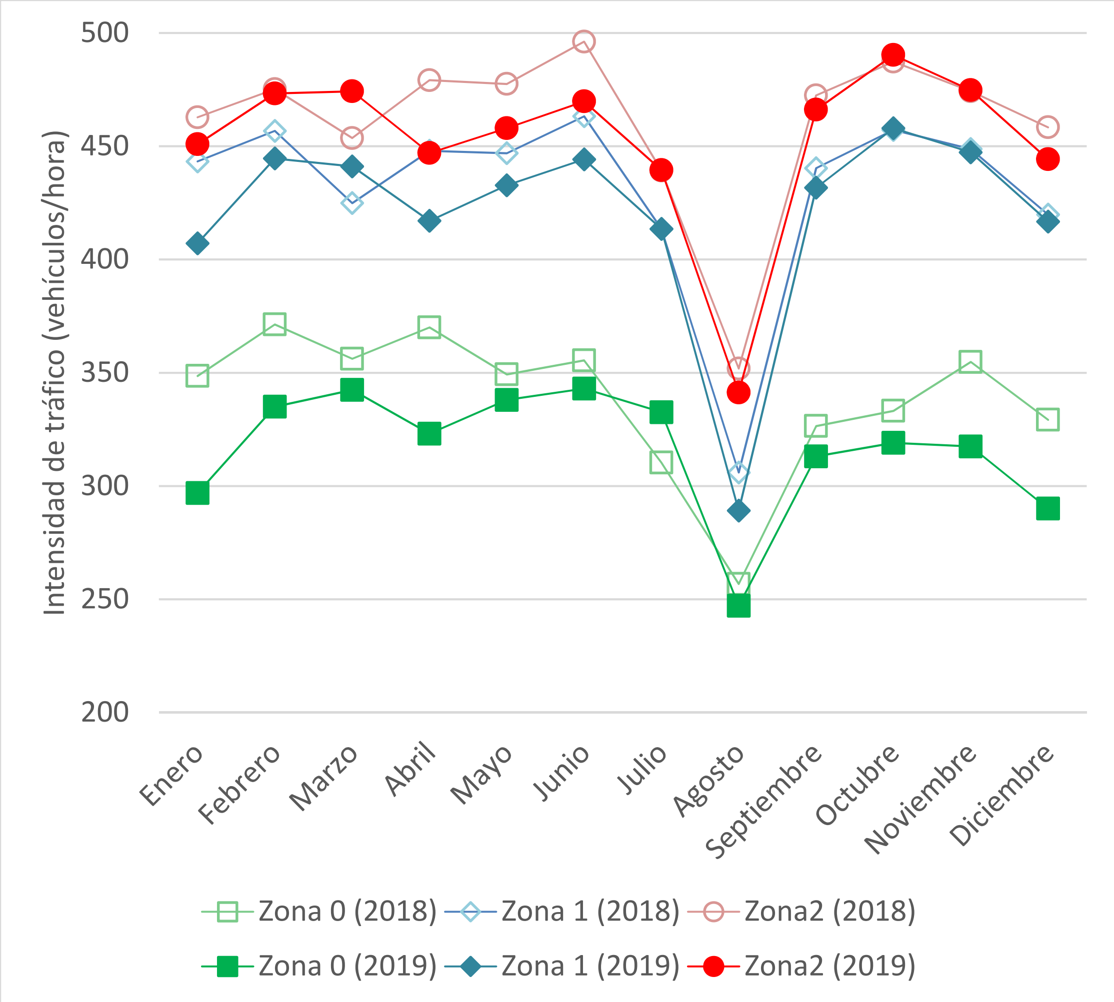

Fig. 3 – Comparación de la evolución de la intensidad de tráfico mensual media en los años 2018 y 2019, durante todo el día (00:00 – 24:00) en las tres áreas de estudio delimitadas (Área 0, Área 1 y Área 2) en Madrid

3.1.2 Diferencias temporales

La intensidad de tráfico tiene una fuerte componente estacional en el tiempo. A lo largo del año se observa un patrón que varía de forma proporcional a lo largo de los meses, ya que en verano disminuye drásticamente la intensidad de tráfico en comparación con el resto de meses tanto en 2018 como en 2019 (Figuras 3 y 4).

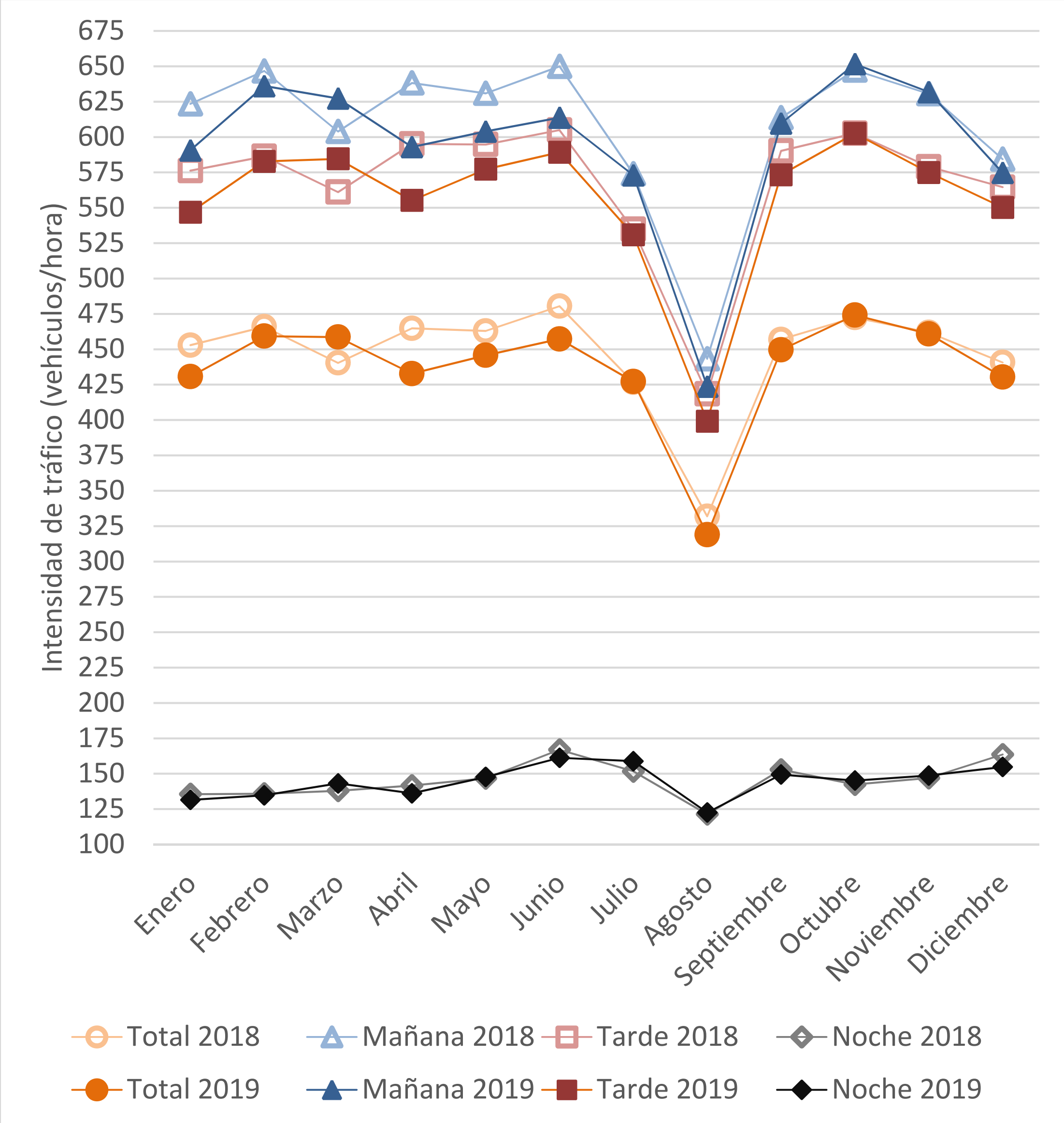

Fig. 4 –Comparación de la evolución de la intensidad de tráfico mensual media en los años 2018 y 2019, durante todo el día (00:00 – 24:00) y en horario de mañana (7:00 – 19:00), tarde (19:00 – 23:00) y noche (23:00 – 7:00), en la zona de estudio

Comparando la intensidad de tráfico media de manera mensual en la franja horaria de día (00:00 – 24:00) entre 2018 y 2019 se matiza la disminución en la intensidad de tráfico, ya que no todos los meses disminuye de manera homogénea (Figura 4). Los meses con una mayor disminución de intensidad son abril, mayo y junio. En el resto de meses, se aprecia una también una disminución en la intensidad de tráfico, aunque menor, y en el caso de marzo llega a aumentar la intensidad de tráfico de 2019 a 2018.

Comparando las diferentes franjas horarias se observa también que cada periodo sigue una tendencia propia, teniendo el periodo de noche significativamente menos intensidad de tráfico que las franjas de por la mañana y por la tarde tanto en 2018 como en 2019 (Figura 4).

Las franjas horarias de la mañana y la tarde, al acumular la mayor parte del tráfico siguen una distribución similar a lo largo del año en el impacto de la medida, mientras que en la franja horaria de la noche las diferencias son menores y, aparte de haber un aumento en la intensidad de tráfico en marzo, también se produce un aumento del tráfico en julio, octubre y noviembre.

3.2 Análisis socioeconómico 2018 -2019

Los datos de población y renta media mensual no han mostrado que tengan correlación con las disminuciones observadas en los diferentes distritos de Madrid estudiados (Figuras 5 y 6). Distritos con rentas anuales bajas, presentan resultados muy diferentes: Villaverde (-7,46%; 26.599 €); Puente de Vallecas (+0,36%; 24.688€). En los distritos con mayor población también aparecen resultados dispares: Puente de Vallecas (-0,36%; 246.021 hab.); Latina (-6,67%; 238.154 hab.).

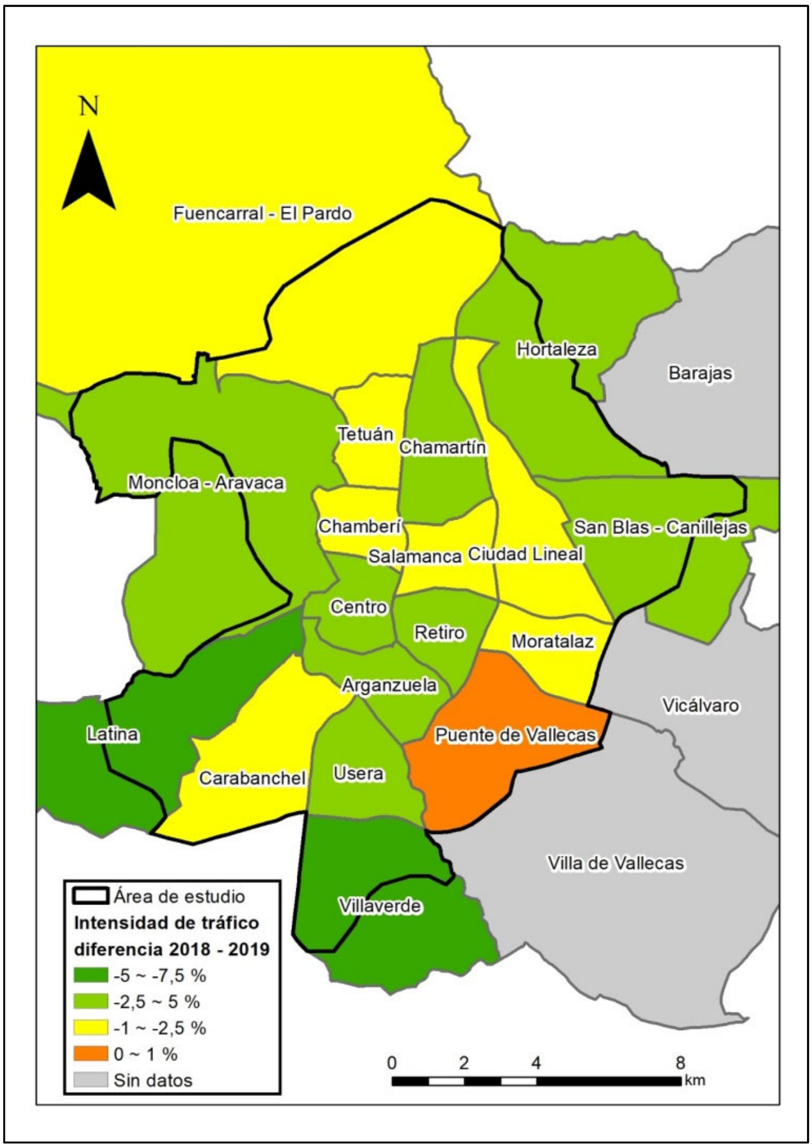

Fig. 5 – Variación porcentual de la intensidad de tráfico en los distritos de Madrid entre 2018 y 2019

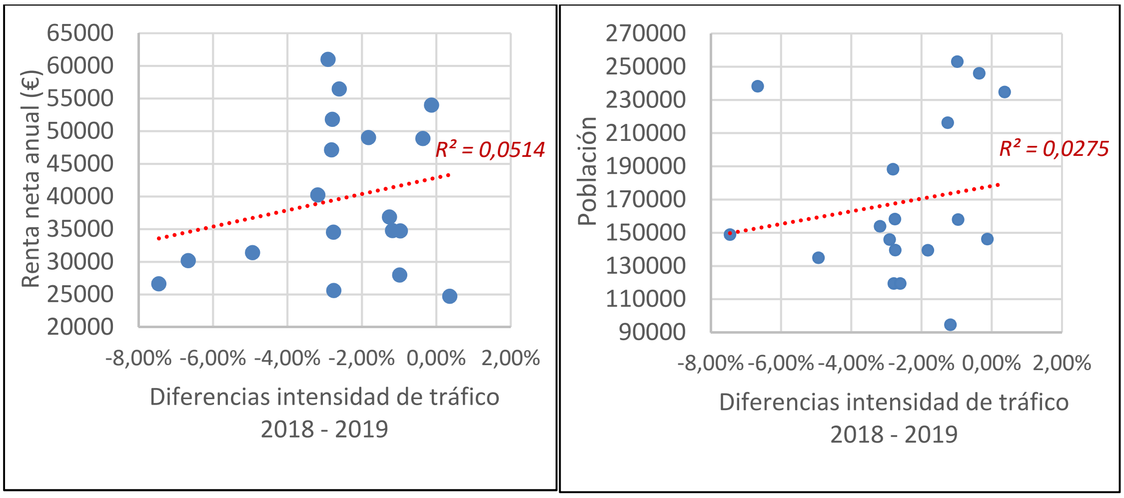

Fig. 6 – Correlación por distritos sobre los datos socioeconómicos (Población y Renta anual media) con la variación de intensidad de tráfico media mensual observada entre 2018 y 2019

4. DISCUSIÓN

El análisis del impacto de la medida de la zona de cero emisiones de Madrid Central es complejo y existen múltiples interpretaciones de los resultados. Por un lado, clasificando temporalmente los resultados, el impacto de la medida en los meses de verano, así como en el periodo nocturno es mucho menor, posiblemente al tratarse de periodos en los que la intensidad de tráfico es más baja y los viajes sobre los que se aplican las restricciones seguramente sean porcentualmente menores. Mientras que el impacto en el horario de mañana y tarde cuando se producen los mayores niveles de tráfico es mayor.

Es importante señalar que, aunque la implantación del Madrid Central se realizó a finales de noviembre de 2018, las sanciones no comenzaron hasta marzo de 2019 y se estableció un periodo cautelar, por lo que puede haber un sesgo en los meses de diciembre, enero, febrero y marzo. Este efecto posiblemente limite el impacto de la medida, y por tanto es posible que comparando con el siguiente año disminuya más la intensidad de tráfico y podría explicar la anomalía encontrada en el mes de marzo, donde se produce un aumento en la intensidad de tráfico entre 2018 y 2019. También se produjo un acuerdo que supuso la suspensión temporal durante una semana a principios del mes de julio de 2019 (Ayuntamiento de Madrid, 2019b) que posteriormente fue anulada por sentencia judicial (Ayuntamiento de Madrid, 2019c), lo cual podría también explicar porque se presenta una anomalía en el mes de julio en el Área 0, donde a diferencia de las otras áreas se produce un aumento del tráfico entre 2018 y 2019.

Por otro lado, clasificando espacialmente los resultados, no existe un impacto homogéneo en todas las zonas de la ciudad. Se observan distritos como Villaverde, donde la medida llega a reducir un 7,46% la intensidad de tráfico, y otros como Puente de Vallecas donde aumenta un 0,36%.

Los resultados parecen indicar que los distritos ubicados en las entradas sur y oeste a Madrid son los que presentan una mayor reducción del tráfico y podrían ser las vías de entrada más afectas por la medida (Figura 5).

La ubicación de las estaciones de medida del tráfico del Ayuntamiento no es homogénea, en dos aspectos: están sobrerrepresentadas las calles con un mayor ancho de calle y la densidad de estaciones por distrito no es homogénea. Está distribución de las estaciones excluye las calles con menor tráfico, siendo necesario matizar que las disminuciones observadas están referidas a calles principales que son donde se acumula el mayor tráfico.

A diferencia del enfoque centrado en las estaciones de medición de contaminación de la ciudad de Madrid (Salas et al. 2021; Izquierdo et al., 2020), existe un mayor número de estaciones de medida del tráfico, y esto ha permitido un análisis espacial más detallado del impacto de la medida. Al analizar directamente los datos de contaminación, la influencia meteorológica puede sesgar los datos (Katsoulis, 1996; Buchhoolz et al., 2010; Grundström et al., 2015; Laña et al., 2016; Chen et al., 2017), por lo que un análisis desde diferentes perspectivas ayuda a unos resultados más precisos.

En el análisis de la intensidad de tráfico no se ha tenido en cuenta la evolución del parque automovilístico de la ciudad, el cual se renueva año a año. Los vehículos más modernos presentan mejoras para disminuir sus emisiones contaminantes, especialmente los vehículos eléctricos e híbridos, que no tienen restricciones de acceso a la zona de cero emisiones. En relación a la intensidad de tráfico, Santiago et al. (2021) señalan que el aumento en la economía genera un aumento en el tráfico de la ciudad, por lo que los resultados observados en la disminución de la intensidad de tráfico pueden haberse visto minimizados al existir una tendencia creciente en la economía de la ciudad en este periodo.

Al igual que se ha relacionado la disminución del tráfico con beneficios a la contaminación, es posible que también haya asociado un impacto negativo a la economía de la ciudad. En el futuro es posible que el efecto de la medida se estabilice y no siga reduciendo el tráfico de la ciudad, aunque es posible que en los próximos años se produzcan efectos inducidos en la reducción del tráfico, ya que reducir la intensidad de tráfico, favorece el uso de transporte público como el autobús, al reducir los tiempos en los trayectos (Higgins et al., 2018), y esto a su vez, favorece la disminución del tráfico.

Basándonos en la información disponible en el Ayuntamiento de Madrid, se podría ampliar el horizonte temporal hasta 2013, ya que se disponen de datos de intensidad de tráfico e incluir los años 2020 y 2021 en el análisis, esto ayudaría a precisar mejor los resultados al distinguir mejor el efecto de la medida respecto a una tendencia general, y también podrían utilizarse otros indicadores del tráfico como la carga y la ocupación para poder relacionar mejor el tráfico con la contaminación.

Por último, en nuevos estudios, sería interesante combinar la evolución del tráfico con trabajos como el realizado por Cárcel-Carrasco et al. (2021), que analizan el impacto en la contaminación de las restricciones a la movilidad en el conjunto de la ciudad, derivadas de la pandemia del COVID-19.

5. CONCLUSIONES

El impacto del Madrid Central ha sido disuasorio para el tráfico de la ciudad, existe una disminución en el uso del vehículo privado como medio de transporte de forma general en toda la ciudad. Este resultado es compatible con trabajos anteriores que han detectado niveles inferiores en la contaminación atmosférica de la ciudad.

Se observan principalmente dos tendencias en la distribución del impacto de la medida: las zonas más próximas al área de Madrid Central son las más beneficiadas por la medida, llegando a una disminución del tráfico del -6,95% dentro del área con restricciones; y los ejes de entrada oeste y sur a Madrid han sido las más beneficiadas.

No existe una tendencia general que indique que la medida no afecta más a las zonas de mayor población o con una situación económica más frágil. Aunque el distrito de Puente de Vallecas (2º en población y último en renta anual media) presenta un aumento de la intensidad de tráfico.

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CITIES AT HUMAN SPEED: A FAVORABLE WAY TO REDUCE THE PACE OF MODERN LIFE. PULL AND PUSH MEASURES FOR CHANGE.

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ABSTRACT

Walking is the wealthiest and fairest, healthiest, safest and strongest, smartest and greenest form of transport (Government of Scotland, 2014). Since Walking is part of the daily life of most people, that is why it is often taken for granted.

To achieve a city for pedestrians, urban planners must reflect on how to stop designing cities with dispersed, discontinuous, and car-centric urban models, because it will be impossible to reverse this trend of development. Currently, contemporary cities must face the stress of its population, due to the speed of urban life, traffic congestion, long travel distances, etc.

This research is underpinned by how pedestrian's scale contributes to better urban environments and for the welfare of citizens through the development and implementation of policies and strategies for encouraging walking. To address this issue, it tries to identify the factors that determine walking, and it explores some existing strategies at three administrative levels: local, regional, and national. In this regard, it proposes push and pull measures as the potential to help more people to walk. The city of Pontevedra is selected as a case study because it is considered a case of success. The results indicate that there is necessarily a transversal organization of mobility in the administration, adequate combinations of pull and push measures have shown to have the greatest effect, and interventions tailored to different parts of the city.

1. THE INVISIBILITY OF WALKING

Walking characterizes the most accessible and greenest way of mobility (International Transport Forum, 2018). Furthermore, people walk to get fit and feel good, and because it is appropriate and social (City of London, 2018).

On the contrary, physical inactivity is responsible for over 5 million deaths annually through its effects on multiple non-communicable diseases (such as heart disease, stroke, cancer, etc.) (Sallis et al., 2016) and it is the second biggest cause of global mortality (Government of Scotland, 2014).

However, walking trips have been largely ignored as a mode of urban transport (CEOs for Cities, 2009; ITF, 2012; Rietveld, 2000), or that walking is treated as the 'Cinderella of transport modes' (Paroah, 2003) despite being the most important of all. Since walking is part of the daily life of most people, it is often taken for granted, which Goodman (2003) calls 'the invisibility of walking'.

The understanding of nonmotorized modes of transport - walking and cycling - is extremely complex. However, in the existing literature, walking is often presented along with cycling (Litman 2017; Buehler & Pucher, 2017; Active Living Research ALR ,2016; Krizek, Forsyth & Baum, 2009; Ogilvie, 2004; Saelens et al., 2003; Tolley, 2015, 2003; Rietveld, 2000). Although there are complementary, greener and sustainable modes, each mode has its distinctive features, and they should be separated in data As Nadal said, it is crucial to promote active mobility, but also 'smart mobility' understood as the one that each person needs in each circumstance and at each moment of their life (Nadal, 2020).

Walking can be characterized along the four 'As' adapted from Carruthers, Dick & Saurka (2005) to understand urban transport: i) Affordability is very high since walking is a universal mode for all citizens, except in some cases of mobility impairments. It does not require any vehicle, it is free; it only requires capable legs and energy to cover the distance; ii) Availability is high since other modes are limited through routes, schedules, and frequencies. Walking is the most available mode of transport, limited only by potential difficulties to walk for long distances, safety concerns, or barriers along the route; iii)

Accessibility is high, most people can reach a certain place on foot. iv) Acceptability depends on the pedestrian; external factors or some individual perceptions, such as personal security, can boost or deter from walking. Citizens are all pedestrians, but they don't have the same conditions to walk (physical, economics, etc).

The study of pedestrian mobility is difficult to address since it is challenging to explain the pedestrian behaviour and the interactions between urban structure, mobility habits, and other factors (Krizek, 2000). Walking is often overlooked as a mode when measuring transport behaviour for the purposes of planning. (ITF,2017).

Walking can be used for different purposes (Paroah, 1996): i) as the sole mode to go from one place to another. In London, it includes a quarter of all daily trips (City of London, 2018); ii) as a means of reaching other modes, e.g., for going to the metro station, to the bus stop, to a parked car. In the US, there is a major reason to walk (Besser and Dannenberg, 2005); iii) as a means of using public space, e.g., to meet other people or window shopping; iv) as a recreational and leisure medium, like long walks without a specific reason or destination or playing in the streets (tend to be longer).

Most surveys only collect the first and second purposes, and it is difficult to obtain reliable data on walking. Their methodology focuses exclusively on car travel and public transport, without taking into account the share of pedestrian trips, even when it is an important component (ITF, 2018; Litman, 2017; Pozueta, 2007; Rietveld 2000; Socialdata, 2013; Trolley, 1990) and excluding walking journeys of less than ten minutes (Litman 2017; Paroah, 1996; Sanz 2004) or it goes together with bike. Consequently, this will limit the comparison of the share of walking between different sources (European Road Safety Observatory, 2006).

Indeed, 63% of all urban trips are less than 5 km in length (ITF, 2018). Thus, it opens a great opportunity to encourage walking in urban areas. Likewise, slightly more than two-thirds of Europeans walk every day (68%) while half use a car every day (50%). However, roughly one in ten Europeans (12%) never uses a car (European Commission, 2013). The weight of the pedestrian mode in many cities is not to be underestimated: in central Paris, the walking modal share is 47%, followed by Barcelona with 44%, New York City with 39%, Mumbai with 33%, London with 32%, Madrid with 30%, Berlin with 29%, Vienna with 27% and Shanghai with 27% (ITF, 2017). Consequently, as Litman (2019) said, “Improving travel options and reducing vehicle traffic tends to benefit everybody in a community”, since inadequate mobility is an important element of social exclusion that determines the level of urban poverty (UN-Habitat 2013).

The present research aims to reflect on the current accelerated pace of life in cities and how to reduce it through the possibilities offered by pedestrian mobility. It starts identifying factors that determine the choice of walking. Secondly, it analyses some examples of policies and strategies for encouraging walking that have launched in three administrative levels: local, regional, national, and presents a review of push and pull measures for increasing walking. Finally, the city of Pontevedra provided the empirical focus. It has been selected because it is considered a case of success and a worldwide reference.

2. CHANGING SPEED OF URBAN LIFE: PEDESTRIAN SCALE

With the outbreak of the coronavirus pandemic in March 2020, cities suddenly stopped, mobility and noise ceased; citizens became more aware of the speed at which they were living and the way of life that was had acquired. Many of the drawbacks of the current urban model have provoked new debates on the need to favor the proximity of daily activities at the neighborhood level, density, and the lack of public quality space. In European cities, by 70-80% public space is occupied by the car (EU, 2020).

Before this health crisis, the climate emergency was giving signs that it was not possible to continue living at this rate of energy consumption and with these environmental repercussions.

On the other hand, people living in larger cities with high urbanization and increasingly sedentary work, are more likely to be physically inactive, to have a higher prevalence of depression and stress, because of the accelerated urban environments and lifestyles.

Now more than ever, humans need to walk to be in contact with others and they need to share public open spaces. In this regard, the quantity and quality of pedestrian public space determines the urban quality. Today, people are full-time interconnected, but at the same time it’s seems to be the most disconnected time from their environment. Outdoors’s environment can reduce stress and aid recovery from stressful conditions (Thompson et al., 2011).

As Gelh (2014) said, the public space is good when there are many nonessential activities in it, when people go out into the public space as an end in itself, to enjoy it and spend time in it (Monheim, 2003). It gives a sense of belonging. Walking not only depends on the pedestrian facilities but is also highly dependent on the built environment (Krizek et al., 2009; Adkins et al., 2012). Monotonous and uninteresting scenarios can deter walking on foot. Conversely, attractive, safe, socially animated scenarios stimulate people to walk more (Pozueta et al., 2013; Saelens & Handy, 2008). Indeed, in many cities, creating attractive walking environments has increased retail turnover and pedestrian flow (Tolley, 1990; TEST, 1988, Government of Scotland, 2014).

Pedestrian mobility implicates highly competitive travel time over short distances, but competitiveness decreases as distance increases, compared to other modes (Pozueta et al., 2013). The travel time per pedestrian per trip that is acceptable by a person is established between 20 and 30 minutes. Distance, real or perceived distance, is a barrier for walking (Krizek et al., 2009) and is one of the key factors influencing the choice of walking (ITF, 2018; Adkins, et al., 2012; Greenwald & Boarnet, 2001; Handy, 1996). However, it is not easy to determine what is the acceptable distance to walk because travel distance is also dependent on the age, physical conditions, the state of the pavement, and urban environment, but mainly on the size of the urban centres (Gelh, 2014).

In the last decades, the design of the city, the public space, and the location of activities have been done with a car-centric planning, which has resulted in a greater consumption of land and energy, causing problems in the environment and inaccessibility to many sectors of citizenship. Some urban planners focus their interest on density but forget to change diversity and design (Cervero & Kockelman, 1997).

To change this trend, urban planning is essential and must avoid the monofunctionalism of urban areas, promoting the balanced diversity of the main functions of the city such as living, working, shopping, recreation and education (Paroah, 1996). This is so called ‘proximity urbanism’, which creates proximity and autonomy.

As seeing above, walking varies a lot depending on the trip purpose (Tolley, 1990; Monheim, 1979). Proximity to employment is the variable that most influences travel distance and modal choice, rather than the existence of commerce and services in the residential area (Cervero & Radisch, 1996; Gainza & Etxano, 2014), especially among women (Cerin et al., 2007). Furthermore, proximity to destinations is the element that most positively influences walking as a mode for nonrecreational travel, more than aesthetic quality, infrastructure, or security (Saelens & Handy, 2008; Cervero & Duncan, 2003).

Less intensity of urban activity implies a greater use of the car and vice versa (Litman, 2019; Newman & Kenworthy, 1989).

There are multiple factors that influence walking. The following is a brief selection of them built upon the impact on the individual places and infrastructure related to walking.

2.1. Pedestrians individual

The individual decision to walk is not only conditioned by personal needs, but several different factors interfere in personal choices and attitudes (ARL, 2016). The walking behaviour is very different among the age and life-cycle stages (Van der Hoorn & Van Wee, 2013, Pozueta, 2007), social status –education level and household characteristics-, gender, (Tolley, 1990), the perception of safety and security, etc. However, income, travel time, and transport costs (in terms of individual expenditure on transport), influence on the choice to walk or not; or pedestrian travel habits are influenced by cultural factors such as societal values (ITF,2012). For instance, in southern European countries, walking 'is part of the lifestyle, is a basic aspect of daily life' (Lamíquiz, 2011).

2.2. Places where people walk

More than two-thirds of the European population live in urban areas and they continue to grow: by 2050, 82% of Europe's population will be urban (European Union, 2011).

This opens a large field of action for pedestrians, above all in many small and medium sized cities. The bigger the city, the more complex the trajectories and the longer the distance. In Spain, according to the Metropolitan Mobility Observatory data (OMM, 2017), small areas have the highest percentage of walking and cycling, followed by large areas and medium ones, as it can be seen in Table 1, by purpose of the trip (obligatory or non-obligatory mobility) and in the main cities:

	Large areas*			Medium areas**			Small areas***		
	Obligatory	Non-Obligatory	Main city	Obligatory	Non-Obligatory	Main city	Obligatory	Non-Obligatory	Main city
Walking & cycling	22,4	47,5	**49,9**	25,3	47,1	**49,5**	24	54,9	**51,9**
Public Transport	19	18	23,1	11	4,7	14,6	9,1	10,4	10,4
Car & motorbike	57,9	34,1	25,8	62	47,2	34,6	66,2	34,2	37,1
Others	1,3	0,9	2,8	1,8	2,7	1,7	1,6	1,7	1

* 7 large metropolitan areas: more than a million of inhabitants
** 7 medium metropolitan areas: more than 500.000 inhabitants
*** 8 small metropolitan areas: less than 500.000 inhabitants

Table 1. **Modal share in Spanish cities. Source: OMM, 2017**

Compact areas can reduce the number of motorized trips and boost the nonmotorized ones (Cervero & Kockelman.,1997), especially for non-work trips. By contrast, sprawl, as the physical pattern of low-density expansion of large urban areas, is one of the major challenges facing urban Europe (EEA, 2006). Sprawl has an "unmistakable and profound influence on travel" and makes public transport services in good condition (frequency, number of lines, etc.) unviable and increase the use of cars. This situation generates the growth of vulnerable population groups that live in the periphery and have to travel great distances (UN- Habitat, 2013).

Moreover, the urban structure and its subsequent transformation by planning have a great influence on human behaviour and the way the city's function (Gelh, 2014). There are some good examples of old compact urban structures with quality urban spaces resulting in lively streets, such as Barcelona, Copenhagen, or Paris. Some street layouts are preferable to others. "*Most old cities have a complex and fine-grained street pattern and that makes them more interesting*" (Hass-Klau, 2015). It can be said that people living in areas with dense, mixed-use, integrated buildings, and with good access to public transport are more likely to walk (City of London, 2018). Moreover, Cervero & Duncan (2003) highlight that urban design influences the choice of walk: curved and cul-de sac street layouts discourage walking. On the contrary, well-connected streets, mixed land use, and small blocks favour short distances and walking.

Rarely in the literature, the data of pedestrian mobility distinguishes among central, inner, or outer cities, and the difference in modal distribution in different parts of the city can become notorious. For example, walking is the most common mode of transport in central and inner Madrid by 40% and 32%, but this percentage decreases by 29,2% in the outer cities (Consorcio Regional de Transportes Madrid, 2020). London strategy outlines different approaches for central, inner, and outer London, where 41% of all trips are made on foot in the central and inner cities and 29% outer (City of London, 2018).

Additionally, the existence of a larger metropolitan area greatly influences the modal shift. In Spain, in cities with less metropolitan development, the percentages of trips on foot are generally higher (Sanz, 1998). For example, the city of Vitoria Gasteiz does not have a metropolitan area and it has the highest walking modal share in Spain. Ewing (2005) found a strong correlation between metropolitan development patterns and walking.

2.3 Infrastructure for walking

Nowadays, the sheer scale of many cities makes a multimodal system necessary, since the majority of the trips require the combination of several modes (Southworth, 2005).

However, *walking is a key element in most multimodal trips* (ITF, 2012) and may be more important than it seems. Likewise, a critical factor supporting walkability in larger cities is accessibility to public transport for longer trips and it is necessary to improve the connectivity and ease of transfer between modes (ITF, 2018; Krizek et al., 2009) and to see if public transport services can be reached on foot (Paroah, 1996).

Any increase in transport modal share is because there is a shift to another mode (Paroah, 2003). In most cases, cycling increases at the expense of walking (Krizek et al. 2009); motorised modes at the expense of nonmotorised modes and public transport at the expense of private transport (Werner et al., 2003). The challenge is to shift users away from the car.

Good walking conditions are considered the following five ‘Cs’ (Paroah, 1996): i) Connected: in a comprehensive network, with short street blocks instead of less permeable large blocks (Pozueta et al., 2013). ii) Convenient: with direct routes without detours. iii) *Comfortable*: adequate surface and pavement, enough widths, non-obstacles, with good lighting. iv) *Convivial*: diversity of public spaces to stay and mix of buildings and activities. v) *Conspicuous*: clear routes in terms of design and signing.

There is no defined average distance to walk. The radius of action of a walking trip, taking as a reference the travel time between 20 and 30 min, is between 1.5-2.5 km. (Pozueta et al., 2013), but to spend a great value of time is often a reason against walking. It is considered as a means of transport that takes a longer time, compared to other mechanized modes (Goodman et al., 2003). The walking speed is also one of the main conditions against other modes, since it varies, under normal conditions, between 4- 5 km/h. Other factors influencing walking speed are the quality of pedestrian facilities, the age and physical state of the pedestrian, the crowd on the streets, or the weather (Gehl, 2014). Improving the quality of the infrastructure, e.g., to include more footways, provide wider pavements with smoother surfaces, making walking spaces more enjoyable (ITF, 2018), and prohibiting cyclists on pavements, have a positive influence on walking (Walcying, EU Project). Providing more infrastructure may not in itself change behaviour.

One of the most important measures is to reverse the hierarchy of public spaces (Government of the Basque Country, 2016), to put pedestrians in the first place and bring them the best conditions to walk. Likewise, ‘intermodality spaces’ are convenient if it is possible to share the space by different means of transport. The ‘coexistence’ between modes is a matter of speed and it would be possible, but not under spatial equality conditions (Gehl, 2014; Monheim, 2003) because it depends on the volume of car traffic, not above 250 cars/h, or either on the speed of cars between 10km/h and 20km/h.

3. POLICIES AND STRATEGIES FOR ENCOURAGING WALKING

Several cities have opted to promote pedestrian mobility, with different purposes such as: for reasons of the health of the population (improving the health of citizens and preventing diseases); for a first step for a mind shift by urban development model on a human scale and proximity; for a requirement to be another means of transport and highlight its importance and benefits, etc.

To establish some principles or objectives, strategies or plans for walking have been launched at different levels, mostly at the city level, but there are also examples at the regional (e.g Scotland) and national (e.g Norway) level. Table 2 shows some selected examples, indicating their main objectives.

Country/Region/ City	*Strategy/Plan*	*Main goals*
City of London (2018)	Walking action plan. Making London the world's most walkable city	i. 80 per cent of all journeys to be made on foot, by cycle or using public transport by 2041. ii. Londoners have to do at least 20 minutes of active travel every day by 2041. iii. Efficient use of street space, improving the experience of walking on London's streets.
Paris (2017)	Stratégie "Paris piéton"	i. Facilitate pedestrian continuity and new sharing of the road. ii. Promote the diversity of street uses. iii. Raise the comfort standards of public spaces. iv. Rethink the orientation of pedestrians. v. Consolidate the pedestrian culture of Paris.
Scotland (2014) Scotland launched in 2003 its first physical activity strategy 'Let's Make Scotland More Active' (LMSMA).	Let's Get Scotland Walking The National Walking Strategy	i. Create a culture of walking where everyone walks more often as part of their everyday travel and for recreation and well-being. ii. Better quality walking environments with attractive, well designed and managed built and natural spaces for everyone. iii. Enable easy, convenient, and safe independent mobility for everyone.
Norway (2014)	The Norwegian Walking Strategy: "Walking for life"	i. Walking should appeal to everyone. ii. More people should walk more.
City of Copenhagen (2007)	More people to walk more. The pedestrian strategy of Copenhagen	i. 20% increase in pedestrian traffic by 2015 compared to 2009 ii. By 2015, Copenhageners walk 12 minutes a day

Table 2. Walking strategies.

The most effective strategies for encouraging walking seem to be "those that are multidisciplinary and include a mix of top-down and bottom-up approaches with buy-in from government and non-government organizations, academic institutions, professional and commercial groups, and passionate citizens" (Walk21, 2017), in short, when they involve all stakeholders of the city.

Some existing strategies (e.g., Scotland) not only establish measures that promote walking, but also connect sectoral policies with each other (for instance, health, transport, urban planning, environment, social, etc.), achieving a comprehensive approach that reinforces each action, and across a range of policy areas at national, regional and local levels (Government of Scotland, 2014).

4. PULL AND PUSH MEASURES FOR INCREASING WALKING.

Before any intervention or action, each city must make a careful diagnosis and it would be wise to start by asking why people do not walk, as London did when it developed the walking strategy. The main reasons they found were: i) time to spend in travel (24%); ii) high traffic (21%); iii) personal security (20%); iv) other travel preferences (18%); v) bad pedestrian facilities (14%); vi) not being fit enough (14%); vii) safety and fear of traffic (12%); viii) having a disability and the state of pavements (10%) (City of London, 2018). If policy makers do not know how people move, it is very difficult to be efficient in the management of measures.

Pull measures to increase walking refer to all incentives that discourage some attitude or habits and promote a modal shift. In this research, it concerns deterring strategies that discourage driving. On the other hand, push measures are considered as enabling strategies (policy, infrastructure investment, or actions) that boost walking (Piatokowski et al., 2019).

Nevertheless, push measures for sustainable modes such as walking, which is necessary but not sufficient to extend a sustainable urban mobility model (Sanz, 2007). Piatkowski et al., (2019) in their study in 4 American cities in which they carried out the *Non-motorized Transportation Pilot Program* revealed that establishing a joint action between actions that boost active transport (push measures) and those that discourage car use (pull measures) is more effective than doing them separately.

They also point out that attention must be paid to the measures applied to deter driving because they can harm the promotion of walking, so it is not only necessary to be careful when carrying out the intervention but also the capacity to implement it.

Combining measures can cause nondesirable effects such ‘Suction effect’, but between sustainable modes instead of subtracting the car, for instance, a new policy that promotes scooters can attract people walking; or ‘Rebound effects**’,** for example, measures that improve the environmental effectiveness of a vehicle also translate into greater use of it; or ‘migratory effect’, the application of measures in the inner city, for example a streets pedestrianization can drive traffic to edge areas (Sanz, 2007).

There are countless of measures to act on, but not all measures are the same in terms of magnitude.

For instance, ‘hard measures’ (big investments in more convenient crossing and redesigning intersections for pedestrians, renovation of the urban streetscape, park & ride outside the city centre, etc.) or ‘soft’ measures like information and promotion campaigns etc. Although it may happen that ‘soft’ measures can enhance the effectiveness of ‘hard’ measures (W21, 2019). Table 3 presents a review of pull measures and Table 4 push measures, both used in walking policies and strategies.

	Type of measure	***Example***
Pull measures	*Car traffic restraint*	Creation of a traffic control center by the city council to give preferential pedestrian use in the centre
		Reducing the speed of vehicles
		Reallocating road space, reducing road space.
		Targeted restrictions on vehicles better than a simple ban
		Parking duration and parking turnover
		Reduction of search traffic
		Car limited zones
		Decrease parking spaces
		Ban pavement parking
		Parking charges
		Park & Ride outside the city centres
		Parking penalties for improper parking
		Permanent or time-of day car bans
		Congestion management
	Road safety	Reducing speed, reducing accidents & injuries
		Separate cycle path from footpath
		Crossing at street levels (no skywalks & subways)
		Reduce road danger
		Speed humps in the carriageways
		Traffic calming: 30 km/h, 20 km/h or 10 km/h
	Enterprise and trip generation pole Coordination:	Promotion of shoft mode of transport to access at work
		Support staff to change employee’s mobility patterns
		Change bonus ‘company cars’ for other economic or tax incentives
		Teleworking or desksharing schemes
		Shuttle bus lines to the main transport nodes of the city. Connect the main attraction / generation points to all the transport networks
	Public transport	Providing convenient, punctual, frequent, and well-connected public transport systems
		Attractive pedestrian connections
		Placing bus stops at shorter intervals
		Improving security and accessibility to the most vulnerable groups: elderly, children and those with mobility constraints.
		Transport mode transfers simple, quick, efficient, safe and confortable

Table 3. Pull measures to encourage walking.

	Type of measure	***Example***
Push measures	*Improving environment for walking*	Pavements fit for walking
		Increase the width of pavements
		Better lighting, with priority to pedestrians
		Construction and improvement of side walks
		Street furniture well placed
		More convenient crossing: redesign the intersections for pedestrians
		Better signing
		Making more attractive places for everybody
		Removed obstructions and obstacles
		Walking routes were clear, connected and well signposted
		Flush dropped kerbs
		Increase the frequency of pedestrian phases in the traffic light cycle
		Removal barriers for disabled people
		Improvements in public spaces: sidewalks, terraces, outdoors activities: cultural, animation, ephemeral art installations, artist and street performers
		Prevent invasion of sidewalks by parked cars or bikes or electric scooters
		Protection from inclement weather
		Avoid elevated and underground pedestrian crossings
		Green and nature in the streets
		Publish walking route maps
		Technology like apps and devices will play an important role in the walkable futures of cities
		School pedestrian routes
		Footway free from litter and dog mess
	Land use planning	Integrating walking into transport and land use planning
		Pilot projects school streets with timed road closures
		Minimise the need to travel
		Improved retail vitality
		Promotion of mixed-use neighbourhoods
		Increase density
		Activity in the ground levels of buildings walls
		Street markets.
	Promotion campaigns The most effective campaigns are those that combine information, education, service developments, legislation and changes to the physical environment (Tolley, 2003).	School mobility programs
		Leisure walking routes
		Information, awareness and communication Campaigns
		Supporting a culture change

Table 4. Push measures to encourage walking

Hereafter, the Spanish city of Pontevedra has been chosen as a case study to analyse push and pull measures for increasing walking in cities and their combinations, because it is considered a word reference for the success in the implementation of the measures, are more focused on enabling (push measures) strategies than on deterring strategies. In addition, the passage of time allows to evaluate the results after almost 20 years of action.

5. RECOVERY OF THE CITY FOR PEOPLE: THE CASE OF PONTEVEDRA

Pontevedra is a small city in Galicia, the capital of the same name province, with a population of 83,209 inhabitants in the capital and 945,408 inhabitants in the metropolitan area. It is located on the Spanish northwest coast.

In 1996, the city monitored the traffic situation (The traffic in the centre of Pontevedra was three times greater than the traffic intensity in the centre of Madrid and 5 times greater than in the centre of London, 74,000 cars entered in 5 km2), which had an impact on poor air and life quality for citizens, the city council decided to carry out an urban reform for improving the quality of the environment for people living, both in regulation and design.

Local authorities analyzed proposals made in other cities to reflect upon what might or might not work as following: congestion charging, improvement of public transport, pedestrianization of the city centre, traffic calming, traffic restrictions on the appearance of license plates, crossings at high or below levels like skywalks and subways, etc.

While most cities focused on trying to solve the problem of urban traffic (pull measures), the actions taken in Pontevedra focused on recovering the city and public space for people (push measures). The city council tried to influence any potential side effects in a positive way rather than negative.

5.1. Pull and pull measures

The decision was made to reverse an unsustainable traffic situation and poor urban quality, and it was important to properly select the measures so that they would be effective from the beginning because any mistake would put even more against the sectors most sensitive to change.

In order not to delay the transformation, it was decided to start acting and in turn adapt the Sustainable Urban Mobility Plan (SUMP), since it had previously been studied in depth what and how to do it. It was a participated and consulted process. The main measures were basically implemented in 4 scopes (Concello de Pontevedra, 2016): i) pedestrian priority; ii) accessibility; iii) drastic reduction of traffic in the city; iv) road safety. Figure 1 shows various actions carried out in Pontevedra during the period between 1999 and 2015.

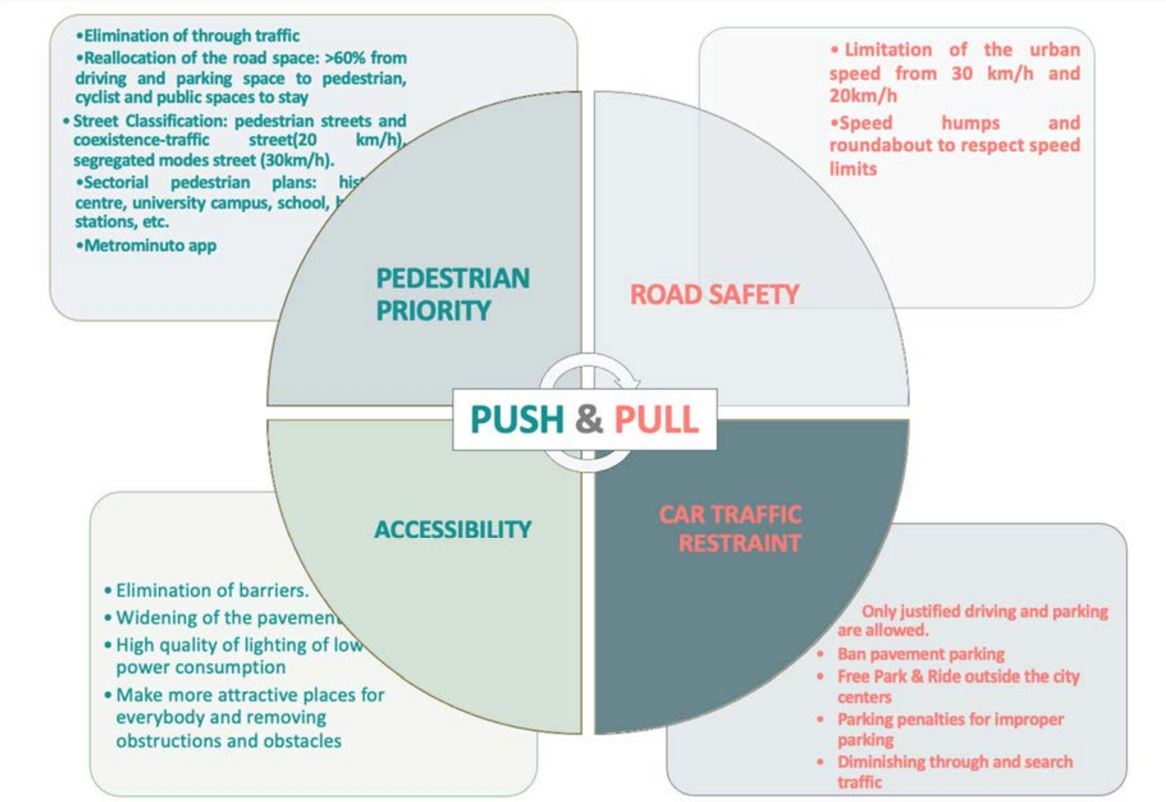

Figure 1. **Pull and push measures applied in Pontevedra (1999-2015).**

Once the implemented measures have been shown, the foremost results are presented below.

5.2 Main outcomes

It can be said that Pontevedra recovers the city for the people for several reasons. First, because the space for cars was reduced to give it to the pedestrian, the ratio was changed from 75-80% for cars to 75-80% for the pedestrians; cars are not prevented from entering the city, but through-traffic is gradually being excluded from the city centre (30% of vehicles); residents and various necessary activities that generate traffic are allowed such as: loading and unloading, access to garages, messaging, public transport and private services (with a maximum of 15 minutes of parking); pedestrianization actions were jointly carried out with cultural actions and events; underground car parks have been increased and since 2010, the speed has been reduced to 30 km/h throughout the municipality; and universal accessibility has been achieved throughout the public space, getting a safe public space, and where children play in the squares and go to school alone. Consequently, in 9 years, accidents have dropped to 0 and air quality has improved and is within WHO limits.

Additionally, the city has a parking system in which free spaces are contemplated to carry out small errands, free parking on the urban edge, and rotating paid parking lots throughout the city.

It is important to ensure that the benefits of change are noticeable. It seems that this has been the case because citizens are proud of their city and the population has been increasing. Decision-makers believe that the success was due to several factors (Concello de Pontevedra, 2016): i) a strong will to achieve the objectives: public spaces for all, accessibility for all; ii) starting with a phase of deep and conscientious reflection on how to act, learn from the successes and errors of other cities and permanent collection of information; iii) comprehensively understanding decision making on the urban space as a whole; iv) global solutions of overall problems instead of isolated and small actions, with imperceptible outcomes; v) outline the actions specifically for each neighborhood or urban area vi) successful political and inter-administrative coordination; vii) weighted use of the car reasoned and optimized, with the consequent change of habits. The car is used only when active modes are not competitive; viii) traffic reduction measures are gradually more intense in the centre than in other parts of the city (in 18 years, a third of the traffic in the center has been reduced); ix) overcome opposition through good information; x) instead of doing a few big festivals or events, more small and diverse actions were carried out in the streets contributing to an improvement in the quality of life for citizens.

6. CONCLUSIONS

A favorable way to reduce the pace of modern urban life is to design cities at human speed, moving at the pace of the person but not the car. Pedestrian mobility adds multiple benefits, first for the individual: it is healthy, it is active, reduces the level of stress and allows him to perceive more details through the human eyes, and normally, it increases the sense of belonging; secondly for the environment: it contributes to reach clean air, it is noiseless, takes up less space than any other mode of transport and no vehicle or device is needed to move (except disable people) and finally, pedestrian infrastructure or facilities are affordable than any road or rail infrastructure.

Reclaiming space for the pedestrian means taking it off to another mode, mainly to the car. This does not mean to ban cars, but to use them only when it is necessary and sustainable modes are not competitive. Initially, it may be an unpopular measure and less impressive than the inauguration of an infrastructure. That is why courageous politicians are needed to push for a more humane urban model and they who know how to achieve it.

Although an important variety of measures has been presented, unfortunately each city must contextualize and find its own way to establish which are the most appropriate combination of measures and how to succeed in their implementation.

It is not a matter that is achieved in the short term, not in one stage. A global action is more efective than the sum of isolated actions. As has been seen in the city of Pontevedra, the combination of pull and push measures maximize the benefits of both.

It is advisable to prevent possible side effects between measures and a different approach in different parts of the city. New projects need to be designed according to the unique urban areas, and for different cycles of life and groups of age (children, youth, older) adapting the concept aforementioned of ‘smart mobility’. In addition, it will be a form of not only to establish measures that promote walking, but also to connect sectoral policies with each other (for instance, health, transport, social and cultural, etc.). Thus, the transversal organization of mobility in the administration is desirable and it contributes to a comprehensively understanding of mobility.

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COSTS AND BENEFITS OF GENDER POLICIES IN TRANSPORTATION. STATE OF THE ART OF QUANTITATIVE APPROACHES

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ABSTRACT

The transport sector has been a pioneer in the quantification and even monetization of complex issues, such as the value of life or the value of time. Gender issues are more and more in the core of many policies, but its analysis is usually qualitative at most. The objective of this paper is to review current quantitative approaches, and highlight their advantages, their drawbacks and their gaps.

The transport sector can be analysed with a gender perspective, either considering its workers or its users. In both cases, men and women show different attitudes and behaviours. To begin with, workforce in transport is predominantly male, while public transportation is used mostly by women.

There are numerous studies with a gender perspective in the transport sector. Most are qualitative and simply describe the problem or the project in question. More and more are using quantitative approaches, but mostly for describing interventions, not for assessing impacts. In many respects, such as gender violence, there have been notable advances, despite methodological difficulties. In others, almost nothing can be found. In any case, evaluations are far from systematic and important gaps remain.

The large experience of the transport sector when dealing with intangible impacts should facilitate the development of quantitative assessments and evaluations, but the lack of quantitative ex-post analyses makes it difficult to assess gender-oriented projects.

1. GENERAL FRAMEWORK

In the transport sector, impacts as diverse as the cost of accidents and life loss or the benefits due to time savings have been quantitatively evaluated for decades. However, the gender approach, which is currently the axis of many policies, is frequently assessed from a merely qualitative point of view.

This article provides a review of quantitative analyses related to the gender approach in the field of transport. Three large analysis groups have been identified, each of which subdivided as follows:

- Regarding women as employees of the transport sector, where two types of impacts arise:
  - Direct ones, either related to labour costs (which include salaries, absenteeism and productivity) or derived from accidents.
  - Indirect ones due to the female participation gap.
- Regarding women as transport users, two types of impacts can be considered:
  - Direct ones related to gender-related violence when using public transport.
  - Indirect ones linked to the mobility of the users.
- In addition, there are other highly important impacts, of indirect nature and delayed over time, derived from female empowerment.

Most these issues may be considered from the point of view of costs, whose reduction are benefits. In the following paragraphs, this distinction is not dealt with and must be taken for granted.

2. WOMEN AS EMPLOYEES

2.1. Labour costs for companies

From a managerial point of view, labour costs in general (men or women) are highly relevant in the transport sector. In Spain, in the freight transport by road, the cost of drivers (without subsistence allowances) ranges between 54.7% of total operating costs for a van and 16.7% for a refrigerated trailer in international transport (Ministerio de Transportes, Movilidad y Agenda Urbana, 2020a). In road passenger transport, the equivalent value varies between 55.8% for a minibus with 10 to 25 seats and 28.8% for a bus with more than 55 seats (Ministerio de Transportes, Movilidad y Agenda Urbana. 2020b).

The wage gap is the difference in salaries between men and women with the same position and performance. In Spain, the harmonized wage gap (isolating the effect of differences in age, seniority, educational level, working hours, etc.) in the transport and storage sector was 10.5%, as an average value for the 2002 - 2014 period. As a comparison, the value of this indicator in the education sector was 5.5%, in the Public Administration 6.7%, in commerce 11.8%, in construction 14.0% and in manufacturing 19.5% (PWC, 2019). Transport is, therefore, in an intermediate position.

A study of direct differential monetary costs for hiring a woman instead of a man in several Latin American countries showed that they are less than 1% of the total labour cost of female employees. The additional cost for companies in Argentina for hiring a woman was 0.39%, in Chile 0.92% and in Uruguay 0.50% (Abramo and Todaro, 2002).

In Spain, and particularly in Andalusia, before the increase in paternity leave, maternity leave represented an extra cost for women of between 0.24 and 0.36% of salary (Junta de Andalucía, 2010).

Productivity refers not to the input cost but to the cost of the input relative to the output. A study carried out with a wide series of data in industries in the United States (data from 1974-1978), Sweden (data from 1990) and Norway (data from 1990) found negative differences of 2%, 1% and 3%, respectively, in the productivity of women compared to men, although it was indicated that it could be due to factors that had not been considered (Trond and Vermond, 2006). In studies related to specific sectors, such as agriculture in various Central American countries and in Mexico, levels of female productivity are very similar to those of men (CEPAL, 2011).

Regarding absenteeism, no specific data has been found for the transport sector, but there are some results of interest for other sectors and certain geographical areas:

- Absenteeism due to family reasons is higher in women with small children, although if absenteeism due to illness or other reasons is taken into account, it may become higher in the case of men (Álvarez, 2000).
- In different Australian companies 84.2% of employees had taken at least one time off during the year for a reason not anticipated by their employer. The absence rate was slightly higher for women (2.7%) than for men (2.3%) (VandenHeuvel and Wooden, 1995).
- In the UK, the average absenteeism rate for the entire population was 3.7%. If only absenteeism due to illness and accidents was considered, this rate dropped to 2.4%. The difference between these two measures was much higher for women than for men. The average total absenteeism rate for women was 5.2% and 2.9% for illness and accidents, respectively. For men, these values were 2.4% and 2.0%, respectively (Bridges and Mumford, 2000).
- In a major metropolitan area in the United States, women were absent more frequently than men, but with a difference that was not very significant (2.88% of women versus 2.14% of men) (Scott and Mabes, 1984).
- In Andalusia (Spain), female absenteeism explains an extra cost of between 0.83% and 0.87% of the average salary with data from 2006 (Junta de Andalucía, 2010).

Regarding accidents, in the transport sector it is relevant to make a distinction between two types of accidents:

- Accident at work, common to any other sector, considering all kinds of accidents.
- Traffic accidents, due to vehicle handling, as a case of accidents in general.

In Spain, and referring to all types of accidents by gender, the "incidence index" is used. It is defined as the number of accidents that occur at work in a given period for every 100,000 people on the workforce. For 2015 the values were as follows (INSHT, 2016):

- For all sectors, the index value was 2,088.9 for women and 4,313.6 for men.
- For the transport and communications sector, the value was 3,331.2 for women and 5,561.2 for men.

About traffic accidents by gender, there is information from several countries, always very favourable for women:

- In Spain, an investigation carried out in Andalusia found that, taking into account the travel time as an indicator of the degree of exposure, the risk of injury in a traffic accident was lower for women: in serious injuries 23.6% less than men and in deaths 35.1% (González, 2019).
- In the United States, an analysis carried out in the road freight sector showed that, compared to a female participation rate of 5.0% of total drivers, women were 2.0% of drivers involved in accidents without injuries and 2.7% of those involved in accidents with injuries (TRB, 2016).
- In Jordan and for an average annual driving distance for women of 12,000 km and for men of 17,000 km, the results regarding the adjusted accident rate per 1,000 drivers and per km travelled was 2.42 times higher for men (Al -Balbissi, 2003).

2.2. Gender gap

The "gender gap" describes any difference between the values of one variable for men and for women. The "wage gap" has already been discussed, as a difference in remuneration between men and women for the same position and performance. The "participation gap" is the difference between men and women in share of the labour force.

The participation of women in the "transport and logistics sector" has increased in the EU countries in recent years, although there are still clear differences between countries. France and Germany show female participation rates of over 25%, while other countries, including Spain, are still around 20-21% (Eurostat, 2019).

Country	2013	2017
France	25.83%	26.23%
Germany	25.48%	25.26%
United Kingdom	19.28%	20.95%
Italy	20.23%	20.22%
Poland	20.73%	19.31%
Spain	17.96%	19.02%

Table 1 – Percentage of women over the total number of people between 15 and 64 years employed in the transport and logistic sector in several EU countries

As a comparison, the percentage of female participation in the transport, storage and communication sector in 2014 in the set of 18 countries in Latin America and the Caribbean was 20.9% (CEPAL, 2017).

If the analysis is carried out in specific subsectors, it is found that in road passenger transport Spain was the EU country with the highest percentage of female drivers: 15% compared to the European average of 12% (IRU, 2019). This is one of the results of the huge growth of women in obtaining a bus driver's license between 2012 and 2018: 60.51% (DGT, 2020).

3. WOMEN AS USERS

3.1. Gender violence

Public transport is one of the environments where women can feel a greater feeling of lack of security, although values vary largely (International Transport Forum, 2018):

- A national survey in the United States found that one in four women had experienced sexual harassment situations on public transportation.
- In Paris (France), 100% of women using the regional public transport system had experienced situations of harassment according to a recent survey.
- In Mumbay (India) a survey of 1,000 users at seven metropolitan railway stations found that 54% of respondents had experienced sexual harassment.

On the other hand, in 2014 a survey of more than 6,500 users of public transport in 16 of the world's most populated metropolitan areas, found that the public transport systems of Bogotá, Mexico City, Lima, Delhi and Jakarta were the areas with the worst overall value in the city, but this problem also stood out, although to a lesser degree, in London and New York (Thomson Reuters Foundation, 2014).

However, an adequate official quantification frequently faces problems of lack of representativeness.

The number of complaints is usually very low, especially in countries with weak police and legal support. Continuous perception and victimization surveys, with adequate preparation of the personnel who ask the questions, could make it possible to assess the evolution gender-specific violence (UN Women, 2017; Galiani and Jaitman, 2016).

Going one step further, it is possible to calculate the monetary value of violence by means of methods closely similar to those used in transport economics:

- For the direct costs related to medical, police and legal care, both of the criminal act itself and of the judicial and penitentiary process in the event of the offender's arrest, the so-called accounting method is used, based on the budgets of the departments of health, police and the judiciary, along with the number of complaints made.
- For the valuation of indirect costs (productivity lost by companies, loss of income of victims, etc.), the results of surveys of companies and victims are often used.
- And, as expected, the valuation of intangibles is complex, due to difficulties in monetizing aspects such as pain and suffering, along with other aspects such as the loss of social capital.

Some examples found consider tangible and intangible costs, but others are limited to tangible ones. In the table that follows, the first four countries include tangible and intangible costs, while the last two take into account only health loss costs (health services, lost economic output and physical and emotional impact).

Country	Crime	Unit cost	Note	Source
United Kingdom and EU	Homicide Injuries Common assault Sexual violence	1,733,192 € 14,209 € 2,316 € 52,486 €	Values in € 2012	EIGE, 2014
USA	Homicide Rape Sexual assault	4,474,501 US$ 103,560 US$ 32,780 US$	Values in US$ 1996	Clark et al., 2002
Canada	Homicide Rape Sexual assault Sexual harassment	7,951,145 C$ 50,007 C$ 14,225 C$ 630 C$	Values in C$ 2009	Canada Department of Justice, 2014
Australia	Sexual violence	26,780 A$	Annual value per victim in A$	PWC, 2015
Guatemala	Homicide Rape	94,604 US$ 6,570 US$	Values in US$ 2005	Balsells, 2006
El Salvador	Homicide Rape	181,510 US$ 5,453 US$	Values in US$. 2007	Acevedo, 2008

Table 2 – Unit costs for crimes of gender violence

3.2. Mobility

The first observation regarding mobility is that, due to their different social roles, men and women move differently. All data lead to the same conclusion: women walk more and use public transport more. With data from the Basque Country (Spain), more than half of trips of women are walking, while for men walking represents just over a third of trips (Emakunde, 2013).

Mode	Women	Men
Car	27.5%	44.8%
Walking	51.7%	37.3%
Bike	1.4%	2.5%
Railway	7.6%	5.3%
Bus	8.0%	3.9%
Motorcycle	0.3%	1.6%
Multimodal	1.3%	1.1%

Table 3 - Distribution of trips according to the main modes of transport in the Basque Country

Improving mobility is the essence of the functionality of a transport system. The benefits of improving women's mobility can be classified into two types:

- The direct benefit is this related to the reduction of travel times, easily monetizable in transport economics.
- The main indirect benefit is associated with the increase in opportunities that the improvement of mobility brings: a greater number of possible jobs, educational premises, places of social interaction, health services, etc.

Regarding the reduction of travel times, most surveys carried out in recent years in metropolitan areas already include the gender perspective in the assessment of travel time according to the trip purpose, the transport mode, etc. Analysis with data from Sweden (Börjesson and Eliasson, 2019) found no general differences in the valuation of travel time according to gender, despite the fact that they had detected different valuations in access to public transport in relation to perceived personal safety (Börjesson, 2012). However, in societies with greater gender inequality, it seems that the social valuation of time is different for men and women, both in terms of travel for work and other reasons. In particular, in Spain it seems that women value travel time between 43 and 50% more than men, as shown in the table below.

Scope and date	Hourly travel time value for women	Hourly travel time value for men	Source
Santander. Bus (2003). Under 24 years and 1,200 Euros/month	3.25 Euros	2.17 Euros	IDAE (2010)
Santander. Bus (2003). More than 24 years old and less than 1,200 Euros/month	13.75 Euros	9.19 Euros	IDAE (2010)
Santander. Bus (2003). Less than 24 years old and more than 1,200 Euros/month	3.59 Euros	2.51 Euros	IDAE (2010)
Santander. Bus (2003). Over 24 years and 1,200 Euros/month	15.19 Euros	10.61 Euros	IDAE (2010)
U. de La Laguna (2000)	8.91 Euros	6.13 Euros	Amador (2005)
Teide National Park. Private and rental car (2016)	12.30 a 13.86 Euros	9.58 a 11.0 Euros	Marina (2017)

Table 4 – Economic valuation of travel time differentiated by gender in Spain

Regarding the benefit for access to opportunities, an interesting study in Buenos Aires obtained the following results (Peralta et al., 2014):

- The need to minimize travel times in order to combine work and domestic activities means that women must look for job opportunities at shorter distances from home. In the workforce, women with children must look for jobs within a 20% shorter distance than men.
- The average distance travelled by men on each trip is much higher than that travelled by women: 6.72 km compared to 4.77 km.
- Regarding the speeds of these trips, tit is 8.62 km/h for women and 10.93 km/h for men. This difference is due to the larger use of public transport by women.

In Spain, a study carried out in Madrid and Barcelona (Matas et al., 2010) stands out. It assessed accessibility in public transport and its impact on women compared to men in terms of labour market. For the metropolitan areas studied, better access to employment in public transport increases the probability of working. The distinction according to educational level shows that the effect is greater for those women with a lower level of education and, probably, with less car availability. Thus, if accessibility by public transport increases:

- Women without studies in Barcelona would see an increase in employment ratio from 34.3 to 40.8% and those in Madrid from 30.7 to 34.0%.
- In the case of women with primary education, the increase would be from 45.0 to 48.0% in Barcelona and from 37.7% to 39.1% in Madrid.

Other studies show that more than 70% of the women surveyed at some point in their life rejected or gave up a better job due to the distance they travelled, while only 40% of men had to do the same. The results also show that the level of exclusion is higher for low-income women (Fédération Internationale l'Automobile, 2014).

4. EMPOWERMENT

Empowerment is defined as the “process of access to resources and development of personal capacities to be able to actively participate in shaping one's life and that of their community in economic, social and political terms” (European Commission, 1998). Therefore, most of the benefits discussed above on women as users also lead to greater empowerment.

A first type of empowerment can be classified as “economic empowerment” and is related to time savings and increased opportunities, as well as increases in income, savings and consumption. It has already been discussed previously, particularly about improving mobility, but it may include other aspects such as increased disposable income if transport costs decrease. In addition, there may be issues of more complex monetization, such as improving access to schools or healthcare facilities.

“Social and political empowerment”, related to participation in the public sphere is an area where the existence of numerous intangibles makes it difficult to find significant examples of impact quantification, let alone monetization. The most complete references found of ex post analyses are related to rural areas in poor countries, and the role of women employed in road and highway improvement and maintenance tasks. Although they are of utmost importance, they provide information only about some isolated indicators, without any consolidation:

- Following the implementation of a rural road improvement program in Bangladesh with active female participation, the results showed a decrease from 31% to 16% of poverty, while girls' school enrolment increased by 5.7% and the number of jobs healthcare coverage doubled (Quader, 2011).
- Various rural road improvement programs in Peru between 1995 and 2013 with female participation entailed an increase in school enrolment of 19.2%, while the number of health consultations increased by 17.8% in the communities that benefited from the project (World Bank, 2017).

5. ECONOMIC EVALUATION

In the research carried out, no manuals or guides with quantitative methods of evaluation of the gender approach have been found, not to mention specific ones in the transport sector.

In terms of women as employees, the economic assessment of the gender gap has not been found for the transport sector, but there are various estimates for the economy as a whole. In Spain, a recent analysis with data from 2018 and 2019 showed that Spanish GDP would increase by more than 200,000 million euros, equivalent to 16.8% of GDP in 2018, if the gender gap was eliminated (PWC, 2019). In any case, the value of impacts and the low cost of implementation make it obvious that the overall balance is neatly positive.

When it comes to women es users, there are interesting efforts to define its main impacts of (Inter-American Development Bank, 2016) or to establish systematic evaluation methods, but they are usually limited to stating general principles, without providing the typical default values that help evaluators so much in other fields of transport (García-Calvente et al., 2016).

Some efforts have been made in several sectors in order to assess gender-oriented projects, but very few in the transport sector, where most analyses are simply valuation of impacts, which in this context is no minor feat. In transportation, some ex-post studies give information on the impact of measures oriented towards the reduction of gender-based violence and the difficulties of valuing it simply:

- The “Viajemos Seguras” (Let's Travel Safely) Program in Mexico City, in operation since 2008 and recently strengthened, is a set of actions that range from prevention to care actions. The impact of the measure to have specific subway cars for women has been evaluated and the results have been mixed: sexual violence disappears but physical violence increases. (Soto et al., 2017).
- The “Bájale al Acoso” (Come Down to Harassment) strategy in Quito (Ecuador) in the main bus and trolleybus corridors began in 2014 and in 2017 it was structured as a program of actions. The latest references obtained from a continuous impact evaluation showed a decrease of 34.5% in situations of sexual harassment, considered to be the result of more than 2,500 complaints and the conviction of 20 harassers (Banco Inter-American Development, 2018).

When it comes to mobility, the higher speed of the private vehicle compared to public transport in Buenos Aires means that, when women have access to the car, the average speed of their trips increases by 5.76 km / h. If the travel speeds of women were compared to those of men (keeping the number of trips), their opportunities in the labour market would open between 20 and 80% (Peralta, 2014). In this case, incidentally, the reflection might be whether, for other social and environmental considerations, the transfer from public transport to private vehicle is desirable.

More structured analyses comparing costs and benefits are very few. Two notable cases in relation to assessing gender-violence related projects have been found. Both have in common the use of the benefit to cost ratio as an indicator.

- Ratios of B/C up to of 17 have been obtained for reducing violent assaults, regardless of the gender of the victim (Copenhagen Consensus Center, 2016).
- A B/C ratio of 9.25 was estimated in an evaluation of five years of actions established by the Violence Against Women Act of 1994 in the United States (Clark et al., 2002).

6. CONCLUSIONS

In a context where gender-responsive policies are ubiquitous, data related to women as a part of the workforce in the transport sector are relatively abundant. Common measures such as the wage gender gap are well established, as it happens in any other sector. Even some specific aspects, such as traffic accidents are well documented. Most indicators are either similar for men and women, or positive in favour of women. This reinforces the need to increase the role of women in the transport sector as employees. Be it from the strict point of view of the operating companies or from the point of view of the whole society, it becomes obvious that the reduction of the gender gap is positive and its social and economic impacts are huge.

But from the point of view of women as transport users, information is not as clear. Some projects in different sector have assessed quantitative impacts of gender-based projects, but in the transport sector experiences are scarce and figures less available. Violence reduction or time savings have been valued, and its final impacts even monetised. But many other aspects are simply not analysed with quantitative tools. More often than not, results are shown in terms of resources spent (investment done, for instance) or, at most, in terms of direct results (such as number of complaints). Concepts such as empowerment, which may be considered the backbone of many policies, are rarely quantified and probably have never been assessed.

If economic evaluation is systematically used in other types of transport projects, including so sensitive issues such as the value of human life, one could expect that actions with a gender focus might be also assessed using, at least, a quantitative approach, but this is the exception to the rule. The main barrier to this improvement is the lack of ex post data: although costs may be well defined, values of benefits (or reduced costs) are unknown.

Rational priority setting requires information of high quality. If such information is not available, governments may be making inefficient decisions. The transport sector is used to dealing with intangibles: well-planned, quantitative ex-post assessments of the many recent and planned actions should be high on the gender agenda.

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THE DIGNITY PROJECT- TOWARD A SYSTEM OF INCLUSIVE DIGITAL MOBILITY IN THE BARCELONA METROPOLITAN AREA

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ABSTRACT

Recent developments in the transport and mobility sectors are radically altering mobility patterns; these include digitization, smart mobility applications, and local digital services, which offer a wide range of innovations that are adaptable to rapidly-evolving lifestyles. However, many services currently are offered as an "online" mode or incorporate digital elements, and the lack of adequate digital literacy or of specific competencies / skills can be expected to generate situations of exclusion.

The DIGNITY project (https://www.dignity-project.eu/), a European initiative in the European Union's H2020 framework, aims to promote an ecosystem of digital mobility services that is sustainable, integrated, and user-friendly, and which improves accessibility, social inclusion, daily mobility experiences, and everyday life of all residents. The project selected four pilot studies in five EU countries (Spain, Italy, Belgium, the Netherlands, and Germany) for their innovative proposals in sustainable and inclusive mobility. The case studies apply the DIGNITY approach, which is based on conducting workshops, interviews, and surveys.

Here, we specifically address the study based in Barcelona, which is at the forefront in smart urban transformation. The digital divide in mobility in the Barcelona Metropolitan Area was evaluated using a mixed approach of combining literature review with a quantitative survey. The results reveal the needs and perceptions of people about local mobility, as well as the gaps in the use of technology products and services.

1. INTRODUCTION

Digital transformation has a great impact on the daily lives of people. Public products and services are becoming more interactive and are being increasingly offered online. Nevertheless, some groups in society do not fully benefit from the opportunities of digitization (Loos, E. et al., 2020; Groth, S., 2019), (for instance, women, people who are older or have functional impairments, low education, low income, as well as short-term migrants and ethnic minorities) and are more likely to be excluded from many services and facilities (Durand, A. and Zijlstra, T., 2020).

In the transport and mobility sector, advances such as digitalization, availability of smart applications, and locally-based digital services are disruptive for mobility patterns and offer a range of mobility innovations that respond to rapid changes in lifestyles. New mobility concepts can include a wide variety of elements, such as novel products, data-based processes, and services inspired by new transport dynamics (e.g., mobility-as-a-service [MaaS] and on-demand public transport), as well as new business models, such as pay-as-you-go. However, technology has not yet contributed to universal access, as most of the new transportation technologies have more greatly benefited a specific demographic: urban, young, tech-savvy, and usually well-off (Vandycke, N., 2018).

Therefore, commuting and mobility produces new challenges for the political agendas and the development of the public and private sectors, with a strong presence of information and communication technologies. In this context, synergies appear that can produce social exclusion in the field of mobility and the use of new technologies. More and more studies are examining the digital divide and transport poverty in greater depth; even so, the growing relationship between mobility and the use of new technologies, as well as the tendencies of governments and companies to move towards digitization, require further studies that relate the two concepts and give a precise overview of social exclusion and situations of inequality that are being generated in this area.

2. THE OPPORTUNITY OF THE DIGNITY PROJECT

The DIGNITY project (DIGital traNsport In and for socieTY; https://www.dignity-project.eu/) is a European initiative funded by the European Union's Horizon 2020 Program. DIGNITY aims to contribute to the development of a transport system that is inclusive, digital, and interconnected, and that meets the needs of all residents. The project has fourteen partners from six European countries.

The overall objective of DIGNITY is to foster a sustainable, integrated, and user-friendly digital travel ecosystem that improves accessibility, social inclusion, travel experiences, and daily life of all inhabitants.

The project thoroughly examines the digital mobility ecosystem to understand the full range of factors that could lead to disparities in the adoption of digitized solutions for different user groups in Europe. The idea is to support public and private mobility providers in their conception of general digital products or services, to make these accessible and usable by the largest possible number of people, regardless of their income, location, social or health situation, or age. Further, results from DIGNITY should help policymakers formulate long-term strategies that promote innovation in transportation while responding to global social, demographic, and economic changes, including the challenges of poverty and migration. Four case studies on implementing inclusive mobility solutions have been selected as pilot projects, based on their ambition of working towards these types of solutions: Ancona (Italy); Barcelona (Spain); Flanders (Belgium), and Tilburg (the Netherlands) (for more information on DIGNITY pilot projects, see https://www.dignity-project.eu/pilots/).

This article is specifically based on the case study of the Barcelona Metropolitan Area (*Àrea Metropolitana de Barcelona*, AMB). The objectives are to: i) characterize the context of digital exclusion with respect to mobility in the AMB, and ii) to understand the patterns of use of digital technologies by residents for their daily mobility.

3. METHODS

The proposed objectives of this study are based on i) a bibliographic review collected in an academic study of a Master's thesis (Bella, R., 2020), as its considerations and recommendations advance the knowledge of the current situation in the field of study; and ii) the preliminary results of a quantitative survey carried out in November and December, 2020.

The fieldwork of collecting interviews was entrusted to the GESOP Institute (*Gabinet d'Estudis Socials i Opinió Pública*, Cabinet of Social Studies and Public Opinion) of Barcelona. The questionnaire with 96-questions/variables is divided into eight parts, each of which addresses specific issues related to mobility and technologies and includes several questions and variables, such as: access to and use of technology; technology for public transportation; general computer and mobile device activities; attitudes toward technology, technology symbols, and interfaces; personal abilities / skills; demographics; and specific questions about daily mobility. The work presented here is mainly focused on specific topics of the survey:

- Technology access and use: related to the access to and frequency of use of different devices;
- Technology for public transport: addresses issues related to the use of digital public transport services;

- Demographics: describes characteristics of the population (e.g., social, educational, residential, etc.);
- Questions about daily mobility.

Although two subsamples were defined (one for the city of Barcelona, and the other for the remaining metropolitan area), this article only presents grouped data. Interviews were stratified by district, and the potential interviewees were selected randomly after taking into account gender, age, and nationality quotas.

4. RESULTS AND ANALYSIS

The bibliographic analysis (Bella, R., 2020), provides essential information to understanding the context of the digitization of mobility in the AMB. The population of Barcelona is uniquely situated with respect to the use of digital tools. In the comparison of the Digital Economy and Society Index (DESI) regarding internet access, use, and connectivity, the city of Barcelona is positioned among the European leaders, well above the average for Europe, Spain, and Catalonia (DESI, 2019). Despite this evaluation, an analysis of the aspects of i) mobility and social exclusion; ii) digital divide; and iii) digital exclusion detects groups that are of special interest due to their vulnerability and/or discrimination:

- Women;
- Older people (e.g., ≥65 years old);
- Individuals who are unemployed, retired, or exclusively dedicated to unpaid household work;
- People with lower levels of education;
- Individuals with high degrees of functional impairment and wheelchair users.

Residents who belong to one (or more) of these groups are seen to have a higher risk of social exclusion in terms of mobility.

The results of the survey highlight interesting characteristics in the use of digital technologies and mobility services, as well as the main limitations and concerns of the main groups analyzed in the Barcelona metropolitan area.

The information on the use of digital technologies in mobility, with respect to the different groups identified as vulnerable, is shown in Figure 1. The importance of using of digital services to find travel information is noteworthy. In general, a considerable percentage of the population (82.2%) uses digital sources to find travel information with women using them slightly less (80.1%). On the other hand, the groups with the lowest educational levels and the older population are the ones that are less likely to use these methods to gather information when planning a trip (62.7% and 56.3%, respectively).

Among older people, there is a higher distrust in the use of digital services for trip planning; approximately one out of three older people feels insecure about planning a trip on public transport using a mobile phone. Furthermore, about 60% of people with a lower level of education experienced similar limitations. A much higher level of trust was observed for the group of women (71.5%). In total, around 75% of the population feels quite confident in using a smartphone to plan a trip. The remaining 25% include people who have access to digital technologies but do not feel comfortable using them, which may lead to exclusion from mobility.

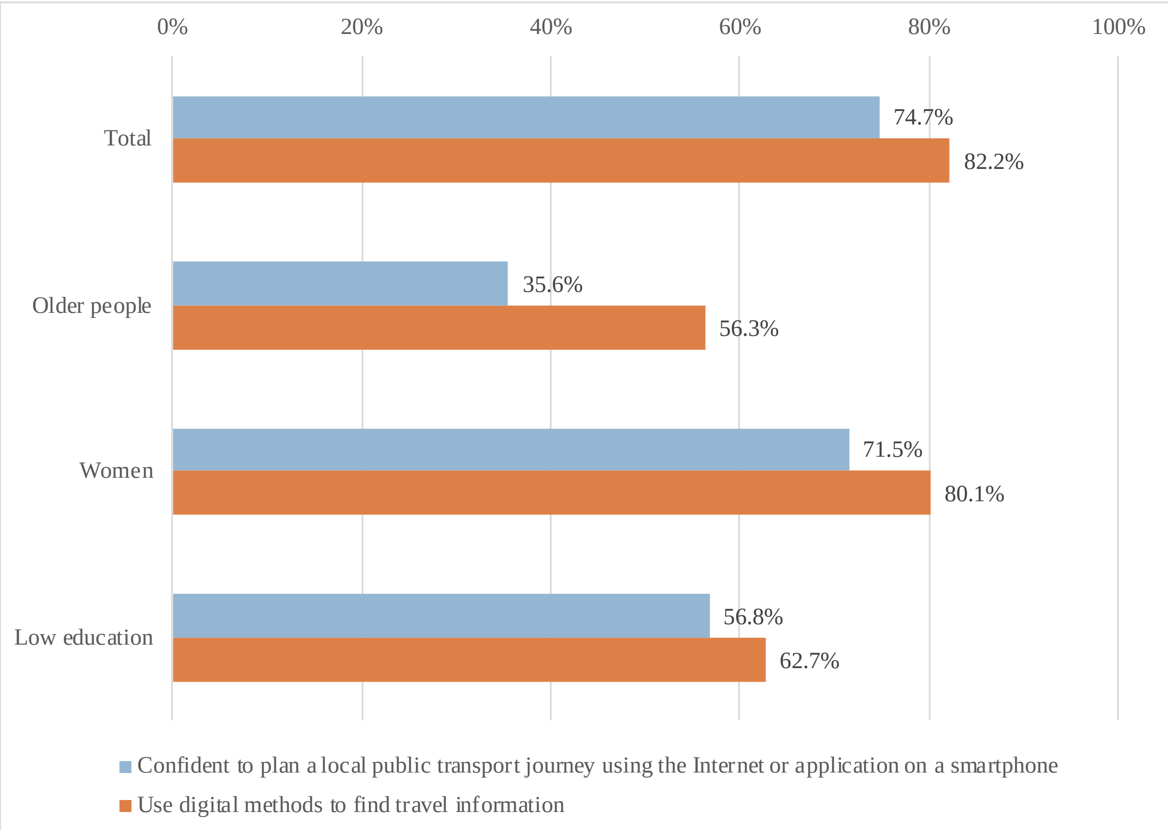

Figure 1. Use of technology for digitally-supported mobility, separated by groups identified as vulnerable

The use of digital transport services by each vulnerable group (Figure 2) revealed that, in general, the percentage of use among all groups is low. The highest percentages are for digital payment for parking and mobile taxi booking. The use of carpooling, carsharing or on-street scooter/motorbike hire services is very low, which shows that these new forms of shared transport remain unpopular among the general population.

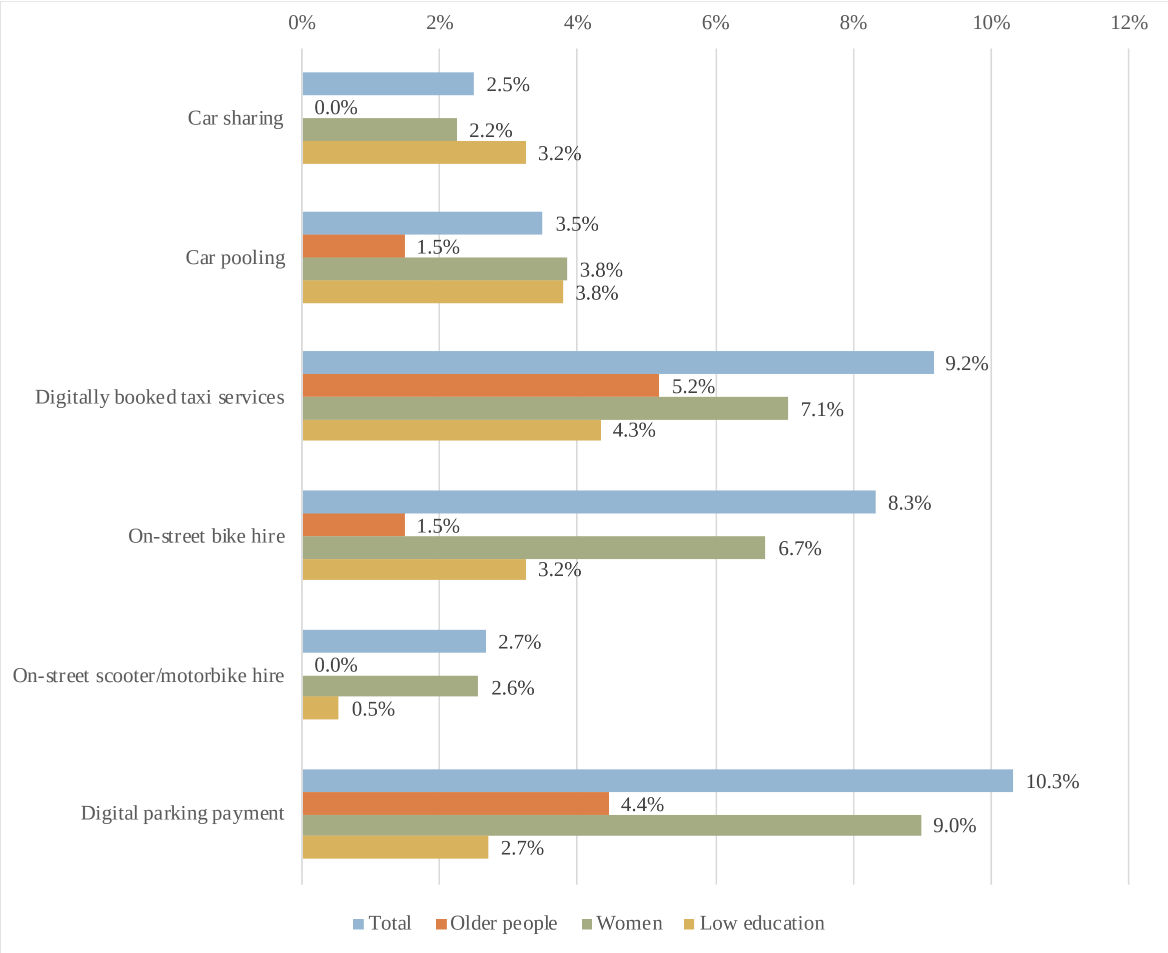

Figure 2. Use of digital transport services per group identified as vulnerable in the past three months (at the time of questionnaire)

Figure 3 analyzes the perceived limitations in regular mobility among the different groups identified as vulnerable. In general, more than 50% of the responses indicate that no particular limitations on mobility are perceived. Of the perceived limitations, safety is among the most important, with a higher percentage of women (50%) and older people (48.1%) perceiving this as a limitation. The cost of transport represents the second-most perceived limitation, cited as the most important one for the groups of the women (47.4%) and the one with the lowest education level (47.0%). Limitations due to lack of digital knowledge are currently less important, although more significant in the case of older and lower-income people.

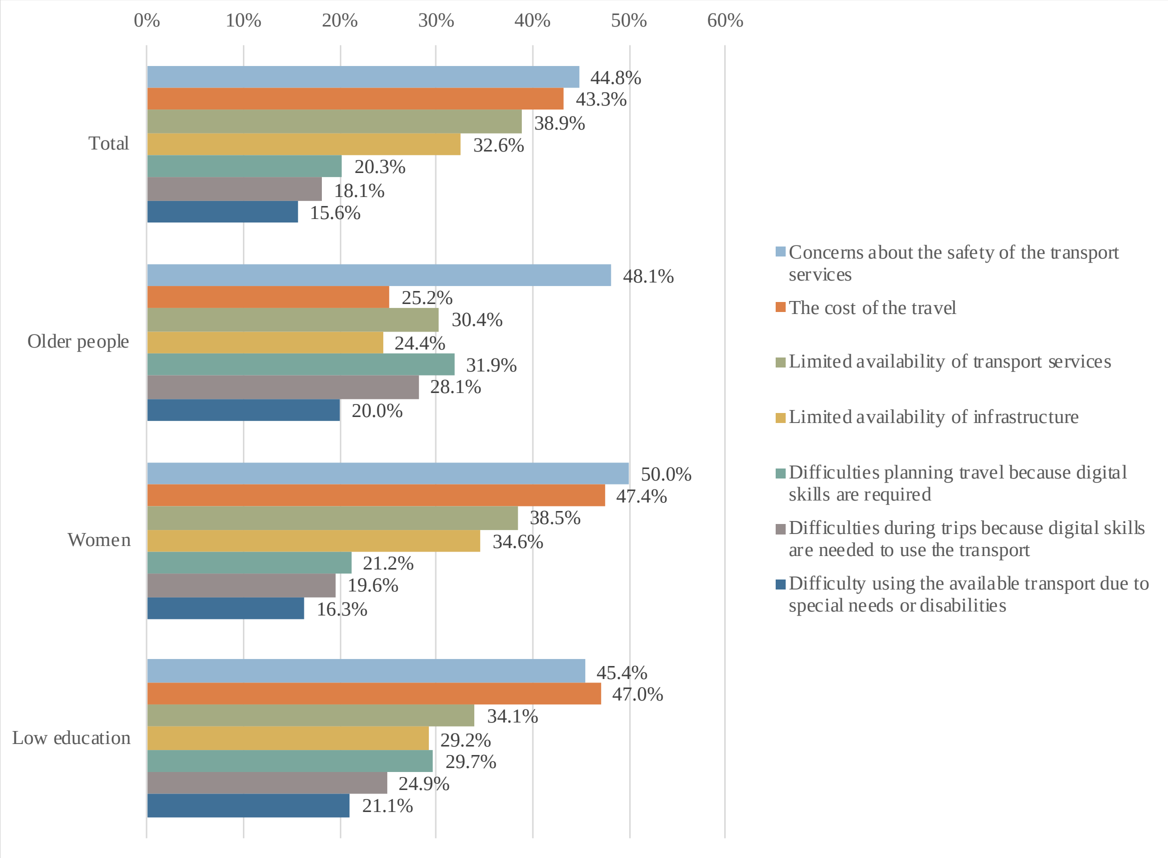

Figure 3. Limitations on regular mobility, per group identified as vulnerable

Figure 4 shows the global perception of the importance that the interviewees assigned to the promotion of different future actions, taking into account that the survey was taking during the COVID-19 crisis of 2020. The post-COVID measure that was indicated as the most important was to an increase in the provision of public transport to avoid congestion (83.5%). This measure is mainly related to perceived safety at the health level and concerns about the risk of contagion, which will be an important issue from now on in the context of public transport that has to be addressed with adequate measures, in order to regain the trust and reliability of this fundamental public service, which is essential for a sustainable urban ecosystem. Notably, the interviewees assigned a high importance to measures that address working conditions—specifically, the flexibility of working hours (75.7%) and an increase of teleworking (73.2%). Promotion of actions such as the implementation of contactless transport tickets or the expansion of pedestrian areas are also considered important for the future of cities, with percentages above 60%. Less importance was assigned to measures such as the expansion of bike lanes (54%) or the promotion of new shared electric vehicle systems (51.4%). Finally, the measure with the lowest perceived importance is the ease of driving to work by car (40.4%).

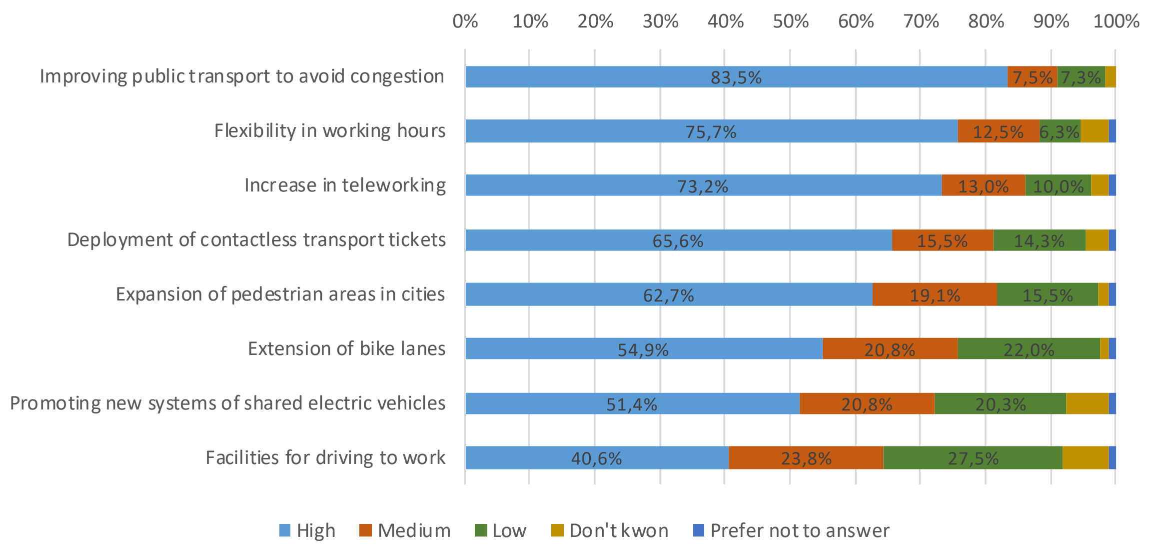

Figure 4. User perceptions about the need to promote specific actions (note that the survey was taken during the COVID-19 crisis in 2020 in Spain)

6. CONCLUSIONS

This study confirmed the problem of potential exclusion related to the mobility of certain social groups in the AMB and recommends that specific studies are carried out to promote a better understanding of the phenomenon, as well as to promote more inclusive policies that better integrate social and technological aspects. In the coming years, an increasingly accelerated development of digital tools focused on mobility—from MaaS to autonomous cars—is likely lead to a total paradigm shift in the way of understanding travel. Therefore, it will be necessary for the entire population to be able to correctly use it, to avoid generating greater social inequalities that strongly limit social development in all its senses. In addition, it will be important to address certain aspects, such as improvement of public transport—with particular attention to categories such as women and older persons, who represent a significant percentage of users—as well as the promotion of working conditions that recognize the flexibility of working hours and the possibility of working remotely. These factors will in turn lead to important changes in the conception of services to be offered and in the conditions of provision of the public transport service.

ACKNOWLEDGEMENTS

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EL RECIENTE CAMBIO DE PARADIGMA DE LA MOVILIDAD EN EL ÁMBITO EUROPEO

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ABSTRACT

Durante décadas, los pilares "teóricos" de la sostenibilidad, -el medioambiente, la economía y la sociedad-, han articulado la planificación de las Administraciones en el ámbito de las infraestructuras y del transporte. En "la práctica", el principal esfuerzo inversor se ha destinado al crecimiento del stock de infraestructuras para superar los déficits de capacidad de las redes.

Recientemente, la rápida digitalización, las nuevas pautas de movilidad y la mayor concienciación social sobre la preservación de nuestro entorno y la urgente lucha contra el cambio climático, han provocado la necesidad de que las Administraciones se replanteen el enfoque con el que afrontar sus políticas de transporte.

El cambio de paradigma pasa por incorporar la movilidad como un concepto más amplio que engloba no sólo a aquello que es inherente al transporte desde una perspectiva tradicional, –el desplazamiento de personas o bienes, entre un origen y un destino, consumiendo recursos cuantificables–, sino que además incluye todos aquellos condicionantes, motivaciones y percepciones de los individuos, situando al usuario y sus necesidades en el centro de todo el sistema.

Tanto la Unión Europea como los Estados miembros están en un proceso de transformación de sus políticas orientándolas hacia la movilidad cotidiana de toda la ciudadanía. Proceso de transformación que se ha visto fuertemente influenciado por la irrupción de la pandemia de la Covid-19 en el año 2020.

Este artículo hace un recorrido a través de las políticas de movilidad europeas más representativas del mencionado cambio de paradigma y en relación con las materias identificadas como más novedosas, con el objetivo de identificar el denominador común de todas ellas. Los ejemplos destacados deben de entenderse siempre en sus correspondientes marcos competenciales y territoriales.

1. INTRODUCCIÓN

La evolución tecnológica surgida desde finales de la década pasada, la concienciación ciudadana y la mayor ambición de las Administraciones públicas por la descarbonización de la economía y la concentración de la población entorno a grandes núcleos urbanos ha motivado un cambio de paradigma en las políticas de movilidad y cambios en las pautas de movilidad, tanto de personas como de mercancías a nivel global. Una mayoría de países han adaptado sus políticas de movilidad, pasando de una política de inversión en infraestructuras y servicios a una nueva manera de proveer un sistema de movilidad más adaptado a las necesidades reales de la ciudadanía, bien a través de la implementación de medidas específicas o de legislación en materia de movilidad y transporte.

Es notorio que la irrupción de la pandemia global provocada por el COVID-19 ha acelerado más si cabe este proceso de adaptación de las políticas públicas a esta nueva realidad. Por un lado, la pandemia ha confirmado ciertas urgencias y ayudado a concienciar más a la población sobre la necesidad de descarbonizar y digitalizar la economía. Por otro lado, la Administración, en este camino hacia la transformación, se encontrará los próximos años con el reto, además, de recuperar la economía. En todo caso, se ha puesto de manifiesto la necesidad de una colaboración entre Administraciones competentes y resto de agentes del sector en materia de movilidad, antes difícilmente pensable, y que es la base sobre la que asentar un sistema de movilidad resiliente y resistente ante futuras crisis por venir.

La coordinación administrativa e institucional parte desde el más alto consenso internacional como es la Agenda 2030 sobre el Desarrollo Sostenible de la ONU (2015), el Acuerdo de París (2015) hoy ratificado por 187 Estados, el “Pacto Verde Europeo” (European Green Deal) anunciado por la Comisión Europea en diciembre de 2019, la Estrategia Europea de Movilidad Sostenible e Inteligente que se describe en mayor detalle en el siguiente epígrafe, así como otra serie de iniciativas de ámbito internacional, y más concretamente europeo, a través de las cuales se suscita decididamente el cambio de paradigma en la movilidad.

En este artículo se hace un recorrido de las políticas novedosas en el ámbito de movilidad de distintos países europeos, fundamentalmente entorno a las vertientes del uso de datos en la movilidad, de la conducción conectada y autónoma, los combustibles alternativos, los sistemas de gestión y financiación de infraestructuras y la integración de urbanismo y movilidad. Destacan las experiencias en estados como Francia, Finlandia, Alemania, Noruega o Países Bajos, de la misma forma que, en un contexto nacional, se tienen en cuenta las políticas de la Administración General del Estado, sobre todo por parte del Ministerio de Transportes, Movilidad y Agenda Urbana y en el marco de su Estrategia de Movilidad Segura, Sostenible y Conectada 2030 y la Ley de movilidad sostenible y de financiación del transporte que la complementará.

2. LA NUEVA ESTRATEGIA EUROPEA Y LAS URGENCIAS TRAS PANDEMIA

Como reacción a los nuevos retos que se plantean en el sector del transporte y la logística, la Unión Europea, y en concreto la Comisión Europea, ha aprobado recientemente estrategias y planes de acción que se enmarcan en esta nueva forma de hacer política del transporte, priorizando ya no tanto la provisión de infraestructuras sino el aprovechamiento de las herramientas digitales y la consecución de objetivos medioambientales y climáticos.

Sobre la base de que la provisión de infraestructuras ha sido y seguirá siendo un elemento clave e imprescindible para la cohesión socioeconómica y territorial, así como para la creación y consolidación de un mercado único competitivo, las prioridades del sector de la movilidad han cambiado ahora hacia:

- El aprovechamiento de las oportunidades que suponen la aplicación de nuevas tecnologías y la digitalización para el sector de la movilidad.
- La consecución de objetivos medioambientales y climáticos, ahora bajo una perspectiva más ambiciosa fruto del Acuerdo de Paris de 2015 y del consecuente Paco Verde Europeo del año 2019. Esta prioridad se alinea fielmente y tiene como soporte las políticas energéticas de la Unión Europea, ámbito profundamente estratégico de la Unión desde su fundación. Dentro del plan de acción del Pacto se incluyen numerosas acciones, que han ido ampliándose en los últimos dos años, entre las que se incluyen una propuesta de una Ley del Clima europea que consagre el objetivo de alcanzar la neutralidad climática en 2050 (y una reducción de emisiones de GEi del 55% respecto a 1990 en 2030), la puesta en marcha del Pacto Europeo por el Clima, la Estrategia de Movilidad Sostenible e Inteligente o la revisión de la Directiva 2014/94/UE sobre la infraestructura para los combustibles alternativos y del reglamento sobre las Redes Transeuropeas – Transporte.

Y todo ello se tendrá que llevar a cabo en un contexto actual e imprevisto como es la pandemia de la Covid-19 y haciendo frente simultáneamente a sus efectos inmediatos y posteriores a corto, medio y largo plazo. Esta pandemia ha traído consigo dos consecuencias al sector del transporte:

- Por un lado, la necesidad de incluir como otro pilar básico además de la digitalización y la sostenibilidad ambiental y climática a la resiliencia. Los efectos devastadores sobre la sociedad y economía de la pandemia en el año 2020 han situado en el foco político a todas aquellas estrategias, acciones y medidas encaminadas a mejorar la capacidad de reacción de los sistemas económicos y sociales. Por suerte, los mismos objetivos de digitalización y sostenibilidad del transporte son piezas clave para lograr esta resiliencia de la movilidad.
- Por otro lado, la creación de los fondos europeos supone una oportunidad histórica para invertir en movilidad que todos los agentes no pueden dejar pasar.

> La inversión en movilidad sostenible y conectada traerá consigo la creación de empleo de calidad, de redes de investigación, la descarbonización de la economía y una mayor cohesión social y territorial, entre muchos otros efectos.

Todas estas necesidades surgidas tras la crisis sanitaria se han tenido en cuenta a la hora de diseñar el paquete de fondos “Next Generation EU”, con motivo del cual cada Estado miembro ha creado sus correspondientes planes nacionales para la gestión de dichos fondos enfatizando las áreas sobre las que incidir en cada territorio. En el caso español, el Plan de Recuperación, Transformación y Resiliencia establece cuatro directrices: la sostenibilidad ambiental, la digitalización, la igualdad de género y la cohesión social e inclusión.

En este contexto surge la Estrategia de Movilidad Sostenible e Inteligente de la Comisión Europea. La estrategia sienta las bases de cómo el sistema de transporte de la UE puede lograr su transformación verde y digital ganando en su capacidad resiliente ante futuras crisis, tratando de conseguir una reducción del 90% en las emisiones para 2050, gracias a un sistema de transporte inteligente, competitivo, seguro, accesible y asequible. Este impulso para transformar el transporte llega en un momento en que todo el sector aún se está recuperando de los impactos del coronavirus. Con una mayor inversión pública y privada en la modernización y ecologización de flotas e infraestructuras, y reforzando el mercado único, se tiene una oportunidad histórica para hacer que el transporte europeo no solo sea más sostenible sino más competitivo a nivel mundial y más resiliente.

En un sentido amplio, la Estrategia de Movilidad Sostenible e Inteligente de la CE ha tenido una buena acogida por los Estados miembros y el sector. Sin embargo, también ha sido foco de algunas críticas relevantes a tener en cuenta. Entre otras, se ha puesto en juicio el excesivo papel de los biocombustibles al tiempo que se echan en falta una mayor importancia de los electrocombustibles y el hidrógeno verde, se demandan compromisos de reducciones de emisiones más ambiciosos o se echan en falta hitos específicos para el uso de la bicicleta (Parlamento Europeo; 2021).

Es necesario resaltar, además, que las políticas europeas se han regido desde hace una década por documentos estratégicos como el “Libro Blanco del Transporte: Hoja de ruta hacia un espacio único europeo de transporte: por una política de transportes competitiva y sostenible”, de 2011, que recogen objetivos no vinculantes y “declaraciones de intenciones” sin haber resultado en acciones concretas. Los retos que recogía aquel Libro Blanco y el diagnóstico que se hacía de la movilidad, salvo los efectos inesperados de la Covid.19, siguen siendo, a grandes rasgos, los mismos que en la Estrategia de Movilidad del año 2020. Desde ámbitos del sector se demanda una mayor ambición de la Comisión Europea.

Sin embargo, bien es evidente que el papel de la Unión Europea en la consecución de los objetivos de descarbonización y digitalización de la movilidad es políticamente limitado.

La movilidad, con efectos sobre la economía mundial e impactos en todo el planeta, está también presente en el día a día de ciudadanos y empresas, por lo que se necesita del compromiso de Autoridades locales, regionales y por supuesto, de los Estados. Por ello, bajar del nivel europeo al nivel local, pasando por el nacional y el regional, resulta clave, y la labor de planificación y gestión de la movilidad en contacto con el territorio resultan determinante.

3. EJEMPLOS DE POLÍTICAS NOVEDOSAS EN EUROPA

A la hora de abordar el análisis de las políticas de movilidad de los Estados miembros de la Unión Europea, es preciso tener en cuenta que la movilidad es un sector transversal a la organización política, administrativa o competencial de los territorios. Para un correcto entendimiento de las distintas aproximaciones relativas a la movilidad deben tenerse en cuenta, por tanto, las distintas Administraciones con competencias en transporte y movilidad, conocerse el régimen competencial en que se engloban y su margen de acción en el ámbito de la movilidad sostenible. Las acciones en el ámbito de la movilidad se pueden dividir en dos vías: la legislativa y la no legislativa. Son pocos los ejemplos encontrados de territorios con legislación global en materia de movilidad, que regule a la vez el ámbito urbano e interurbano y todos los modos y segmentos. El análisis se enfocará también en los otros instrumentos y herramientas de planificación de la Administración (estrategias, planes, etc.)

A nivel de los estados miembros, previo y posterior a la crisis sanitaria, destacan las labores de ciertos gobiernos, por novedosas y por bien ejecutadas, a juicio de los redactores. Estas acciones se han clasificado en 5 ámbitos de actuación que son tendencia actualmente:

- Uso de datos en la movilidad
- Conducción conectada y autónoma
- Combustibles alternativos
- Sistemas de gestión y financiación de infraestructuras
- Integración de urbanismo y movilidad

3.1 Uso de datos en la movilidad

La digitalización en el transporte en particular, pero en toda la economía en general, ha dado suma importancia a un elemento en todo el sistema de movilidad: el dato.

Los datos son ahora el centro de muchas soluciones e incluso modelo de negocio de empresas de movilidad. Por otro lado, la digitalización (sobre todo la telefonía móvil) ha creado un elevado, incluso inabarcable a veces, volumen de datos, de cuyo almacenamiento, gestión y análisis depende el presente y futuro del sector.

Las empresas y Administraciones han detectado la importancia del uso eficiente de los datos y su transformación en información relevante para el desarrollo del negocio y la mejora en la eficiencia. Las herramientas de explotación masiva de datos o big data hacen en este sentido su labor desde hace unos años. Por otro lado, desde la Administración se pretende fomentar el uso de datos abiertos, fiables y de calidad en el sector de la movilidad, que sirvan para desarrollar un sistema competitivo de empresas, servicios y aplicaciones de movilidad amigables para el beneficio de los usuarios.

Muchas Administraciones, tanto del ámbito estatal como regionales o locales, por todo el mundo, están lanzando portales de acceso a datos abiertos actualizados, como pueden ser en el caso de la Unión Europea, los Puntos de Acceso Nacionales. Es el caso de, por ejemplo, el portal “transport.data.gouv.fr” en Francia o “mdm-portal.de” en Alemania.

Además, la publicación de estos datos permite la consulta de los ciudadanos. Sobre la base de la disposición de mejor información se fomenta la transparencia y la participación pública libre e interesada en debates y consultas.

Esta difícil labor de fomento del uso del dato abierto se debe realizar, no obstante, garantizando los derechos de los usuarios. El reto del sector público en el ámbito de la regulación, pero también en el ámbito de la técnica, pues muchas veces adolece un cierto retraso frente al sector privado, más avanzado y disruptor, es muy grande.

En este sentido, cabe destacar la labor del Gobierno de Finlandia, que en julio de 2018 aprobó una nueva Ley de Servicios de Transporte (LVM; 2021), acción que corresponde a uno de sus 26 proyectos estratégicos y que está englobada dentro del eje llamado “Digitalización, experimentación y desregulación” de su programa de gobierno. Se trata de una norma innovadora cuyo objetivo es eliminar las barreras de acceso al mercado y fomentar nuevas formas de servicio basados en la digitalización de la información y la tecnología. Al mismo tiempo, digitalización y tecnología son motivo y fin de la ley. Entre otras cuestiones, la ley obliga a los operadores a aportar al usuario información en plataformas abiertas y formato-código legible, de manera accesible a todos, utilizando interfaces abiertas que permitan al resto de proveedores la venta de *tickets* combinados y obligando a la Administración a incorporar también la información de los servicios que preste directamente.

Por otro lado, la Ley de Orientación de la Movilidad francesa, LOM, (Légifrance; 2019), aprobada en diciembre de 2019 y que, a diferencia de la ley anterior de Finlandia, sí que es una ley global de movilidad, también regula el uso de datos compartidos en el sector de la movilidad.

Compartiendo el mismo objetivo de promover nuevas soluciones de movilidad, la ley, al igual que incluye artículos para favorecer el desarrollo de la conducción autónoma o la movilidad compartida, dedica un capítulo a la aceleración del uso de datos abiertos (Capítulo 1, Título III).

Mediante la norma se garantiza que el 100% de la información sobre la oferta de servicios sea accesible en tiempo real al usuario, a más tardar a finales de 2021. De esta manera Administraciones y empresas podrán desarrollar aplicaciones y ofrecer servicios innovadores, dando la posibilidad de que se puedan ofrecer servicios y viajes puerta a puerta, con un único billete (movilidad como servicio MaaS).

Conviene destacar que la LOM es el fruto de un amplio proceso de participación ciudadana, consulta con grupo de expertos y consenso con las diferentes Administraciones territoriales. Todo ello coordinado en las Conferencias Nacionales de Movilidad entre septiembre y diciembre de 2017, que constituyen un gran ejemplo de gobernanza de la política de movilidad de un gobierno y que derivó no sólo en la elaboración de la LOM sino en la elaboración de otras estrategias.

3.2 Conducción conectada y autónoma

La conducción de vehículos de manera conectada, en el corto-medio plazo, y autónoma, en el largo plazo, son posibles y están siendo desarrolladas gracias a tecnologías emergentes como los sensores, las redes de comunicación 5G o el uso masivo de datos. Se trata de elementos tecnológicos ampliamente desarrollados hoy en día, pero de los que se prevé un mayor auge en la próxima década cuando el uso de la Inteligencia Artificial e *Internet of Things* pueda ser masivo en el transporte en particular y en la economía en general.

Según la Asociación Europea de Fabricantes de Automóviles, ACEA, los sistemas de conducción se basan en vehículos e infraestructuras conectadas entre sí de tal manera que los vehículos pueden "sentir" (percibir), pensar y actuar (ACEA; 2019). En últimas etapas de desarrollo de la tecnología, los vehículos serán capaces de hacerlo sin control humano alguno, mientras que inicialmente se deberá acompañar a los equipos de un cierto grado de interacción hombre-máquina. En función de ese grado de automatización existen, según la Sociedad Internacional de Ingenieros de Automoción, SAE, 5 niveles de conducción conectada y/o autónoma. Solamente en el Nivel 5 el sistema toma el control total en todas las situaciones de tráfico y a cualquier velocidad. El humano es exclusivamente un pasajero, su intervención en la acción de conducir ya no es necesaria (SAE International; 2018).

Las ventajas de la automatización y de la conducción autónoma, y conectada, de vehículos son muy numerosas. La conducción autónoma revolucionará el tráfico rodado mitigando las externalidades actuales, especialmente reduciendo los accidentes (el factor humano es el responsable del 90% de los accidentes de tráfico (PARLAMENTO EUROPEO; 2020) y reduciendo la contaminación y la congestión (el vehículo autónomo se demuestra más eficiente en la conducción).

Además, mediante un uso masivo y una gran penetración de vehículos autónomos y asequibles en las carreteras y ciudades puede contribuir a una movilidad más inclusiva, haciendo posible que personas que no pueden conducir (algunas personas de edad avanzada o con discapacidad, menores o personas sin carné) puedan desplazarse en estos vehículos sin necesidad de depender de otra persona. Se pude concluir que el empleo de altos niveles de automatización puede ser fuente de una mejor calidad de vida tanto en ámbitos urbanos como rurales.

Pero resulta imprescindible destacar el gran número de retos a los que se enfrenta la sociedad a la hora de desarrollar y asentar esta tecnología. Estos desafíos que se plantean no son únicamente tecnológicos (relativos tanto a los vehículos como a la infraestructura física por la que circulan, así como la infraestructura digital) sino que el uso sostenible de la conducción autónoma implica también la consideración de un gran abanico de aspectos éticos, regulatorios, laborales y socioeconómicos.

Los aspectos regulatorios y legislativos serán importantes también en el desarrollo tecnológico a corto plazo, pues solamente con el marco normativo adecuado se puede acometer la gran labor experimental que se requiere para poder hacer frente a estos retos y lograr los objetivos deseados. Es por ello por lo que muchos Estados están trabajando en adaptar sus marcos normativos para permitir y dar cobertura legal a pruebas piloto. Es el caso de los llamados *sandbox* regulatorios, marcos jurídicos específicos que permiten la prueba controlada de proyectos innovadores para testear, por ejemplo, nuevas tecnologías, nuevos modelos de negocio, aplicaciones o procesos para la prestación de servicios de movilidad y transporte. En definitiva, espacios experimentales en los cuales se pueden testear soluciones para las que no hay todavía un marco normativo, o que suponen cambios tan disruptivos que impiden prever adecuadamente el impacto final que pueden tener en el ecosistema de la movilidad.

En este sentido destaca la labor que está llevando a cabo actualmente el Gobierno Federal de Alemania, principal productor automovilístico de Europa, que prevé la aprobación de una nueva ley de conducción autónoma, como parte del pacto del gobierno de coalición (GOBIERNO FEDERAL ALEMÁN; 2021). Ya ha desarrollado un borrador de ley para introducir vehículos autónomos de Nivel 4 en áreas operativas concretas de la red de carreteras. Desde el Gobierno Federal se defiende que este marco regulatorio ofrecerá a Alemania la oportunidad de avanzar en la investigación y el desarrollo y de hacer que la movilidad del futuro sea más versátil, más segura, más respetuosa con el medio ambiente y más orientada al usuario. Numerosos fabricantes de vehículos alemanes aprovecharán este marco regulatorio para acelerar la investigación en el campo y seguir posicionándose estratégicamente en el mercado.

Es el caso de la reciente alianza estratégica entre Volkswagen y Microsoft (Microsoft; 2021).

La Ley de Conducción Automatizada actual, en vigor desde el 21 de junio de 2017, regula el funcionamiento de los vehículos altamente automatizados, que en determinadas condiciones pueden asumir la tarea de conducción de forma autónoma, pero siempre con un conductor. La nueva ley federal regulará el uso de vehículos autónomos sin conductor hasta Nivel 4 en los siguientes escenarios:

- transportes de lanzadera, de corto recorrido (people movers)
- conexiones sin conductor entre centros logísticos (transporte Hub2Hub)
- servicios de transporte orientados a la demanda en horas valle en las zonas rurales,
- vehículos de doble modo, como en el "Automated Valet Parking" para la búsqueda de plaza y aparcamiento de vehículos en modo autónomo en parkings.

La ley crea las condiciones para el uso de vehículos de motor autónomos en todo el Estado federal, aunque en zonas de funcionamiento definidas previamente por las autoridades competentes en cada estado federado. Se regulan también las obligaciones de los propietarios y de los fabricantes.

La creación de sandboxes regulatorios es práctica extendida también para otros ámbitos de la movilidad internacionalmente, como puede ser el desarrollo de soluciones de movilidad compartida, aunque no como ejemplo en Europa, si es relevante en Japón (HBR; 2020), o el desarrollo de sistemas de movilidad aérea urbana Urban Air Mobility en el Reino Unido (CAA; 2020).

La LOM de Francia también creó el marco regulatorio para el desarrollo y la investigación en el ámbito de la conducción autónoma mediante la definición de un programa nacional de experimentación, el seguimiento de la percepción ciudadana o la realización de un estudio del impacto sobre el empleo.

En España, el Ministerio de Transportes, Movilidad y Agenda Urbana prevé en el Documento para el Debate de su futura Estrategia de Movilidad Segura, Sostenible y Conectada la creación de estas figuras normativas para facilitar la experimentación en el campo de la conducción autónoma (MITMA; 2020)

En cualquier caso, mediante avances normativos y/o tecnológicos, la conducción conectada y autónoma está en todas las estrategias de movilidad a nivel internacional. Y ya es una realidad en ciertos ámbitos. Así, por ejemplo, sin ser referencia europea pero sí especialmente relevante, en Guangzhou, China, se despliegan taxis autónomos como parte de una nueva plataforma multimodal de MaaS (Intelligent Transport; 2021). En Europa existen numerosas pruebas piloto en sistemas de transporte público. En concreto en España destacan las dos experiencias hasta la fecha de puesta en marcha de autobuses autónomos en Madrid (“Alsa pone en marcha el primer autobús autónomo en España que circula en tráfico abierto”; 2020) y Málaga (“Avanza e Irizar 'conducen' en las calles de Málaga el primer autobús autónomo eléctrico”; 2021).

3.3 Promoción de combustibles alternativos

El futuro de la movilidad es un futuro descarbonizado y para el año 2050 ha fijado la Unión Europea el plazo para la tener una economía climáticamente neutra. Para lograr este objetivo de descarbonizar la movilidad es crucial el desarrollo de la movilidad eléctrica en paralelo a la producción de energía eléctrica mediante fuentes de energía renovables.

Pero no solo la electricidad ayudará a mover los vehículos, sino que otros combustibles alternativos pueden contribuir a reducir la dependencia del carbono en el corto y en el largo plazo. Se trata sobre todo de los biocombustibles y los combustibles sintéticos. Los primeros están ampliamente desarrollados y en uso, son útiles en el corto plazo para avanzar hacia la descarbonización, pero su uso masivo es insostenible a largo plazo por gran consumo de recursos asociados a su producción. Por otro lado, el propio hidrógeno verde (producido mediante electricidad proveniente de fuentes renovables) y los combustibles sintéticos, (producidos a base de hidrógeno verde) son combustibles todavía en desarrollo, aunque en creciente uso y que sí que se prevé que sean esenciales para descarbonización de sectores como el aéreo o el marítimo que no pueden ser descarbonizados eléctricamente. Además, en el medio plazo, los vehículos de pila de combustible de hidrógeno verde pueden competir con los vehículos de batería eléctrica y sobre todo suponer una gran oportunidad para descarbonizar el tráfico pesado en las carreteras o el ferrocarril.

Actualmente, por tanto, el consenso en los Estados miembros de la Unión Europea es desarrollar ampliamente la movilidad eléctrica fomentando la adquisición de este tipo de vehículos e instalando puntos de recarga, mientras se continúa avanzando en el aumento de las cuotas de renovables en la producción eléctrica.

3.3.1 Flota de vehículos

Las matriculaciones de vehículos electrificados que publica la Agencia Europea de Medioambiente, EEA por sus siglas en inglés (European Environment Agency) son todavía escasas y hay mucho camino por recorrer todavía si se quiere alcanzar el objetivo de la Estrategia Europea de Movilidad, donde se fija en 2030 la existencia de 30 millones de vehículos de cero emisiones (5 millones en España según el PNIEC 2021-2030) (MITECO; 2020). Las cifras publicadas por la agencia para el año 2019 incitan, sin embargo, al optimismo al compararlos con el año anterior (EEA; 2020).

En el entorno europeo (UE-27, Islandia, Noruega y Reino Unido), como se muestra en la Figura 1, en el año 2019 se registraron 534.583 nuevos turismos eléctricos, un 81,6% más respecto al 2018 y un 464,9% más que en 2010. Pero la penetración en el mercado es todavía baja, pues los coches eléctricos suponen solo un 3,5% del total. Las 20.000 furgonetas eléctricas registradas en 2019 suponen un todavía más reducido 1,3% (EEA; 2020).

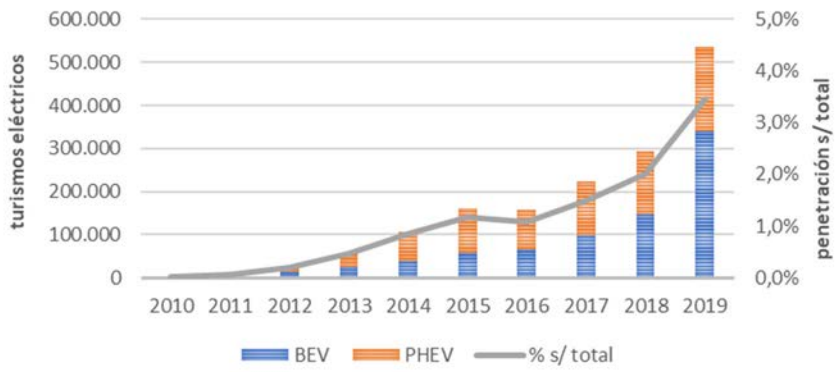
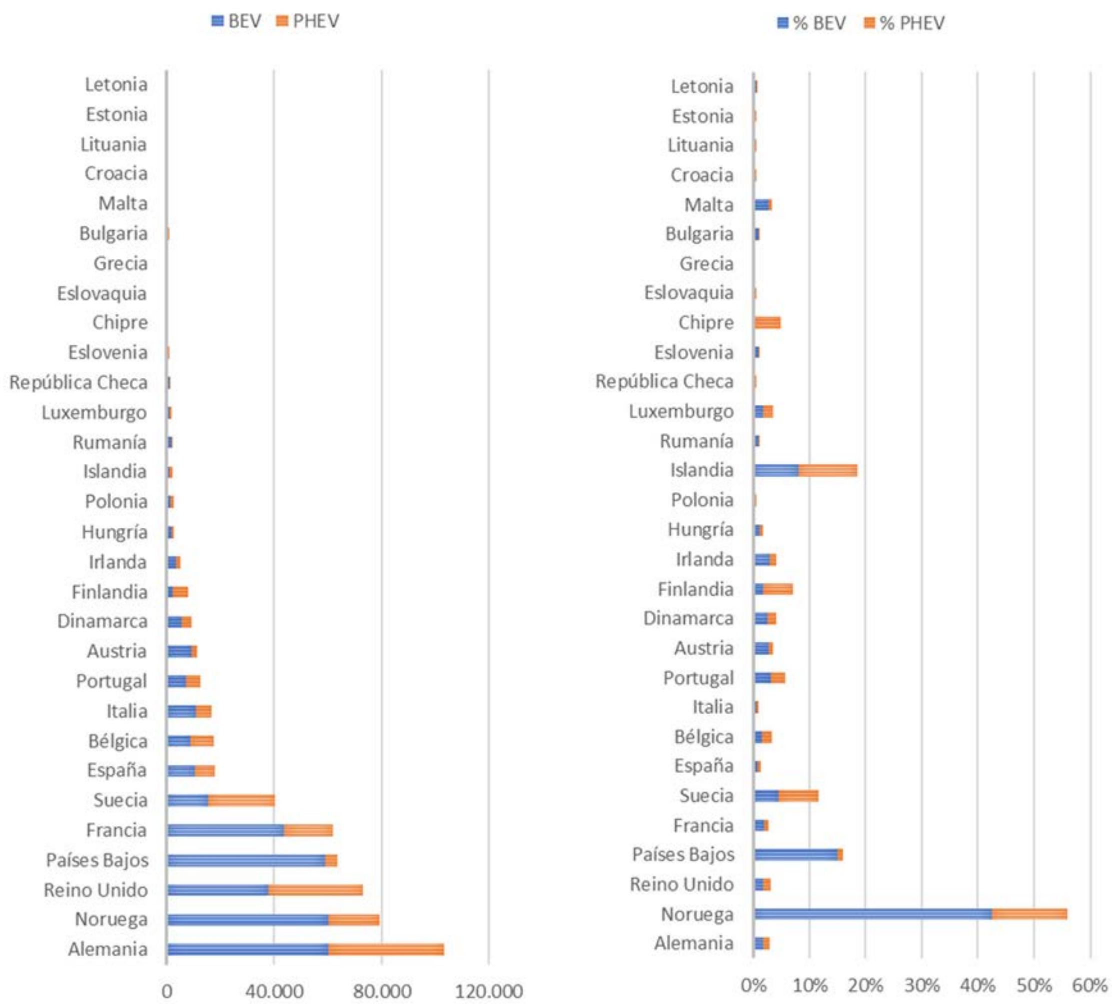


Fig. 1 – Matriculación de turismos (EU-27, Isalndia, Noruega y Reino Unido). Años 2010 – 2019; Fuente EEA

En la siguiente Figura 2 se observa como existe una gran disparidad entre los grados de penetración de turismos eléctricos en los países del ámbito de estudio. En países con un elevado volumen de matriculaciones de turismos como Alemania, Reino Unido o Francia, existen penetraciones cercanas al 3% del vehículo eléctrico. Los datos en Italia o España son todavía peores con el 0,8% y el 1,3% respectivamente. Destacan los Países Bajos y países nórdicos Noruega, Suecia e Islandia por tener altos grados de penetración, en el entorno del 20% analizando los cuatro países conjuntamente, mientras que en el resto de los países el porcentaje medio es tan solo del 2,4%. La media de todo el ámbito de estudio se sitúa en el 3,5% (EEA; 2020).



*. BVE: Battery Electric Vehicles (vehículos de batería eléctrica); PHEV Plug-in Hybrid Electric Vehicles (vehículos eléctricos enchufables o vehículos híbridos enchufables)

Fig. 2 – Turismos matriculados (Valores absolutos –izquierda- y relativos -derecha- por país (EU-27, Islandia, Noruega y Reino Unido) (*). Año 2019; Fuente: EEA

A continuación se detallan algunas de las mejores prácticas que, según informe elaborado por el Ministerio Federal de Transporte y Digitalización de Alemania (BMVI; 2018), han llevado a cabo países pioneros en la incentivación a la compra de vehículos eléctricos como Noruega o Países Bajos:

En Noruega, los conductores de BEVs y los vehículos de pila de combustible de hidrógeno (Fuel Cell Electriv Vehicles FCEV), no siempre los PHEV, tienen los siguientes privilegios:

- No pagan ni peajes de autopista ni urbanos.
- También tienen acceso a aparcamientos públicos gratuitos y a plazas de aparcamiento designadas exclusivamente para vehículos eléctricos.
- El uso de los puntos de recarga públicos es gratuito
- Los vehículos eléctricos tienen derecho a utilizar los carriles bus en algunos municipios siempre que haya al menos dos personas en el vehículo.
- La exención del IVA (25%), del impuesto sobre vehículos y del impuesto sobre vehículos nuevos hace que los BEV sean más baratos que los vehículos de combustión comparables en Noruega. La exención del IVA y del impuesto sobre vehículos nuevos está limitada hasta 2025.

En los Países Bajos los privilegios que se introdujeron en el sistema en los últimos años han ido abandonándose por considerarse que podrían provocar el colapso de determinadas infraestructuras y por considerarse contrarios a la igualdad de todos los usuarios de la vía pública. Sin embargo, sí que ha habido una apuesta fuerte por la electrificación de sistemas de transporte público, flotas de taxi y vehículos de reparto. Para 2025, todo el sistema de transporte público se convertirá en vehículos electrónicos, y en las grandes ciudades sólo los autobuses electrónicos estarán en funcionamiento a partir de 2022. Los operadores de flotas comerciales reciben subvenciones de 3.000 euros del Ministerio de Infraestructuras y Medio Ambiente para la compra de e-taxis y vehículos de entrega electrónica.

También existen incentivos a la compra de vehículos eléctricos, pero solo a los BEV, con una exención del impuesto de matriculación y del impuesto sobre vehículos de motor.

Pero el éxito del caso holandés radica sobre todo en el despliegue de infraestructura de recarga pública y semipública. Entre otros factores, destacan:

- El uso de un protocolo de punto de carga abierto en todos los puntos permite la interoperabilidad del hardware y el software, así como el uso de una única tarjeta de usuario para todos los proveedores
- Un sistema de carga inteligente permite evitar cuellos de botella y una mejor gestión de la energía renovable utilizada

3.3.2 Infraestructura de recarga

La infraestructura de recarga es sin duda, como bien demuestra el caso holandés, uno de los elementos clave para el desarrollo de la movilidad eléctrica.

La Directiva 2014/94/UE sobre el despliegue de la infraestructura de combustibles alternativos (AFID por sus siglas en inglés – Alternative Fuel Infrastructure Deployment) es la normativa europea en esta materia. Exige a los Estados miembros que elaboren Planes Nacionales o Marcos de Acción para el desarrollo del mercado de los combustibles alternativos y su infraestructura. También pretende servir de base para el uso de especificaciones técnicas comunes para los puntos de recarga y ofrecer información adecuada al consumidor sobre localización de puntos de recarga, tipos de combustibles y precios.

Un informe reciente de la Comisión Europea (EUR-LEX; 2021) analiza el nivel de despliegue de estas infraestructuras en la Unión Europea y las acciones incluidas en cada plan nacional de despliegue. La conclusión es que el efecto de la directiva ha sido positivo, pero también destaca el informe que existe gran disparidad en el avance hacia la movilidad eléctrica entre todos los países motivo, en parte, de la falta de una metodología detallada y vinculante por parte de la UE, así como de la disparidad de objetivos y las políticas de los Estados miembros.

La infraestructura de recarga actual en la Unión Europea es suficiente para el escaso parque automovilístico existente. Sin embargo, no existe una red global en toda la Unión Europea y tampoco se prevé que con el actual marco legislativo europeo se pueda desarrollar la red necesaria para alcanzar en el 2030 el objetivo de la Comisión de reducir las emisiones de GEI en un 55% respecto a las del año 1990.

En el ámbito nacional, el Ministerio para la Transición Ecológica y el Reto Demográfico, en colaboración con el Ministerio de Transportes, Movilidad y Agenda Urbana, acaba de presentar la tercera edición del programa MOVES de incentivos a la movilidad eficiente y sostenible que incluye ayudas para instalación de puntos de recarga y a la adquisición de vehículos electrificados (MITECO; 2021)

3.4 Sistemas de gestión y financiación de infraestructuras y servicios

En cuanto a las políticas europeas de gestión y financiación de infraestructuras y servicios públicos, la UE desde sus inicios ha mantenido una política de transporte clara enfocada a unificar las regulaciones de los Estados miembros, con el fin de favorecer el mercado común y la liberalización de la competencia entre modos de transporte. Este hecho surgió desde el Tratado de Roma en 1957 y se vio fortalecido a partir del Tratado de Mastrich el año 1992 donde se estableció una base jurídica cuya adopción sería de obligado cumplimiento.

El libro blanco de la Comisión Europea “curso futuro de la política común de transportes” publicado en 1922, fundamentaba el hecho de que los usuarios no asumieran de manera completa los costes derivados de su propia actividad como una de las razones principales que suponían el desequilibrio modal y la ineficiencia del transporte. Desde entonces han sido distintas Directivas como la Directiva 1993/89/CE, la Directiva 2006/38/CE las que han ido ampliado la cobertura a las políticas europeas para la evaluación de un modelo de cálculo de todos los costes externos para todos los modos de transporte (Liechti y Renshaw; 2007). Igualmente favorecer una unificación en materia de fiscalidad y de tarificación en pro de una mayor eficiencia en el sistema de transporte de Europa (Comisión Europea, 1998) y la recuperación a través de un peaje, permitir a las

Administraciones externalización de costes por el uso que realizan los usuarios de las infraestructuras, así como el control de que ese cobro sea realizado de modo exhaustivo, justo y fiable (Saldaña y Vassallo; 2012).

Es a partir de este momento cuando algunos países de Centroeuropa comenzaron a operar sus redes de carreteras mediante peajes o mediante la introducción de tasas sobre el transporte de mercancías. Entre los países más significativos se encontraron Austria, Alemania, Francia, Suecia, Bulgaria, República Checa, Hungría, Polonia, Rumanía y Eslovaquia (Saldaña, et al; 2012).

Son dos los principios fundamentales que la UE promueve en su actual política de transporte, "el pago por uso" de infraestructuras y "quien contamina paga". En este sentido, dependiendo del tipo de infraestructura modal, los modelos de gestión y financiación son similares en Europa en torno al modo ferroviario y aeroportuario, que se financian fundamentalmente a través de cánones que los distintos operadores que sufragan el coste del uso de las infraestructuras a través de un canon, mientras que aun en la actualidad existen divergencias en cuanto al modelo de gestión y financiación de las carreteras. En este último caso hay que diferenciar aquellos países que tarifican de manera mayoritaria su red de carreteras de alta capacidad, de aquellos otros que no lo hacen y ofrecen a los usuarios el uso de las carreteras sin coste, o bien recuperando una parte de este a través de gravámenes fiscales a los hidrocarburos:

- En el caso de los primeros, más propio de Centroeuropa, tarificando la red principal de carreteras a los vehículos pesados, como es el caso de Alemania, la República Checa o Eslovaquia,
- y en el caso de los segundos, una mayoría de países periféricos que consideran que este tipo de modelos de financiación pueden restar su competitividad en el mercado común, al ser países generalmente destino y no de paso de mercancías. No obstante, países como Portugal, Italia o Francia cuentan con notables redes de autopistas de peaje directo a los usuarios, con el fin de amortiguar los costes de sus inversiones o del mantenimiento de estas.

El ejemplo **alemán** es uno de los más relevantes, quien en el año 2002 decidiera optar por la implementación de un modelo de pago por uso que posibilitara la tarificación de vehículos pesados, principalmente para atender el continuo crecimiento del volumen global en transporte de mercancías que suponía una considerable carga para las autopistas alemanas y conllevaba importantes inversiones en materia de mantenimiento y ampliación de carreteras.

En el año 2002, el consorcio Toll Collect, fue designado por la autoridad alemana como adjudicatario del contrato que instalaría un novedoso sistema electrónico de cobro de peajes basado en tecnología de flujo libre, más conocido como free flow, que calcula y recauda el peaje proporcionalmente al trayecto recorrido (Toll Collect; 2021). Así, tras repetidos retrasos en la implementación de la tecnología en la red objeto de tarificación, TOLL COLLECT completó el despliegue del sistema a finales de 2004, comenzando a operar en enero de 2005 (Haan J. et al; 2011) en aproximadamente 12.000 km de vías de alta capacidad, estimándose que el número de kilómetros recorridos por vehículos pesados, sujetos a tarificación, se estiman en aproximadamente 22.700, de los que el 35% se corresponden a los efectuados por vehículos extranjeros (Ullber F.; 2005). Desde mediados de la década pasada se ha suscitado un debate en Alemania en cuanto a la posibilidad de extender la tarificación no sólo a los vehículos pesados sino al conjunto del parque automotor, aunque sin éxito hasta la fecha presente (BMVI; 2021).

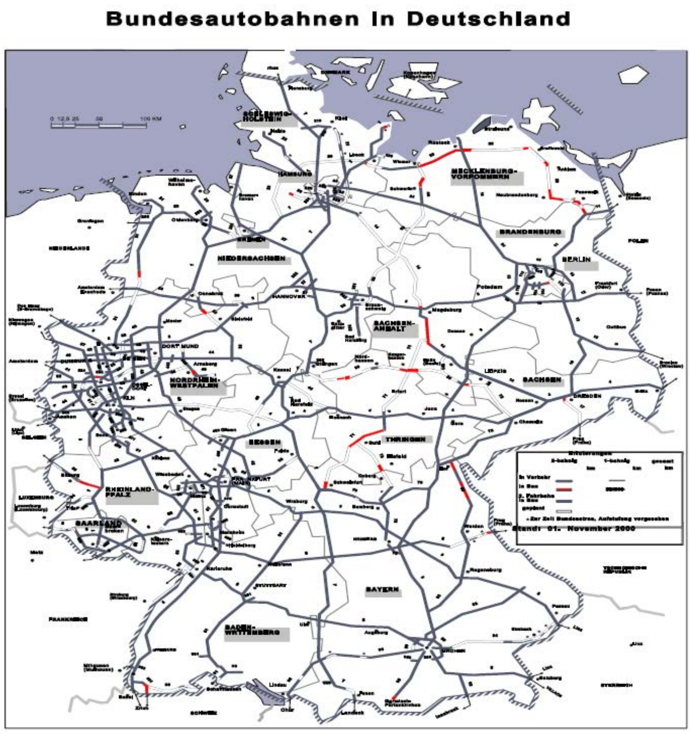


Fig. 3 – Red federal alemana tarificada; Fuente: Ullber; 2005

La tecnología y modalidad de cobro del sistema de peaje establecida por las autoridades alemanas y Toll Collect estableció un sistema de peaje que combinaba por primera vez, a nivel mundial, la técnica de localización mediante satélites (GNSS) y la tecnología de telefonía móvil (GSM). Las tarifas se establecen proporcionalmente al trayecto recorrido por el vehículo pesado, su número de ejes y su categoría, según las emisiones de gases que genera. La introducción de este nuevo sistema en Alemania supuso una tarificación por uso de infraestructuras más justa y equitativa.

La **República Checa** es otro ejemplo de país que ha recurrido a la tarificación de su red, principalmente desde su entrada en la UE en el año 2004 cuando, fruto del dramático estado de conservación de sus carreteras secundarias, el gobierno checo en el año 2008, aprobó un proyecto piloto de free flow híbrido, a partir del cual se aprovechase el sistema de tarificación existente, basado en pórticos DSRC, con un nuevo sistema de tarificación basado en tecnología satelital (GNSS), cuyo alcance posibilitara una mayor flexibilidad y la tarificación de las carreteras consideradas como de ámbito rural (KAPSCH; 2008).

Actualmente la República Checa cuenta con aproximadamente 1.200 km de vías tarificadas mediante el sistema free flow DSRC, que con la última modificación de la Regulación checa No. 240/2014 Coll and Decree No. 470/2012, de enero de 2021, pasa a incluirse la contaminación del aire y del ruido de los vehículos pesados, en el cómputo de la tarificación vial. (MYTO CZ; 2021)

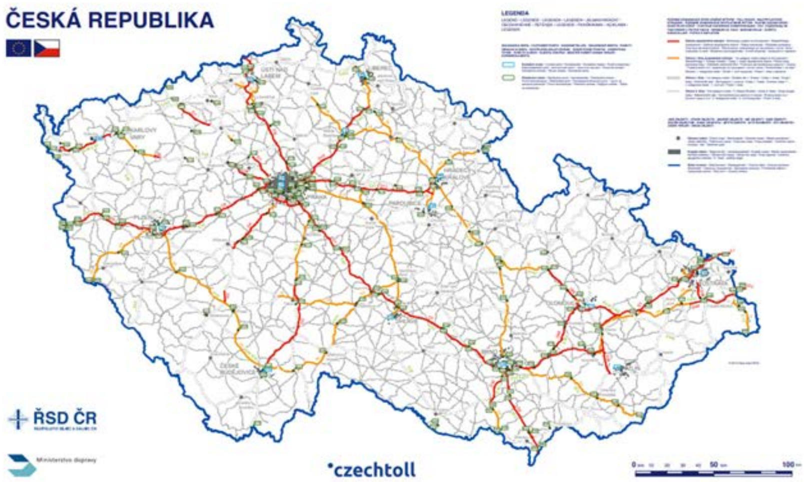


Fig. 4 – Red de carreteras tarificadas CZ; Fuente: MYTO CZ

En el caso checo, el país cuenta con un sistema electrónico de cobro de peajes interoperable basado en tecnología free flow satelital GNSS y de pórticos DSRC. El uso compartido de ambas tecnologías ha posibilitado ampliar el alcance de la red tarificada, englobando no sólo vías de gran capacidad, sino también carreteras de segundo orden. Asimismo, la madurez del sistema previamente existente ha contribuido al éxito del nuevo modelo en su conjunto.

El modelo de pago por uso de infraestructuras **portugués** tradicionalmente ha distinguido entre vías de alta capacidad, autopistas de peaje y las autopistas conocidas como SCUT libres de pago, y la red de carreteras de segundo orden. Las autopistas de peaje se gestionan mediante contratos de concesión establecidos entre la Administración contratante (Estradas de Portugal) y los concesionarios adjudicatarios de los contratos. En cuanto a las autopistas SCUT (libres de pago), su gestión se estableció inicialmente a través de la figura del peaje en sombra, aunque desde 2008 y especialmente en el año 2010, como consecuencia de la insostenibilidad presupuestaria motivada por las cuantiosas necesidades económicas que requirieron la explotación y mantenimiento de la red de utopistas SCUT, el gobierno portugués decidió expandir el pago por uso de las mismas, expandiendo el sistema de cobro electrónico free flow (DSRC) a toda la red de autopistas

SCUT. Cabe subrayar que más de la mitad de la partida de mantenimiento de carreteras del presupuesto portugués ha llegado a estar destinado al pago de los peajes SCUT, situación claramente insostenible.

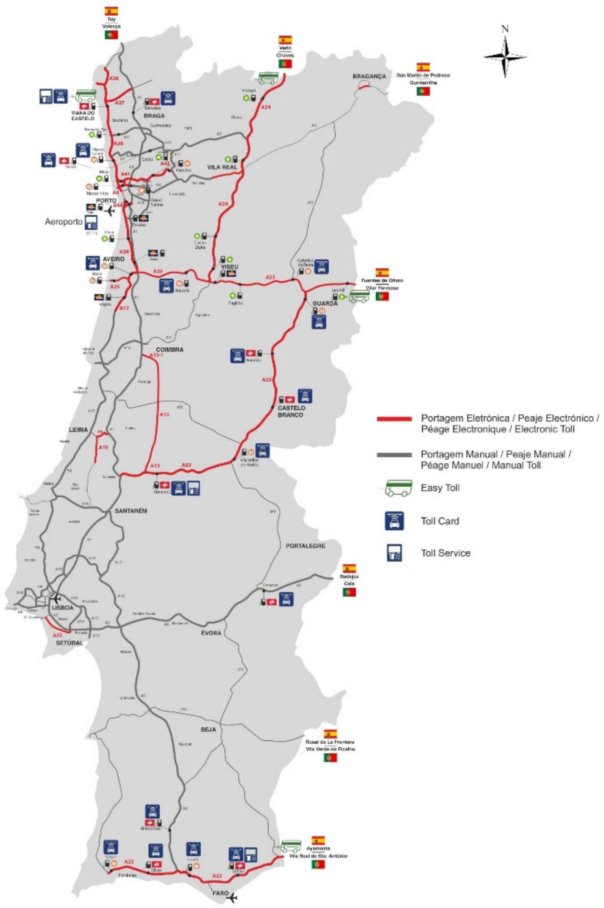


Fig. 5 – Alcance de la red tarificada; Fuente: Portugaltolls

El sistema de cobro de peaje portugués se distingue entre las tradicionales autopistas de peaje con barrera y las exSCUT en el que las autoridades portuguesas han instaurado pórticos DSRC que registran el paso de los vehículos y se categoriza la tarifa correspondiente.

Países como España, Francia e Italia cuentan con una amplia red de vías de alta capacidad, en el que conviven autopistas de peaje con las de tipo gratuito. Cuentan con estándares similares unas y otras si bien la diferencia principal es el modelo de financiación. Así, mientras que, en las vías de alta capacidad gratuitas, tanto la inversión y los costes de mantenimiento corren a cargo del presupuesto público, en las de peaje se financian generalmente a través de la participación público-privada en la que un privado adelanta los costes de su inversión y el mantenimiento durante un plazo que será recuperado a través del pago de una tarifa durante todo el periodo concesional por parte de los usuarios que recorran estas. Existen otras modalidades de financiación en el caso de las autopistas de peaje, bien a través de las modalidades de peaje en sombra y de pagos por disponibilidad, que, aunque resultan inicialmente gratuitas para los usuarios, son igualmente desarrolladas por empresas privadas que adelantan su financiación.

Con el nuevo cambio de paradigma son cada vez más países, entre ellos España ("El Gobierno se compromete con la UE a cobrar en autovías para financiarlas"; 2021), quienes reconocen la limitación del erario público, no solo para invertir en nuevas infraestructuras, sino también para mantener y conservar las existentes, por lo que se ha abierto un debate público en torno al fin de la gratuidad de las infraestructuras viales y la conveniencia del establecimiento de un nuevo modelo de gestión y de financiación que permita la tarificación de estas, permitiendo sufragar el coste de mantenimiento e internalizar el impacto ambiental del tráfico. Por ello España a través del MITMA y bajo el paraguas de su Estrategia de movilidad segura, sostenible y conectada (MITMA; 2020), ha puesto de manifiesto la necesidad de trabajar en pro de:

- una priorización de las inversiones desde una perspectiva de rentabilidad social y de una metodología expost de las infraestructuras,
- una mejor panificación y gestión de la red vial estatal, haciendo hincapié en la fiscalidad de las carreteras y el estudio de los modelos de gestión y financiación,
- la planificación y gestión de la red ferroviaria de interés general, principalmente a través de la Estrategia indicativa ferroviaria,
- del impulso de una fiscalidad verde, tanto del transporte urbano como del interurbano
- y, finalmente, del impulso de nuevos mecanismos de gobernanza, bajo los pilares de la transparencia y de la participación.

El impacto de la pandemia a nivel europeo ha acelerado este debate, dado que los presupuestos públicos, cada vez más exiguos, son insuficientes para poder acometer las necesidades actuales de los ciudadanos, más en un momento en el que es necesario la priorización de otro tipo de equipamientos a gran escala como los de tipo sanitario o la dotación de grandes partidas de gasto público al amparo de los efectos de la crisis sanitaria y los efectos económicos y sociales que esta ha producido.

3.5 Integración de urbanismo y movilidad

Como se ha comentado inicialmente, uno de los mayores retos que afronta el sector de la movilidad es hacer frente a la creciente urbanización. Según el Banco Mundial (Banco Mundial; 2021) a fecha abril de 2020 cerca del 55 % de la población mundial, 4.200 millones de habitantes, vivían en ciudades. Esta tendencia continuará acentuándose hasta alcanzar previsiblemente en 2030 una población urbana de 5.500 millones de habitantes.

En 2050 el Banco Mundial prevé que 7 de cada 10 personas vivirán en ciudades. La gestión de servicios en ámbito urbanos será de gran dificultad. La consecuencia directa en el ámbito del transporte y la movilidad es una concentración excesiva de necesidades de movilidad en el tiempo y el espacio entorno a la actividad económica y la geografía urbana, lo que conlleva con el modelo actual de movilidad enfocado en el vehículo privado a numerosos impactos negativos sobre la salud, la calidad de vida y la productividad (emisiones de contaminantes y ruido, uso del espacio público y congestión).

La tendencia tiene, además, un reverso igualmente preocupante: la despoblación de las zonas rurales, algo especialmente crítico en países como España. Según el Banco Mundial, en España el 80% de la población habita en áreas urbanas, pese a que solo representan el 20% del territorio. En contrapartida, la contrapartida de esta concentración de población es igualmente preocupante: la despoblación de las regiones de interior.

Además, en los últimos años el crecimiento urbano se ha producido acompañado de un proceso de dispersión poblacional en las coronas metropolitanas. Por ejemplo, en España en 2018 la población ha disminuido ligeramente en la ciudad central, al tiempo que ha crecido un 10,32% en las zonas periféricas respecto a 2017 (OMM; 2018).

Resulta crucial revisar los modelos de movilidad en los ámbitos urbanos. Políticas de movilidad que prioricen los desplazamientos cortos y que ponen el foco en primer lugar en la reducción del volumen de desplazamientos pueden empezar a tener un papel importante en la planificación de la movilidad en entornos urbanos. Una vez que el desplazamiento está justificado, las administraciones y autoridades estatales, regionales y locales deben priorizar el uso de medios de transporte colectivos y poco contaminantes. La aplicación del principio de Avoid-Shift-Improve (SUTP; 2011) o Evitar-Cambiar-Mejorar en la planificación de la movilidad o el desarrollo de ámbitos urbanos orientados al uso del transporte público (Transit Oriented Development) (ITDP; 2017) son estrategias ampliamente avaladas y empleadas para este fin desde hace décadas. Y en ambos casos, se requiere de una sincronización total de la planificación urbana y la planificación del transporte.

La urgencia ambiental y la creciente tensión a la que está sujetas las ciudades puede acelerar el cambio y/o la consolidación de este tipo de acciones. Muestra de ello es la aprobación reciente de la Agenda Urbana Española del Ministerio de Transportes, Movilidad y Agenda Urbana (AUE; 2021), con medidas destinadas a reducir la movilidad en vehículo privado y a fomentar la movilidad de proximidad, y pilar de la política de movilidad urbana del ministerio.

Por lo general, son estrategias de movilidad y urbanismo que se llevan aplicando en numerosas regiones europeas desde hace décadas. Entre ellas se destacan las experiencias en los Países Bajos con su regulación ABC para la localización de empresas bajo principios de accesibilidad desde 1988 (De Vos; 2015), así como la Ley de Movilidad de Cataluña desde 2003 (y sus Directrices Nacionales de Movilidad de 2006 y decretos que las desarrollan) que establecen la obligatoriedad de que los nuevos planeamientos urbanos incorporen estudios de movilidad generada. Recientemente desde el Ayuntamiento de París se está impulsando la movilidad de proximidad mediante la llamada "Ciudad de los 15 Minutos" (c40knowledgehub; 2021) promovida por la red de ciudades C40. Esta estrategia de fomento de la "movilidad de cuarto de hora", siendo uno de los principales puntos estratégicos de la administración local.

4. RESULTADOS Y CONCLUSIONES

La evolución tecnológica surgida desde finales de la década pasada, el aumento de la concienciación social y el mayor compromiso de las Administraciones públicas por la descarbonización de la economía y la concentración de la población entorno a grandes núcleos urbanos ha motivado un cambio de paradigma en la movilidad, tanto de personas como de mercancías a nivel global.

En este artículo se recogen las principales novedades que el cambio de paradigma en la movilidad ha supuesto en un contexto internacional europeo, destacando las siguientes conclusiones:

- A nivel supranacional, desde la Unión Europea se acompaña este cambio de paradigma mediante diversas acciones normativas y estrategias sectoriales, todas ellas bajo el paraguas del Pacto Verde Europeo y, recientemente, condicionadas al plan de recuperación "Next Generation UE". Destaca especialmente la Estrategia Europea de Movilidad Sostenible e Inteligente de la Comisión Europea, presentada en 2020 y basada en los tres pilares de descarbonización, digitalización y resiliencia.
- De manera general, atendiendo a los principales retos detectados de descarbonización, digitalización y crecimiento urbano, los países analizados comparten objetivos y priorizan los mismos objetivos. En concreto, se han detectado 5 ámbitos de especial interés en las políticas nacionales de movilidad: (i) el uso de datos en la movilidad, (ii) la conducción conectada y autónoma, (iii) los combustibles alternativos, (iv) los sistemas de gestión y financiación de infraestructuras, así como (v) la integración del urbanismo y la movilidad.
- Así, en lo relativo al "uso de datos en la movilidad", la importancia de los datos en la movilidad se ha hecho evidente en las últimas décadas, en especial por la irrupción de la telefonía móvil. La gestión de estos datos no solo ha propiciado la aparición de nuevos modelos de negocio, sino que las técnicas de Big Data permiten obtener de un gran volumen de datos una información valiosa para la planificación y la gestión de la movilidad. La labor de la Administración debe ser la de garantizar el uso y compartición de datos entre todos los agentes, para fomentar la existencia de un ecosistema de empresas y soluciones de movilidad que mejoren la experiencia del usuario. Y todo ello protegiendo los derechos de los ciudadanos.
- En cuanto a "la conducción conectada y autónoma", esta presenta grandes oportunidades para hacer más sostenible la movilidad y tanto la industria del automóvil

como las Administraciones la consideran un elemento clave a largo plazo. Para el desarrollo de la tecnología, sin embargo, se debe de fomentar en el corto plazo la investigación y el desarrollo normativo.

- Relativo al uso de "combustibles alternativos", la urgencia climática y la mayor concienciación ambiental de la población se está traduciendo sobre todo en programas de fomento de la movilidad eléctrica y en la cada vez mayor penetración del vehículo electrificado en los países europeos. Existen también políticas para fomentar combustibles alternativos avanzados de origen no biológico como el hidrógeno verde y los electrocombustibles, con mayor potencial en la descarbonización de la aviación y el transporte marítimo.
- Atendiendo a los "sistemas de gestión y financiación de infraestructuras", las limitaciones presupuestarias de las AAPP y el constante crecimiento de las redes de infraestructuras multimodales en Europa ha supuesto un cambio de paradigma en cuanto a la priorización de las inversiones de estas, bajo criterios de rentabilidad social y análisis expost, así como de una armonización de los modelos de gestión y financiación en el ámbito europeo, vial y ferroviario, a favor de un modelo de pago por uso, a través del cual sean los usuarios de las infraestructuras quienes se hagan cargo, a través de cánones o peajes, del coste de las propias inversiones, así como de su mantenimiento y sostenibilidad durante su vida útil.
- Como parte de la estrategia para descarbonizar el transporte, las políticas de "integración de la planificación movilidad y el urbanismo", aplicadas por ciertas Administraciones desde hace décadas, vuelven a estar presentes en estrategias y leyes globales de movilidad. Solo así, se puede conseguir reducir el número de viajes innecesarios y convertir al transporte público en elemento vertebrador de la movilidad.

Los retos actuales en el sector de la movilidad, la gran mayoría ya detectados previamente a la pandemia de la Covid-19, pero a los que se unen otros derivados de la crisis económica y social derivada de esta, requieren cambios en las políticas de las Administraciones, empezando por el nivel supranacional y la Unión Europea, pasando por los Estados miembros y afectando también a las autoridades regionales y locales.

Los principales ámbitos de actuación detectados y sobre los que en el presente artículo se han recogido las principales líneas de actuación de los estados miembros son solo ejemplos de las muchas medidas y estrategias sectoriales de influencia directa en el sector holístico de la movilidad y que se deben acometer para lograr los objetivos por lo general compartidos por todos los estados de la Unión Europea.

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DISPOSICIÓN DE LOS VIAJEROS A ADOPTAR SOLUCIONES MAAS EN ÁREAS METROPOLITANAS EUROPEAS

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RESUMEN

Se espera que la movilidad como servicio (MaaS) cambie la forma en la que nos movemos.

Sin embargo, todavía no está claro quién adoptará este nuevo modelo de movilidad, ni cómo afectará a los comportamientos de los viajeros. En este estudio, exploramos la disposición de los individuos a adoptar MaaS. Con este objetivo, realizamos una campaña de encuestas online en dos áreas metropolitanas europeas: Madrid (España) y Randstad (Países Bajos). En general, encontramos actitudes positivas hacia las soluciones MaaS.

Tanto las características socioeconómicas y demográficas de los individuos, como sus hábitos de viaje, determinan la probabilidad de que adopten dichas innovaciones tecnológicas. En general, reconocemos dos barreras principales que pueden frustrar la aceptación del MaaS: la baja afinidad tecnológica y la baja apertura a los comportamientos multimodales. Las políticas que se centran en estos dos aspectos pueden fomentar la adopción del MaaS y promover, por tanto, un cambio de comportamiento hacia opciones más sostenibles.

1. INTRODUCCIÓN

El disruptivo avance de las Tecnologías de la Información y la Comunicación (TICs) ha traído consigo nuevas oportunidades para el desarrollo de soluciones innovadoras en el sector del transporte. En los últimos años se han implementado en nuestras ciudades nuevos servicios de movilidad basados en aplicaciones (móviles), como los servicios de uso compartido de coches, bicicletas y patinetes.

A medida que un mayor número de personas adopta estos nuevos servicios, el modelo de movilidad reclama ser reestructurado. En este marco, se propone la noción de *Mobility as a Service* (MaaS), que propone una transición hacia comportamientos de viaje más sostenibles.

El concepto de MaaS fue introducido por primera vez por Heikkilä (2014), quien en su trabajo fin de máster lo describe como "un sistema en el que los operadores de transporte proporcionan una amplia gama de servicios de movilidad a los viajeros". De acuerdo con la autora, un operador de transporte debe entenderse como "una empresa que compra servicios de movilidad a los productores de servicios, los combina como una oferta y los ofrece a los usuarios". Desde ese momento, se han sugerido otras muchas definiciones para la noción de MaaS. Y aunque todavía no existe un consenso claro sobre una única definición (Arias-Molinares y García-Palomares, 2020), los expertos coinciden en que puede concebirse como la combinación de diferentes tipos de movilidad en una única interfaz digital (normalmente, una aplicación móvil o una página web). En base al desarrollo de una revisión exhaustiva de la literatura y de acuerdo con los objetivos de este estudio, decidimos adoptar la definición dada por la *European MaaS Alliance*. Esta institución público-privada describe el concepto de MaaS como "la integración de diversas formas de servicios de transporte en un único servicio de movilidad accesible bajo demanda para satisfacer las expectativas de los viajeros" (MaaS Alliance, 2019).

En los últimos años, el término de MaaS ha ganado gran popularidad gracias a su potencial para reducir las externalidades negativas del sector del transporte, es decir, la congestión del tráfico, la contaminación atmosférica y acústica, el número de accidentes, etc. Sus defensores creen que MaaS permitirá adquirir comportamientos de movilidad más sostenibles y, en particular, disminuir la dependencia del coche privado (Polydoropoulou et al., 2018). Por definición, MaaS representa el paso de un "sistema basado en la propiedad del vehículo privado" a una "perspectiva de movilidad basada en el acceso". En otras palabras, MaaS representa la compra de servicios, y no de los modos de transporte en sí mismos.

Aunque se espera que las oportunidades asociadas a MaaS sean numerosas, un requisito previo para el éxito de este modelo innovador es su "aceptación pública". De acuerdo con Caiati et al. (2020), diferentes innovaciones tecnológicas han fracasado históricamente a la hora de lograr una amplia difusión debido a su incapacidad para responder a las expectativas reales de los usuarios. Especialmente en el caso de MaaS, con su inherente orientación centrada en el usuario, comprender el punto de vista de los individuos es de extrema importancia.

Teniendo en cuenta la (relativa) novedad del concepto, actualmente no se sabe mucho sobre la disposición de los viajeros a adoptar estas nuevas soluciones. Y aunque algunos autores han abordado esta perspectiva (véase la Sección 2), es necesario continuar investigando. Como afirman Danquah y Amankwah-Amoah (2017): "a pesar del creciente cuerpo de investigación sobre el capital humano y la innovación, nuestra comprensión de los efectos y las funciones del capital humano en la mejora de la innovación y la adopción de tecnología en el mundo en desarrollo... sigue siendo limitada".

Además, dado que los resultados científicos tienden a depender del diseño experimental, la especificación del modelo y la selección de variables, cualquier investigación adicional se convierte en una contribución bienvenida a la actual escasez de conocimientos empíricos.

En definitiva, ¿están los viajeros dispuestos a adoptar MaaS? En este estudio, contribuimos a la comprensión de quién está dispuesto a adoptar MaaS, centrándonos en un conjunto de factores socioeconómicos, demográficos y relacionados con los hábitos de movilidad. El estudio se desarrolla en dos áreas metropolitanas europeas con diferentes estructuras urbanas: Madrid (España), con una configuración monocéntrica, y el Randstad (Países Bajos), con una policéntrica.

El documento se organiza como sigue. Tras este capítulo introductorio, la Sección 2 explora los estudios previos centrados en la disposición de los individuos a adoptar MaaS. A continuación, la Sección 3 describe el enfoque metodológico, que se aplica a los casos de Madrid y Randstad en la Sección 4. Por último, la Sección 5 analiza los resultados y la Sección 6 ofrece las conclusiones obtenidas.

2. REVISIÓN DE LA LITERATURA: DISPOSICIÓN DE LOS VIAJEROS A ADOPTAR MAAS

Numerosas ciudades de todo el mundo se sienten atraídas por la noción de MaaS y su potencial para promover comportamientos de viaje más sostenibles. Sin embargo, aunque estas oportunidades sean ciertas, el compromiso de los individuos es un requisito fundamental para lograr una amplia aceptación de estas innovaciones tecnológicas (Strömberg et al., 2018). La Tabla 1 incluye un conjunto de estudios que ya han explorado la disposición a adoptar y utilizar MaaS desde la perspectiva de los viajeros. La literatura considera diferentes tipos de factores explicativos al abordar este tema.

Año	Autor	Factores explicativos [1]			
		1	2	3	4
2018	Ho et al,	■	■	■	
	Polydoropoulou et al,			■	■
	Strömberg et al,	■	■	■	
2019	Fioreze et al,	■	■	■	■
	Hesselgren et al,	■	■	■	■
	Matyas & Kamargianni	■	■	■	
2020	Alonso-Gonzalez et al	■	■	■	■
	Casadó et al,	■	■	■	■
	Caiati et al,	■	■	■	
	Feneri et al,	■	■	■	■
	Liljamo et al,	■	■	■	
	Loubser et al,	■	■	■	■
	Schikofsky et al,	■	■	■	■
	Storme et al,	■	■	■	■
	Vij et al,	■	■	■	
	Ye et al,	■	■	■	■
	Zijlstra et al,	■	■	■	■

[1] 1: factores socioeconómicos; 2: factores demográficos; 3: factores relacionados con los hábitos de movilidad; 4: actitudes personales.

Tabla 1 – Revisión de la literatura: intención de adoptar MaaS por parte de los viajeros.

Aunque estas investigaciones (Tabla 1) constituyen un primer paso, es necesario seguir investigando para desarrollar un cuerpo de conocimientos completo sobre la aceptación de MaaS. Siguiendo un modelo centrado en el usuario, MaaS proporciona a los viajeros servicios de movilidad personalizados. Por lo tanto, entender las motivaciones, necesidades y preferencias de los individuos es esencial para definir con éxito estas soluciones. En este estudio, exploramos la disposición a adoptar MaaS centrándonos en un conjunto de factores socioeconómicos, demográficos y relacionados con los hábitos de movilidad.

3. METODOLOGÍA

En esta Sección, explicamos la metodología aplicada en el estudio.

3.1 Diseño de la encuesta

En base a estudios previos con un alcance similar (véase la Tabla 1), diseñamos un cuestionario para cumplir nuestros objetivos, que se estructura en las siguientes cinco secciones:

- Sección 1. Introducción. Una sección inicial presenta una descripción conceptual de MaaS y una aplicación ficticia, cuyo diseño se basa en la interfaz de Whim (https://whimapp.com/). Esta sección pretende proporcionar a los participantes un nivel de conocimiento razonable sobre MaaS y sus servicios.
- Sección 2. Características socioeconómicas y demográficas generales, es decir, sexo, edad, nivel de educación (completado), ocupación, estructura del hogar y localización de la residencia.
- Sección 3. Adopción y uso de herramientas tecnológicas. Dado que los viajeros interactúan con MaaS a través de una única interfaz digital, se pide a los individuos que califiquen, en una escala Likert de cinco puntos, su experiencia con las innovaciones tecnológicas. En particular, se les pregunta por el uso de las aplicaciones de planificación de viajes, que se consideran el nivel 1 de las tecnologías MaaS (Schikofsky et al., 2020).
- Sección 4. Hábitos de movilidad y características relacionadas con los viajes. Teniendo en cuenta que los hábitos de movilidad son predictores relevantes de futuros comportamientos, analizamos los patrones de movilidad de los individuos, es decir, la propiedad y disponibilidad de coche, la posesión de permiso de conducir y de abono de transporte público, la frecuencia de los viajes en diferentes medios de transporte y las características del viaje más frecuente (VMF).
- Sección 5. Se pregunta a los participantes sobre su intención de adoptar MaaS, así como su disposición a pagar por utilizar estas innovaciones tecnológicas.

3.2 Análisis de los datos

Los datos se analizaron con el programa estadístico SPSS (versión 25) mediante técnicas de análisis descriptivo, exploratorio y de regresión.

4. APLICACIÓN DE LA METODOLOGÍA A LAS AREAS METROPOLITANAS DE MADRID (ESPAÑA) Y EL RANDSTAD (PAÍSES BAJOS)

4.1 Descripción de los casos de estudio

Como se ha introducido anteriormente, este trabajo explora la disposición de los individuos a adoptar MaaS en dos áreas metropolitanas: Madrid (España) y el Randstad (Países Bajos). Estas regiones presentan similitudes en términos de población, superficie y poder económico. Estudios anteriores (Arias-Molinares y García Palomares, 2020; Caiati et al., 2020; Feneri et al., 2020) han señalado ciertos atributos que hacen de estas áreas potenciales candidatas para la implementación de MaaS: (i) importantes tasas de penetración digital, (ii) un sistema de transporte público integrado y bien estructurado, y (ii) una creciente oferta de servicios de movilidad compartida. La Tabla 2 resume las principales características de cada caso de estudio.

Caso de estudio		Población	Área	Densidad de población	PIB per cápita
AM [1]	Ciudad	*Habitantes*	*Km²*	*Habitantes por Km²*	*Euros*
Madrid	**-**	6.800.000	5.335	1.275	37.621
	Madrid	3.300.000	604	5.464	43.075
Randstad	**-**	6.550.000	5.130	1.277	52.540
	Ámsterdam	872.680	220	3.967	60.855
	Rotterdam	651.450	325	2.004	51.455
	La Haya	544.770	100	5.447	48.010
	Utrecht	358.450	100	3.584	52.900
[1] AM: área metropolitana.					

Tabla 2 – Descripción de los casos de estudio.

4.1.1 El área metropolitana de Madrid (España) y sus patrones de movilidad

El área metropolitana de Madrid es una región monocéntrica localizada en el centro de la península Ibérica, alrededor de la ciudad de Madrid. No está relacionada con ninguna demarcación administrativa y, por tanto, sus límites son ambiguos. En este estudio, adoptamos la definición dada por la Comunidad de Madrid (2002) en el "Atlas de la Comunidad de Madrid en el umbral del siglo XXI". Según este documento, el área metropolitana de Madrid comprende 27 municipios y cubre una superficie de aproximadamente 5.335 kilómetros cuadrados. El área metropolitana de Madrid tiene una población de casi 6,8 millones de habitantes, siendo la tercera más poblada de la Unión Europea (UE), tras París y el Rurh alemán (Ayuntamiento de Madrid, 2020). Siguiendo las tendencias europeas, presenta una densidad de población (relativamente) alta, con un valor medio de 5.464 habitantes por kilómetro cuadrado dentro de su núcleo: la ciudad de Madrid. Madrid es la ciudad más poblada del país, con unos 3,3 millones de habitantes, así como uno de sus centros económicos más relevantes. En las últimas décadas, esta ciudad ha experimentado un rápido crecimiento y un proceso de suburbanización.

De acuerdo con la última Encuesta de Movilidad de Madrid (CRTM, 2019), en el área metropolitana de Madrid se producen (de media) 14,7 desplazamientos en un día laborable.

Estos desplazamientos se reparten entre múltiples modos, con un 39,0% de los viajes realizados en coche/moto, un 34,0% en modos activos (a pie o en bicicleta) y un 24,3% en transporte público. En total, aproximadamente el 33,3% de estos viajes son multimodales.

La movilidad en Madrid se caracteriza por un sistema de transporte público multimodal consolidado, altamente integrado y bien estructurado, que incluye 12 líneas de metro, 209 líneas de autobús urbano, 444 líneas de autobús de cercanías, ocho líneas de ferrocarril de cercanías y cuatro líneas de tranvía/metro ligero (Monzón et al., 2019). Desde 2010, Madrid se ha visto inundada por una amplia oferta de "nuevas movilidades" (es decir, servicios de movilidad compartida y de micro movilidad), que complementan la red de transporte público "tradicional". Según Arias-Molinares y Garacía-Palomares (2020), Madrid concentra actualmente 35 servicios de movilidad compartida gestionados por 29 operadores (públicos y privados) de transporte. Además, en esta área metropolitana existen actualmente varias aplicaciones de planificación de viajes como, por ejemplo, Google Maps, Moovit, City Mapper, Chipi o Mi Transporte. No obstante, ninguna de ellas ofrece la integración del billete electrónico o del pago.

4.1.2 El área metropolitana de Randstad (Países Bajos) y sus patrones de movilidad

El área metropolitana de Randstad es una región policéntrica situada en el centro-oeste de los Países Bajos. Comprende las cuatro mayores ciudades holandesas (Ámsterdam, Rotterdam, La Haya y Utrecht) y una serie de conurbaciones de tamaño medio. La población total del Randstad es de aproximadamente 6,55 millones de habitantes, lo que la convierte en la cuarta región metropolitana más poblada de la UE, tras París, el Rurh alemán y Madrid. El Randstad es de gran importancia social y económica para los Países Bajos, ya que alberga más del 40% de la población nacional y aporta casi el 50% de la renta nacional. La organización administrativa de esta área metropolitana es bastante compleja debido a la estructura urbana desagregada (Spaans et al., 2012). Sin embargo, se cree que el carácter interconectado y complementario de sus ciudades, así como su proximidad, aumenta las ventajas de aglomeración para la región.

En el Randstad, la mayor parte de los viajes y desplazamientos tienen lugar dentro y alrededor de sus cuatro grandes ciudades. Según un informe publicado por el Instituto de Análisis de Políticas de Transporte de los Países Bajos (KiM, 2016), estos viajes se reparten entre múltiples modos, siendo los principales el coche/motocicleta privada (50,0%), la bicicleta (28,0%), los desplazamientos a pie (17,0%) y el transporte público (5,0%). Esta área metropolitana presenta una de las redes de carreteras más densas del mundo, que se utiliza de forma significativa. El Randstad cuenta también con una red de transporte público bien estructurada, compuesta por servicios de ferrocarril, metro (o tren ligero), tranvía y autobús. Además, las bicicletas desempeñan tradicionalmente un papel relevante en la movilidad diaria. En los últimos años, se han implantado diversos servicios de movilidad compartida y de micro movilidad (como servicios de uso compartido de coches, bicicletas o patinetes). Sin embargo, la disponibilidad de estas innovaciones es todavía limitada en comparación con otros países de la Unión Europea. Al igual que en el caso de Madrid, existen varias aplicaciones de planificación de viajes (por ejemplo, Google Maps, HERE Maps, OpenStreetMap, Times Upp, 9292ov y NS Reisplanner), que facilitan el uso de la compleja red de transporte.

4.2 Recogida de datos: cuestionario online

Se consideró que una encuesta online era el método más adecuado para recoger los datos de este estudio, principalmente por las siguientes razones (i) el MaaS está dirigido a un grupo objetivo que tiene acceso a Internet; (ii) los cuestionarios basados en la web permiten contactar fácilmente con usuarios de diferentes medios de transporte; y (iii) los cuestionarios online ya se han aplicado en investigaciones anteriores sobre la disposición a adoptar y pagar por soluciones MaaS (véase la Tabla 1). El cuestionario web se distribuyó entre abril y junio de 2019 en las áreas metropolitanas de Madrid (España) y el Randstad (Países Bajos). Para el reclutamiento de la muestra, nos asociamos con un proveedor de paneles online especializado en cada país. Para garantizar una alta representatividad de las dos poblaciones, se incluyeron cuotas de género, edad y frecuencia de uso del transporte público.

Antes de la encuesta definitiva se realizó un piloto con 300 encuestados en ambas regiones para comprobar la validez del cuestionario y corregir posibles errores. A partir de las respuestas del piloto, el cuestionario se perfeccionó en cuanto a contenido, estructura y diseño gráfico, y se ajustó a los límites de tiempo (unos 20 minutos).

5. RESULTADOS Y DISCUSIÓN

5.1 Análisis descriptivo de la muestra

En total, recibimos 1.000 respuestas completas en Madrid (España) y 418 en el Randstad (Países Bajos). Esta sección resume las características de la muestra de ambos casos de estudio en términos de atributos socioeconómicos y demográficos, y de hábitos de viaje. Algunos de estos datos no pueden considerarse plenamente representativos, lo que parece razonable dado que el método de recogida de datos en la campaña de encuestas requiere que el cuestionario se rellene en línea. Sin embargo, consideramos que la muestra incluye un nivel de heterogeneidad suficiente para nuestros fines científicos.

Las características socioeconómicas y demográficas de los encuestados se recogen en la Tabla 3. En Madrid, la mayoría de los encuestados viven en el centro de la ciudad (83,7%), y sólo un 16,3% en la periferia (o anillo metropolitano). Estas cifras indican que el segmento urbano está sobrerrepresentado. Un primer análisis muestra una proporción de participantes mayores de 65 años inferior a la esperada (7,9%), tal vez debido a la menor afinidad tecnológica que suele mostrar este grupo generacional (Fioreze et al., 2019). También encontramos una alta proporción de individuos con estudios universitarios y trabajadores, y una baja proporción de hogares unipersonales. En el Randstad, una alta proporción de los encuestados viven en las áreas de alta densidad (Niveles 3 y 4). Además, casi el 40% de los encuestados viven en hogares de dos personas.

La Tabla 4 presenta las características relacionadas con los hábitos de viaje de los individuos. La frecuencia de uso de los servicios de transporte público se controló mediante cuotas, ya que estudios anteriores destacan su papel central en las estrategias de MaaS (Alonso-González et al., 2020).

En Madrid, la disponibilidad de un abono de transporte público (personal) es bastante alta entre los encuestados, quizá debido a su atractiva y eficiente red de servicios. Al mismo tiempo, casi el 80% de la muestra dispone de carné de conducir. La encuesta permitió evaluar los hábitos de viaje de los individuos. Se preguntó a los participantes si utilizaban un medio de transporte concreto en sus viajes más frecuentes. El 41,5% de la muestra son viajeros multimodales y el 58,5%, unimodales: el 7,8% de los viajes se realizan en modos activos (a pie y en bicicleta), el 33,6% en transporte público y el 16,6% en coche/moto.

Además, los servicios de movilidad compartida parecen bastante populares. En cuanto a la penetración tecnológica, encontramos valores muy significativos. Más del 60% de los encuestados declararon ser usuarios frecuentes de aplicaciones de planificación de viajes.

En el Randstad, la disponibilidad del carné de conducir entre los encuestados es significativamente mayor que la disponibilidad de un abono de transporte público personal (84,9% frente al 55,3%). A diferencia del caso de Madrid, la proporción de viajeros multimodales parece ser baja (31,8%), mientras que casi el 70% de los individuos son unimodales: con un 16,3% de los viajes realizados en modos activos (a pie y en bicicleta), un 13,0% en transporte público y un 35,6% en coche/moto. Al igual que en el caso de Madrid, la penetración tecnológica parece significativamente alta y casi el 60% de los encuestados utiliza con frecuencia aplicaciones de planificación de viajes.

Caso de estudio			**Madrid AM [1] (España)**		**Randstad AM [1] (Países Bajos)**	
Indicador	**Categoría**		**n**	**%**	**n**	**%**
Lugar de residencia	Madrid (ciudad)	Nivel 4 [2]	837	83,7	157	37.6
		Nivel 3 [2]	-	-	82	19.6
	Corona metropolitana	Nivel 2 [2]	163	16,3	54	12.9
		Nivel 1 [2]	-	-	23	5.5
Género	Hombre		500	50	213	51,0
	Mujer		500	50	205	49,0
Grupo de edad [3]	18-24 años		109	10,9	43	10,3
	25-34		164	16,4	107	25,6
	35-44		216	21,6	65	15,6
	45-54		216	21,6	89	21,3
	55-64		216	21,6	65	15,6
	>65		79	7,9	49	11,7
Nivel educativo	No Universitario		414	41,4	259	62,0
	Universitario		586	58,6	159	38,0
Ocupación	Estudiante		65	6,5	24	5,7
	Trabajador tiempo parcial		106	10,6	84	20,1
	Trabajador tiempo completo		621	62,1	192	45,9
	Jubilado		75	7,5	42	10,0
	Otro		133	13,3	76	18,2
Tamaño del hogar	1 persona		164	16,4	92	22,0
	2 personas		272	27,2	165	39,5
	3 personas		267	26,7	62	14,8
	4 o más personas		297	29,7	99	23,7

[1] AM: área metropolitana; [2] Nivel de urbanización [3]. Nivel 1: <1.000 direcciones/km^2; Nivel 2: 1.000 – 1.500; Nivel 3: 1.500 – 2.500; Nivel 4: > 2.500; (102 casos desconocidos); [3] La muestra incluye participantes de entre 18 y 90 años.

Tabla 3 – Características socioeconómicas y demográficas de los individuos encuestados.

Caso de estudio		**Madrid AM [1] (España)**		**Randstad AM [1] (Países Bajos)**	
Indicador	**Categoría**	**n**	**%**	**n**	**%**
Frecuencia del VMF [2]	Menos de 1 viaje/semana	97	9,7	75	17,9
	Entre 1-3 viajes/semana	278	27,8	163	39,0
	Más de 3 viajes/semana	625	62,5	180	43,1
Multimodalidad del VMF [2]	No – unimodal (todos)	585	58,5	285	68,2
	Andando (unimodal)	64	6,4	10	2,4
	Bicicleta	12	1,2	58	13,9
	Coche	152	15,2	143	34,2
	Moto/Scooter	14	1,4	6	1,4
	Transporte público	336	33,6	54	13,0
	Servicios de movilidad compartida	7	0,7	5	1,2
	Otros	0	0,0	9	2,2
	Sí – multimodal	415	41,5	133	31,8
Tiempo del viaje VMF [2]	0-14 minutos	42	4,2	56	13,4
	15-29	392	39,2	153	36,6
	30-59	448	44,8	158	37,8
	60 o más	118	11,8	51	12,2
Abono TP [3]	Sí	685	68,5	231	55,3
Carné de conducir	Sí	785	78,5	355	84,9
Uso de servicios de movilidad compartida	Desconozco estos servicios	210	21,0	81	19,4
	No, pero los conozco	371	37,1	245	58,6
	Sí	419	41,9	92	22,0
Motivo del VMF [2]	Trabajo/Escuela	670	67,0	230	55,0
	Compras	112	11,2	76	18,2
	Ocio	166	16,6	92	22,0
	Llevar/recoger a alguien	36	3,6	9	2,2
	Otro	16	1,6	11	2,6
Frecuencia de uso de aplicaciones de movilidad	Nunca	40	4,0	21	5,0
	Casi nunca	77	7,7	33	7,9
	Ocasionalmente	262	26,2	122	29,2
	A menudo	425	42,5	176	42,1
	Siempre	196	19,6	66	15,8
[1] AM: área metropolitana; [2] VMF: viaje más frecuente; [3] TP: transporte público.					

Tabla 4 – Hábitos de movilidad de los individuos encuestados.

5.2 Intención de los viajeros de adoptar MaaS

En la encuesta, se preguntó a los participantes sobre su disposición a adoptar MaaS. Los resultados muestran actitudes y expectativas positivas hacia estas innovaciones tecnológicas en los dos casos de estudio. En particular, en el área metropolitana de Madrid, casi el 50% de los encuestados declaró un nivel "muy alto" de afinidad con estas soluciones (Figura 1).

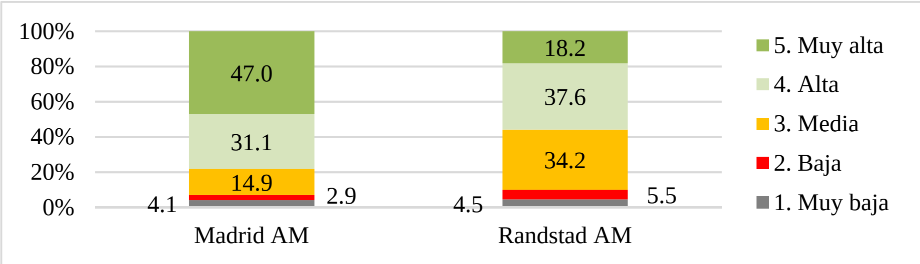

Fig. 1 – Disposición de los individuos a adoptar MaaS:

¿Está dispuesto a adoptar tecnologías MaaS? Nivel de intención: Escala Likert de 1 (mínimo) a 5 (máximo). Sección 5 de la encuesta.

Con el objetivo de comprender en profundidad las motivaciones de los individuos hacia MaaS, exploramos su relación con factores socioeconómicos, demográficos y relacionados con los viajes.

5.2.1 Disposición a adoptar MaaS: características socioeconómicas y demográficas

Como se muestra en la Tabla 5, exploramos la disposición de los individuos a adoptar MaaS en relación con sus características socioeconómicas y demográficas. Las variables consideradas fueron: lugar de residencia, género, edad, nivel de educación completado, ocupación y tamaño del hogar.

En Madrid, la distribución obtenida ilustra que las mujeres muestran una mayor intención a utilizar MaaS que los hombres. Sorprendentemente, la edad no es significativa y la probabilidad de adoptar MaaS parece similar para los diferentes grupos generacionales. No esperábamos este resultado, dado que las personas mayores suelen asociarse negativamente con el uso de las innovaciones tecnológicas (Alonso-González et al., 2020). De acuerdo con nuestros resultados, el lugar de residencia tampoco afecta a la disposición de los individuos a adoptar MaaS, quizás debido a la extensa y bien estructurada red de transporte que sirve al área metropolitana de Madrid. El nivel educativo parece influir en la aceptación del MaaS, así como la ocupación. Por un lado, tener un grado universitario aumenta la afinidad hacia estas soluciones innovadoras. Y, por otro lado, los jubilados muestran una menor afinidad con el MaaS que los estudiantes y los trabajadores. Esto parece razonable dado que (en general) este grupo está compuesto por individuos de mayor edad que tienden a realizar menos viajes (Mulley et al., 2017).

Por último, el tamaño del hogar también resulta significativo. Las personas que viven con dos o más compañeros muestran mayores intenciones de adoptar MaaS.

En el Randstad, los resultados obtenidos revelan que ni el género ni la edad afectan a la disposición a adoptar MaaS. Al contrario que en Madrid, el lugar de residencia parece ser significativo. Los encuestados que viven en las zonas más densas y urbanizadas muestran una mayor afinidad con las soluciones MaaS, quizá motivados por su mayor accesibilidad a los diferentes servicios de movilidad. Al igual que en el caso de Madrid, el nivel educativo y la ocupación parecen influir en la probabilidad de que los individuos adopten MaaS, así como el tamaño del hogar. En esta área metropolitana, los hogares unipersonales resultaron ser los más proclives a las nuevas soluciones tecnológicas.

5.2.2 Disposición a adoptar MaaS: características relacionadas con los hábitos de movilidad

Como se muestra en la Tabla 6, exploramos la disposición de los individuos a adoptar MaaS en relación con sus hábitos de viaje.

En consonancia con investigaciones anteriores (Alonso-González et al., 2020), los viajeros multimodales de Madrid son más proclives a adoptar MaaS que los unimodales. Estas soluciones están también positivamente correlacionadas con el uso de servicios de movilidad compartida, que complementan la oferta "tradicional" de transporte público.

Además, nuestros resultados muestran que el motivo y la duración del viaje más frecuente influyen en la probabilidad de utilizar MaaS. Por un lado, aquellos individuos que se desplazan por cuestiones de trabajo o estudios parecen ser los más inclinados hacia dichas innovaciones tecnológicas. Y, por otro lado, en los viajes cortos (menos de 15 minutos) la disposición a utilizar MaaS disminuye. Por último, la distribución obtenida ilustra que la intención de adoptar MaaS está positivamente asociada a la frecuencia de uso de las aplicaciones de planificación de viajes.

En el Randstad, los comportamientos multimodales y el uso de planificadores de viajes también están positivamente correlacionados con la aceptación de MaaS. Como en el caso de Madrid, el propósito del viaje más frecuente influye en la inclinación de los individuos hacia estas nuevas soluciones. Los individuos que se desplazan por cuestiones de trabajo o estudios parecen ser los más interesados en dichas tecnologías innovadoras. En el área metropolitana de Randstad, la disponibilidad de un pase de transporte público personal resulta estar directamente correlacionada con la intención de adoptar MaaS.

En general, encontramos que tanto las características socioeconómicas y demográficas como las variables relacionadas con los hábitos de viaje determinan la disposición de los individuos a adoptar MaaS.

6. CONCLUSIONES

El documento explora la disposición de los individuos a adoptar MaaS. En general, reconocemos actitudes positivas hacia estas nuevas soluciones en nuestros dos casos de estudios: Madrid (España) y Randstad (Países Bajos). Los resultados confirman que tanto las características socioeconómicas y demográficas como las variables relacionadas con los hábitos de viaje determinan la probabilidad de que los individuos adopten dichas innovaciones tecnológicas.

Por un lado, nuestros resultados muestran que las personas con un alto nivel de estudios y no jubiladas son los segmentos de la población con una mayor probabilidad de adoptar MaaS. Dado que para adoptar estas nuevas tecnologías se requieren ciertos conocimientos tecnológicos (por ejemplo, habilidades para manipular un móvil), esperábamos que las personas de mayor edad estuvieran menos interesadas. Sin embargo, los diferentes grupos generacionales mostraron niveles similares de afinidad con MaaS. Por otro lado, nuestros resultados sugieren que los viajeros multimodales se sienten significativamente más atraídos por MaaS que los unimodales. Esto parece razonable, ya que el MaaS se basa en la integración de varios servicios de movilidad. El propósito del viaje también parece ser clave. Los viajes por trabajo o estudios se reconocen como los más inclinados hacia estas soluciones innovadoras. Por último, la distribución obtenida ilustra que la intención de adoptar MaaS está positivamente asociada a la frecuencia de uso de las aplicaciones de planificación de viajes.

Entender las motivaciones que impulsan a los viajeros a adoptar MaaS es esencial para definir estrategias exitosas orientadas al usuario. Adaptar las soluciones de viaje a las expectativas de los individuos puede conducir a un cambio de comportamiento hacia opciones más satisfactorias y asequibles. La investigación tiene algunas limitaciones que deberían abordarse en futuras contribuciones. Pensamos que es necesario desarrollar pilotos reales con el objetivo de obtener y profundizar en el conocimiento para elaborar nuevas recomendaciones.

Caso de estudio			**Madrid AM [1] (España)**						**Randstad AM [1] (Países Bajos)**					
Disposición a adoptar MaaS - Likert (1-5) [2]			**1**	**2**	**3**	**4**	**5**	**M(DE) [4]**	**1**	**2**	**3**	**4**	**5**	**M(DE) [4]**
Lugar de residencia	Madrid (ciudad)	Nivel 4 [3]	3,8	2,6	15,5	32,3	45,8	*4,17 (1,140)*	3,8	7,0	29,3	35,0	24,8	*3.70 (1.041)*
		Nivel 3 [3]	-	-	-	-	-	-	0,0	11,0	41,5	30,5	17,1	*3.54 (.905)*
	Corona metropolitana	Nivel 2 [3]	5,5	4,3	11,7	25,2	53,4	*4,14 (1,022)*	9,3	0,0	35,2	42,6	13,0	*3.50 (1.042)*
		Nivel 1 [3]	-	-	-	-	-	-	8,7	-	34,8	43,5	13,0	*3.52 (1.039)*
Género	Hombre		5.8	3,8	16,8	31,6	42,0	*4,00 (1,125)*	4,2	5,6	33,8	39,4	16,9	*3,59 (,975)*
	Mujer		2.4	2,0	13,0	30,6	52,0	*4,28 (,933)*	4,9	5,4	34,6	35,6	19,5	*3,60 (1,018)*
Grupo de edad	18-24 años		2.8	2,8	14,7	29,4	50,5	*4,22 (,985)*	11,6	7,0	23,3	41,9	16,3	*3,44 (1,201)*
	25-34		5.5	3,0	15,2	29,3	47,0	*4,09 (1,112)*	3,7	4,7	32,7	34,6	24,3	*3,71 (1,009)*
	35-54		3.2	1,6	15,7	33,1	46,3	*4,18 (,974)*	1,3	7,1	37,7	38,3	15,6	*3,60 (,882)*
	>55		5.1	4,7	13,6	29,8	46,8	*4,08 (1,117)*	7,0	3,5	35,1	37,7	16,7	*3,54 (1,041)*
Nivel educativo	No Universitario		5.8	3,9	15,2	30,9	44,2	*4,04 (1,128)*	5,8	6,2	36,7	36,3	15,1	*3,49 (1,013)*
	Universitario		2.9	2,2	14,7	31,2	49,0	*4,21 (,971)*	2,5	4,4	30,2	39,6	23,3	*3,77 (,943)*
Ocupación	Estudiante		3.1	3,1	13,8	27,7	52,3	*4,23 (1,012)*	8,3	8,3	20,8	50,0	12,5	*3,50 (1,103)*
	Trabajador		3.6	1,9	15,4	31,4	47,7	*4,18 (1,000)*	3,6	6,5	36,2	32,2	21,4	*3,61 (1,008)*
	Jubilado		9.3	8,0	18,7	25,3	38,7	*3,76 (1,303)*	14,3	2,4	35,7	40,5	7,1	*3,24 (1,122)*
	Otro		4.5	5,3	10,5	34,6	45,1	*4,11 (1,082)*	1,3	2,6	30,3	51,3	14,5	*3,75 (,785)*
Tamaño del hogar	1 persona		7.9	1,2	19,5	20,7	50,6	*4,05 (1,212)*	4,3	4,3	30,4	34,8	26,1	*3,74 (1,036)*
	2 personas		5.5	5,1	19,1	34,9	35,3	*3,89 (1,113)*	5,5	6,1	31,5	43,6	13,3	*3,53 (,985)*
	3 o más personas		2.3	2,3	11,5	32,3	51,6	*4,29 (,922)*	3,7	5,6	39,1	32,9	18,6	*3,57 (,979)*

[1] AM: área metropolitana; [2] ¿Estás dispuesto a adoptar soluciones MaaS? Escala Likert: 1 (mínimo) – 5 (máximo) (Sección 5 de la encuesta); [3] Nivel de urbanización de los Países Bajos [3]. Nivel 1: <1.000 direcciones/km2 / Nivel 2: 1.000 – 1.500 / Nivel 3: 1.500 – 2.500 / Nivel 4: > 2.500. (102 casos desconocidos); [4] M (DE): Media (Desviación Estándar) (Escala Likert 1-5).

Tabla 5 – Disposición a adoptar MaaS según las características socioeconómicas y demográficas.

Caso de estudio		**Madrid AM [1] (España)**						**Randstad AM [1] (Países Bajos)**					
Disposición a adoptar MaaS - Likert (1-5) [2]		**1**	**2**	**3**	**4**	**5**	**M(DE) [4]**	**1**	**2**	**3**	**4**	**5**	**M(DE) [4]**
Frecuencia del VMF [3]	Menos de 1 viaje/semana	9,3	3,1	21,6	26,8	39,2	*3,84 (1,247)*	8,0	5,3	33,3	36,0	17,3	3,49 (1,095)
	Entre 1-3 viajes/semana	6,1	2,9	18,0	31,7	41,4	*3,99 (1,124)*	6,7	4,9	38,7	38,0	11,7	3,43 (,994)
	Más de 3 viajes/semana	2,4	2,9	12,5	31,5	50,7	*4,25 (,949)*	1,1	6,1	30,6	37,8	24,4	3,78 (,923)

Multimodalidad del VMF [3]	No – unimodal (todos)	3,8	2,6	17,4	33,2	43,1	*4,09 (1,020)*	6,0	5,6	40,4	34,0	14,0	3,45 (1,001)
	Andando (unimodal)	14,1	6,3	15,6	28,1	35,9	*3,66 (1,394)*	10,0	0,0	60,0	20,0	10,0	3,20 (1,033)
	Bicicleta	8,3	16,7	41,7	16,7	16,7	*3,17 (1,193)*	1,7	6,9	43,1	29,3	19,0	3,57 (,939)
	Coche	2,0	1,3	18,4	40,1	38,2	*4,11 (,888)*	6,3	4,9	43,4	36,4	9,1	3,37 (,947)
	Moto/Scooter	7,1	0,0	21,4	21,4	50,0	*4,07 (1,207)*	0,0	0,0	50,0	16,7	33,3	3,83 (,983)
	Transporte público	2,4	2,1	15,5	32,7	47,3	*4,21 (,941)*	7,4	7,4	27,8	37,0	20,4	3,56 (1,127)
	Movilidad compartida	0,0	0,0	57,1	0,0	42,9	*3,86 (1,069)*	0,0	0,0	20,0	80,0	0,0	3,80 (,447)
	Sí – multimodal	4,6	3,4	11,3	28,2	52,5	*4,21 (1,070)*	1,5	5,3	21,1	45,1	27,1	3,91 (,908)
Tiempo del viaje VMF [3]	0-14 minutos	9,5	7,1	26,2	11,9	45,2	*3,76 (1,358)*	5,4	5,4	46,4	26,8	16,1	3,43 (1,006)
	15-29	3,6	2,3	17,3	31,9	44,9	*4,12 (1,012)*	5,2	6,5	38,6	35,3	14,4	3,47 (,994)
	30-59	3,8	2,9	11,8	31,9	49,6	*4,21 (1,016)*	1,3	3,8	29,7	43,0	22,2	3,81 (,868)
	60 or more	5,1	3,4	14,4	32,2	44,9	*4,08 (1,091)*	11,8	7,8	21,6	39,2	19,6	3,47 (1,239)
Abono TP [4]	No	2,9	2,9	17,5	31,1	45,7	*4,14 (,993)*	5,9	5,9	42,2	34,8	11,2	3,40 (,969)
	Sí	4,7	2,9	13,7	31,1	47,6	*4,14 (1,064)*	3,5	5,2	27,7	39,8	23,8	3,75 (,989)
Carné de conducir	No	4,7	2,3	14,0	22,3	56,7	*4,24 (1,080)*	7,9	9,5	25,4	39,7	17,5	3,49 (1,134)
	Sí	3,9	3,1	15,2	33,5	44,3	*4,11 (1,030)*	3,9	4,8	35,8	37,2	18,3	3,61 (,969)
Usos de servicios de movilidad compartida	Desconozco estos servicios	3,3	2,4	21,9	33,8	38,6	*4,02 (1,002)*	3,7	2,5	35,8	38,3	19,8	3,68 (,946)
	No, pero los conozco	3,5	3,2	12,9	33,4	46,9	*4,17 (1,008)*	3,3	7,3	34,7	38,8	15,9	3,57 (,954)
	Sí	5,0	2,9	13,1	27,7	51,3	*4,17 (1,087)*	8,7	3,3	31,5	33,7	22,8	3,59 (1,140)
Motivo del VMF [3]	Trabajo/Escuela	2,2	1,6	12,7	33,3	50,1	*4,27 (,906)*	2,2	6,5	32,2	38,3	20,9	3,69 (,946)
	Compras	9,8	5,4	19,6	27,7	37,5	*3,78 (1,278)*	6,6	2,6	38,2	38,2	14,5	3,51 (1,000)
	Ocio	5,4	6,6	17,5	26,5	44,0	*3,97 (1,173)*	6,5	5,4	37,0	37,0	14,1	3,47 (1,021)
	Llevar/recoger a alguien	13,9	2,8	27,8	19,4	36,1	*3,61 (1,379)*	0,0	11,1	44,4	33,3	11,1	3,44 (,882)
Frecuencia de uso de aplicaciones de movilidad	Nunca	30,0	15,0	32,5	7,5	15,0	*2,63 (1,390)*	23,8	4,8	42,9	23,8	4,8	2,81 (1,209)
	Casi nunca	6,5	10,4	36,4	26,0	20,8	*3,44 (1,130)*	15,2	21,2	36,4	24,2	3,0	2,79 (1,083)
	Ocasionalmente	5,0	1,9	26,0	42,7	24,4	*3,80 (,995)*	3,3	5,7	47,5	35,2	8,2	3,39 (,849)
	A menudo	2,1	2,4	8,2	33,6	53,6	*4,34 (,887)*	2,3	3,4	30,1	42,0	22,2	3,78 (,906)
	Siempre	1,0	0,0	2,6	16,8	79,6	*4,74 (,607)*	1,5	3,0	16,7	40,9	37,9	4,11 (,897)

[1] AM: área metropolitana; [2] ¿Estás dispuesto a adoptar soluciones MaaS? Escala Likert: 1 (mínimo) – 5 (máximo) (Sección 5 de la encuesta); [3] VMF: viaje más frecuente; [4] TP: transporte público; [5] M (DE): Media (Desviación Estándar) (Escala Likert 1-5).

Tabla 6 – Disposición a adoptar MaaS según las características relacionadas con los hábitos de movilidad

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IMPACTO EN LA ACEPTABILIDAD Y REPARTO MODAL DE LAS MEDIDAS PARA MEJORAR LA CALIDAD DEL AIRE EN MADRID CENTRAL

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RESUMEN

Las ciudades han intensificado la implementación de Zonas de Bajas Emisiones (ZBE) para mejorar la vida urbana a partir de la mejora de la calidad del aire. En este contexto, se ha prestado limitada atención tanto a la aceptabilidad de las medidas adoptadas como al efecto producido sobre los patrones de viaje. Este estudio lleva a cabo un enfoque de modelización para conocer el impacto de cinco grupos de variables (características socioeconómicas y demográficas, actitudes personales, variables relacionadas con el viaje, percepciones y hábitos de movilidad relacionados con la ZBE y elección modal en la ZBE) en la aceptabilidad pública y en el cambio modal hacia modos de transporte más sostenibles. La ciudad de Madrid ha servido como caso de estudio debido a la reciente implementación de Madrid Central. Los datos para realizar los modelos de elección discreta se han obtenido de una encuesta con un total de 799 participantes. Los resultados muestran el poder explicativo de la conciencia ambiental, el modo de transporte más utilizado, el uso de sistemas de movilidad compartida y la frecuencia de viaje a Madrid Central en cuanto a la aceptabilidad pública así como el impacto de la ZBE en la reducción del uso del vehículo privado y la promoción de modos de transporte sostenibles, relacionados principalmente a las características sociodemográficas y a los hábitos de movilidad y las percepciones hacia la ZBE. Estos resultados pueden extrapolarse a otras ciudades en el contexto internacional y servir a los responsables políticos para comprender mejor los factores que influyen en la efectividad de las políticas de transporte.

1. INTRODUCCIÓN

La movilidad sostenible se está convirtiendo en una prioridad en las agendas de planeamiento de muchas ciudades (Banister 2008; Schwanen et al., 2011). Esta situación refleja el creciente interés en el reto que supone mejorar la contaminación atmosférica producida por el transporte a la vez que revela el conflicto entre maximizar los beneficios de la movilidad y reducir su impacto ambiental (Polichetti, 2017; Ramos et al., 2017). Para abordar esta problemática, muchas ciudades (Sao Paulo, Beijing, París, Londres, etc.) han decidido implementar una Zona de Bajas Emisiones (ZBE) para limitar el uso de vehículos de combustión en favor de vehículos eléctricos, movilidad compartida y modos activos (Zainol et al., 2014; Szarata et al., 2017).

La adopción de ZBEs es una de las políticas de transporte más frecuentes para abordar los retos de la calidad del aire en las ciudades (Togel et al, 2014). Las ZBE consisten en un conjunto de políticas específicas que limitan el acceso de los automóviles dentro de un área definida. Dichas restricciones pueden establecerse a través de una variedad de políticas específicas: limitaciones de franjas horarias, cargos a los vehículos de motor, promoción del uso compartido del coche y peatonalización (Cass y Faulconbridge, 2016). La implantación de las ZBEs se produce en lugares con niveles de tráfico muy elevados y con una concentración relevante de actividad económica y social. La naturaleza, la extensión y las características de las ZBEs varían en función, entre otras cosas, de las normas culturales, los sistemas jurídicos y los objetivos de calidad del aire, (Alduán, 2014; Holman et al., 2015).

La implementación de ZBEs en Europa responde principalmente a los requerimientos de la Agenda Urbana de la UE y a su marco legal. La Agencia Europea de Medio Ambiente ha establecido unos límites de emisión para ciertos contaminantes siendo los miembros de la UE los responsables de cumplirlos. En el contexto europeo se han establecido normas específicas sobre las emisiones de contaminantes en las carreteras (por ejemplo, PM y NOx), que desencadenan restricciones al tránsito urbano aplicadas por las autoridades locales en función del tipo de vehículo (de Euro I a Euro VI). Estas restricciones al tráfico de automóviles parecen herramientas adecuadas para lograr ciudades habitables, transitables y saludables, pero su efectividad y viabilidad también está ligada a la alta controversia social que se genera cuando se implementan (Soria-Lara et al., 2019) ya que llevan asociadas cambios significativos en los patrones de movilidad de los ciudadanos (Moser et al, 2007; Graham-rowe et al, 2011; Ahanchian et al, 2019).

La literatura previa referente a ZBE se ha centrado principalmente en la medición directa de sus efectos sobre la calidad del aire y la renovación de la flota (Lutz, 2009; Ellison et al., 2013; Ferreira et al., 2015, Lebrusán & Toutouh, 2020). Para reducir la controversia social generada por estas áreas se considera prioritario estudiar la aceptabilidad social de la ZBE.

Además, se debe analizar su efectividad en cuanto a la reducción del uso del vehículo privado y su impulso al cambio modal hacia modos más sostenibles, para una mejor comprensión de la medida en cuanto a las emisiones producidas por el transporte, tal y como se ha hecho previamente en otras políticas similares (prohibición temporal del uso de vehículos privados, incentivos para los modos sostenibles, suministro de información en tiempo real a los viajeros, la aplicación del sistema de información de estacionamiento telemático, etc.). De esta manera, pueden conocerse repercusiones económicas, ambientales y sociales asociadas a las ZBE que ayuden a los profesionales y a los responsables políticos a nuevos diseños y enfoques de implementación de estas zonas.

Esta investigación tiene como objetivo identificar las variables claves que explican la aceptabilidad de las ZBEs así como el impacto modal de las mismas en contextos urbanos (en especial el cambio modal experimentado por los usuarios de vehículo privado) utilizando un análisis de elección discreta. Para ello, se han utilizado los datos extraídos de una encuesta realizada a 799 ciudadanos de la Comunidad de Madrid. Dicha encuesta está estructurada en cinco bloques: (i) Características socioeconómicas y demográficas; (ii) Actitudes personales; (iii) Variables relacionadas con el tipo de viaje; (iv) Hábitos de movilidad y percepciones relacionadas con la ZBE; y (v) Elección modal de viaje respecto a la ZBE. La ciudad de Madrid ha servido como caso de estudio, por su reciente implementación de Madrid Central (2018).

El artículo se encuentra estructurado de la siguiente manera. El capítulo 2 muestra la literatura previa en este campo. El capítulo 3 presenta el caso de estudio de Madrid. La encuesta realizada y los datos obtenidos se muestran en el capítulo 4. El capítulo 5 describe la metodología utilizada mientras que el capítulo 6 desarrolla los principales resultados obtenidos. Finalmente, el capítulo 7 concluye con las observaciones finales y la propuesta de futuras iniciativas de investigación.

2. REVISIÓN DE LITERATURA: ANÁLISIS DE ZBEs

El análisis previo de las ZBEs y su impacto en la sostenibilidad es un tema de creciente interés en la literatura académica. Para contextualizar la revisión realizada, se han consultado dos grupos de estudios. En primer lugar, aquellos estudios basados en comparar la calidad del aire antes y después de la implementación de una ZBE. En segundo lugar, aquellos estudios que analizan el cambio modal producido por políticas de transporte similares a las ZBEs.

Dentro del primer grupo de estudios revisados, Duque et al. (2016) evalúan un conjunto de estrategias para reducir la contaminación atmosférica en la ZBE de Oporto utilizando una herramienta de modelización numérica. Sus resultados muestran que la ZBE tiene beneficios locales asociados a reducciones del 3% de la concentración de NO_2 mientras que no se observan reducciones en las concentraciones de PM. Del mismo modo, Dias et al. (2012) desarrollaron un enfoque de modelización integrada para evaluar los impactos en la calidad del aire de una ZBE en Coimbra, Portugal. Los autores encontraron una pequeña mejora de la calidad del aire dentro de la ZBE, teniendo dificultades para alcanzar los objetivos de calidad del aire. Además, observaron que las emisiones previstas a nivel de la ciudad podrían aumentar debido a la reconfiguración de los patrones de movilidad. Otro estudio digno de mención fue realizado por Boogaard et al. (2012) en varias ciudades holandesas. Sus conclusiones muestran la escasa capacidad de las ZBE para producir reducciones significativas reducciones significativas de la contaminación de los coches.

Otros autores destacan el impacto de las ZBE en la renovación del parque automovilístico de vehículos en todo el mundo (por ejemplo, en Berlín, Londres y Lisboa), provocando avances tecnológicos que reducen las emisiones por vehículo y mejoran la calidad del aire (Lutz, 2009; Ellison et al., 2013; Ferreira et al., 2015). Por último, el estudio realizado por Holman et al. (2015) en diferentes ciudades europeas, señala las dificultades para distinguir entre los efectos causados por una ZBE en la calidad del aire y los efectos provocados por otras medidas políticas. como la renovación de la flota. En el mismo sentido, York y Rouleau (2017) señalaron la escasa evidencia entre la aplicación de la ZBE y la mejora de la calidad del aire, dado el escaso número de evaluaciones ex-post, la influencia de los efectos de rebote no controlados y el desarrollo de la tecnología de los vehículos.

El segundo grupo de estudios se centra en el análisis de la elección modal impulsada por diferentes políticas de transporte similares a las ZBE, con especial interés en la reducción del tráfico de automóviles. Como indican Graham-Rowe et al. (2011), cabe destacar que no hay muchos estudios de alta calidad metodológica para evaluar la reducción del uso del vehículo privado. Sus autores señalan la escasa evaluación de las políticas de transporte con datos de movilidad ex-ante y ex-post como uno de los puntos más débiles de los estudios de investigación anteriores. A pesar de los problemas mencionados, cabe mencionar las siguientes aportaciones sobre el impacto de las políticas de movilidad en el cambio modal. Tertoolen et al. (1997) detallan cómo varias razones psicológicas (independencia, dinamismo de la persona, ingresos, etc.) pueden determinar el uso (o no) del vehículo privado. Los autores realizan una investigación basada en el suministro de información sobre el coste económico y medioambiental del uso del coche de 350 usuarios de la ciudad de Gouda (Países Bajos). Los resultados indican un aumento de la conciencia económica y medioambiental de los conductores, que no se refleja en un cambio de sus hábitos de elección modal. Eriksson et al. (2008) realizaron un experimento en dos ciudades suecas que consistía en interrumpir las pautas habituales de uso del coche. Se reclutó a un total de 71 usuarios de automóviles para el experimento. Los resultados muestran una relación directa entre la voluntad de reducir el uso del vehículo privado y el cambio modal. Croci (2016) realizó una evaluación comparativa de tres experiencias de tarificación vial en Europa para evaluar su eficacia en la reducción de las externalidades generadas por el tráfico rodado: Londres, en funcionamiento desde 2003; Estocolmo, en funcionamiento desde 2007; y Milán, en funcionamiento desde 2012. En todos los casos, se evidenciaron reducciones los niveles de tráfico y un cambio en los patrones de movilidad. La principal tendencia fue un cambio de los conductores de automóviles al transporte público superior al 10% en las tres ciudades europeas.

Más recientemente, Ahanchian et al. (2019) desarrollaron un modelo basado en agentes para simular patrones emergentes derivados de las acciones individuales para analizar las oportunidades de cambio modal en Dinamarca. Establecieron cuatro escenarios alternativos para probar el efecto sobre el cambio modal, con un enfoque especial en el cambio modal desde el vehículo privado: incentivos para los modos sostenibles, expansión de la infraestructura pública, desincentivos para los coches privados y combinación de estas medidas. Los resultados muestran, para el horizonte de 2050, una reducción general del uso del vehículo privado en todos los escenarios y el consiguiente aumento del transporte no motorizado y del uso del transporte público. Otros estudios destacan diferentes efectos que pueden cambiar los hábitos de movilidad y reducir el uso del vehículo privado, como un cambio de residencia (Bamberg, 2006), o una reubicación laboral para reducir el tiempo de desplazamiento (Mullins y Mullins, 1995).

Esta investigación añade a la literatura una evaluación ex post de la aceptabilidad pública hacia la implementación de una ZBE y la exploración de los efectos de las ZBE en el cambio modal.

3. LA IMPLEMENTACIÓN DE LA ZBE DE MADRID CENTRAL

La ciudad de Madrid (España) tiene una superficie de 605 km^2 y una población de más de 3 millones de habitantes (5300 habitantes/km^2), por lo que se trata de una ciudad compacta con una alta densidad de población. Desde la década de 1990, Madrid ha experimentado un rápido proceso de suburbanización, expandiéndose por su área metropolitana (8.022 km^2 y 6,5 millones de habitantes). Sin embargo, la ciudad de Madrid sigue ofreciendo la mayor oferta de empleo, comercio y ocio entre los municipios situados en su área metropolitana, generando una fuerte interdependencia con sus municipios circundantes. Como dato, sólo la ciudad de Madrid concentra el 60% del PIB regional.

Los índices de movilidad han aumentado significativamente en la región en los últimos años. Según la última encuesta de movilidad, se producen 15,8 millones de desplazamientos en día laborable en Madrid (Monzón, 2019). El número de desplazamientos dentro del área metropolitana ha aumentado un 30,4% desde 1996 hasta 2017, siguiendo un ritmo similar al del crecimiento de la población (32,7%). Sin embargo, se observan notables diferencias en función del modo de transporte. Por ejemplo, el número de viajes en transporte público ha aumentado un 10%, mientras que el crecimiento del uso del vehículo privado es mucho mayor (+60%). Esta tendencia es el resultado del proceso de suburbanización comentado anteriormente.

El reparto modal muestra un uso predominante del vehículo privado, incluyendo coches y motos (57,8%), entre las áreas metropolitanas, mientras que el uso del transporte público cubre el 36,9% de esos viajes, y los modos de transporte no motorizados (bicicleta y caminar) alcanzan el 3,8%. Se observa un reparto modal diferente dentro de la ciudad de

Madrid, donde la relevancia de los sistemas de transporte colectivo y de los modos no motorizados asciende al 37,8% y 36,8%, respectivamente. Por el contrario, el uso del vehículo privado es del 24,7%.

El área metropolitana de Madrid cuenta con una amplia red de transporte por carretera, que incluye diez autopistas. En particular, hay cuatro autopistas alrededor de la ciudad de Madrid (M-30, M-40. M-45 y M-50) que conectan diferentes municipios de su área metropolitana. La red de transporte público existente se basa en un sistema integrado, compuesto por autobuses, ferrocarril y servicios de metro. Para la fijación de las tarifas del transporte público, tanto la ciudad de Madrid como su área metropolitana se dividen en ocho zonas de transporte. Para cada una de estas zonas, el consorcio de transporte ofrece tres tipos de billetes: billete sencillo, billete de diez viajes y abono de transporte público, que permite el uso ilimitado del transporte colectivo durante un mes o un año. Dicho abono de transporte colectivo es muy utilizado entre los viajeros habituales, llegando a los 3,6 millones de usuarios. Además, existen precios reducidos en el abono de transporte colectivo para usuarios jóvenes (<26 años), mayores (>65 años), familias numerosas y personas discapacitadas. Además, para incrementar las oportunidades de elección modal en la ciudad, el gobierno local ha implantado un sistema público de bicicletas compartidas (BiciMAD). Otros servicios recientes de movilidad compartida son ofrecidos por operadores privados, como patinetes, motocicletas y coches eléctricos. La oferta de estos sistemas de movilidad compartida se concentra en el centro de la ciudad.

El elevado crecimiento de los desplazamientos motorizados dentro del área metropolitana de Madrid ha aumentado las emisiones de gases de efecto invernadero (GEI) y de contaminantes (por ejemplo, NOX y PM). El mayor problema se produce en la ciudad de Madrid, donde el tráfico rodado genera el 74,4% de las emisiones locales, según los datos del Ayuntamiento de Madrid (2017). Desde 2011, los límites de calidad del aire establecidos por la UE se han superado durante varios episodios, sobre todo para el NOx y el O3. Las condiciones meteorológicas desfavorables de la ciudad de Madrid (inversión térmica) dificultan la eliminación de dichos contaminantes de la atmósfera de la ciudad, especialmente durante el otoño y el invierno. Para abordar este problema, el gobierno local de Madrid desarrolló un plan de calidad del aire llamado "Plan A" (2017), siendo la implantación de una Zona de Bajas Emisiones uno de los más destacados esquemas políticos del Plan. Dicha ZBE fue implementada con el nombre de Madrid Central.

Madrid Central fue implementado el 30 de noviembre de 2018, abarcando una superficie de 5 km^2 en el centro de la ciudad de Madrid. Cuenta con múltiples modos de transporte para acceder a dicho área, con un total de 70 líneas de autobús, 4 líneas de metro, 57 estaciones de bicis compartidas 27 paradas de taxi y 5946 plazas de aparcamiento subterráneo. Su objetivo es mejorar la calidad del aire y promover un centro de la ciudad más amigable para peatones, ciclistas, vecinos y visitantes.

Las restricciones de tráfico para los vehículos privados dependen de un sistema de etiquetado según el tipo de motor (Cero, Eco, C, B o A; de menor a mayor nivel de contaminación). Las características del parque automovilístico de Madrid y su área metropolitana se muestran en la Tabla 1.

Población		Etiqueta ambiental				
		A	B	C	Eco	Zero
No residentes	Coche	No	Excepto parking/garajes	Excepto parking/garajes	Sí	Sí
	Motocicleta	No	Horario restringido (7 a 22h)	Horario restringido (7 a 22h)	Sí	Sí
	Distribución de mercancías	No	Horario restringido	Horario restringido	Sí	Sí
Invitados (máx.20/mes)		Sí (hasta 2020)	Sí	Sí	Sí	Sí
Residentes		Sí (hasta 2025)	Sí	Sí	Sí	Sí

Tabla 1 – Características de la flota de vehículos en Madrid y su área metropolitana.

Con el objetivo de reducir el uso de vehículos privados, se han impuesto restricciones de tráfico a los coches y motos privados para entrar en "Madrid Central" en función de cinco etiquetas medioambientales: Cero (nivel de contaminación más bajo), Eco, C, B o A (nivel de contaminación más alto) (Tabla 2). Estas categorías medioambientales están armonizadas a nivel nacional, en función del tipo de motor, la antigüedad y el tipo de vehículo. Hay que destacar que las restricciones para motocicletas son menores que para los coches. Asimismo, existen excepciones de acceso para residentes, discapacitados y vehículos de seguridad y emergencia. Además, los residentes disponen de un máximo de 20 invitaciones al mes para acceder a Madrid Central en vehículo privado.

Flota de vehículos	Etiqueta ambiental (%)				
	A	B	C	Eco	Zero
Motocicleta particular	25.4	17.1	56.6	0.9	0.0
Coche particular	25.5	34.1	37.4	2.7	0.3

Tabla 2 – Características de la flota de vehículos en Madrid y su área metropolitana.

Madrid Central fue una de las medidas políticas emblemáticas aplicadas por el antiguo gobierno de la ciudad, que contaba con el apoyo de una coalición de partidos de izquierda.

La aplicación de la medida suscitó una gran controversia en el debate político y en la opinión pública, tanto antes como después de su aplicación. Las disputas fueron sobre todo sobre la eficacia de la medida para reducir la contaminación, y su impacto en los viajeros y los servicios minoristas de la zona. La coalición de derechas que gobierna la ciudad desde mayo de 2019 ha establecido un nuevo plan de movilidad, con el nombre de Madrid 360, que mantiene la ZBE con algunos pequeños cambios en su funcionamiento y operación.

4. BASE DE DATOS: ENCUESTAS A LA POBLACIÓN

Se utiliza un enfoque basado en la modelización para abordar el objetivo principal de esta investigación, a saber, identificar las variables clave que explican la aceptabilidad pública y el cambio modal de Madrid Central. La principal fuente de datos fue una encuesta individual online que recogía diferentes tipos de variables: socioeconómicas y demográficas, actitudes personales, variables relacionadas con el viaje, percepciones y hábitos de movilidad vinculados a Madrid Central, y elección modal respecto a Madrid Central. Se realizó una encuesta piloto con un pequeño grupo de personas. Sus respuestas proporcionaron al equipo de investigación información para perfeccionar el diseño de la encuesta (por ejemplo, la legibilidad), añadiendo nuevas preguntas cuando fue necesario.

La encuesta definitiva se difundió entre los ciudadanos de Madrid y su área metropolitana de enero a junio de 2019. El plan de difusión incluyó redes sociales, páginas web especializadas y la difusión en la calle de folletos indicando el objetivo de la investigación.

Con esto último se pretendía incluir una adecuada heterogeneidad en la muestra en cuanto a las características sociodemográficas de la misma, dadas las limitaciones de difusión online para captar a todos los segmentos de población. Un total de 1300 personas rellenaron el cuestionario. Al final se obtuvieron 799 respuestas válidas. La encuesta constaba de los siguientes cinco bloques principales (Tabla 3):

(i) Características socioeconómicas y demográficas de los individuos: género, edad, nivel de educación, ingresos mensuales y código postal de residencia.
(ii) Actitudes personales, recogiendo información sobre las creencias y la ideología de los individuos, incluida la conciencia económica, social y medioambiental.
(iii) Variables relacionadas con los viajes que afectan a los desplazamientos diarios: posesión individual de un permiso de conducir o un abono de transporte, la disponibilidad de un vehículo privado y la frecuencia de uso de los distintos modos de transporte (transporte colectivo y servicios de movilidad compartida).
(iv) Percepciones individuales y hábitos de movilidad vinculados a la implementación de Madrid Central: frecuencia de viajes para acceder a Madrid Central, principales actividades realizadas dentro de esta zona, modos de transporte elegidos para acceder/salir de Madrid Central antes y después de la implantación de la ZBE, percepción de Madrid Central como peatón; y nivel individual de aceptabilidad de Madrid Central, incluyendo una pregunta abierta sobre posibles acciones para mejorar la aceptabilidad de la ZBE.
(v) Elección modal en Madrid Central: cambio modal tras la implantación de Madrid Central, modos de transporte frecuentes para acceder a Madrid Central (máx. 2) antes y después de la implantación de la ZBE, factores que determinan la elección modal.

Bloque	Variables	Descripción	Tipo de pregunta
Características socioeconómicas y demográficas	Edad	Edad del encuestado (varias categorías)	Pregunta multirespuesta
	Género	Hombre/Mujer	
	Nivel de estudios alcanzado	Universitario / No universitario	
	Estado de empleo	Estudiante; trabajador; estudiante y trabajador; otro (amo de casa, desempleado, jubilado)	
	Sector de empleo	Sector primario e industria; comercio minorista u hostelería; transporte y logística; administración pública; estudiante, jubilado o sin empleo; ocio y otros.	
	Estructura del hogar	Composición y número de personas en el hogar (varias categorías)	
	Ingresos mensuales	Ingresos mensuales individuales (varias categorías)	
	Código postal de residencia	Código postal de la vivienda	Pregunta voluntaria
	Código postal de trabajo	Código postal del trabajo	
Actitudes personales	Ideología política	Izquierdas, derechas, centro, sin ideología	Pregunta multirespuesta
	Concienciación ambiental	Grado de concienciación ambiental	Escala-Likert de 5 puntos 1-Muy baja 5-Muy alta
	Concienciación social	Grado de concienciación social	
	Concienciación económica	Grado de concienciación económica	
Variables relacionadas con el viaje	Permiso de conducir	Posesión de carnet de conducir	Pregunta multirespuesta
	Disponibilidad de coche propio	Disponibilidad de al menos un coche en el ámbito del hogar	
	Disponibilidad de motocicleta propia	Disponibilidad de al menos una motocicleta en el ámbito del hogar	
	Disponibilidad de abono transporte público	Posesión de abono transporte público	
	Uso de servicios de transporte público	Frecuencia de uso de servicios de transporte público	Escala-Likert de 5 puntos 1-Muy baja 5-Muy alta
	Uso de servicios de movilidad compartida	Frecuencia de uso de servicios de movilidad compartida	
Percepciones y hábitos de movilidad relacionados con Madrid Central	Aceptabilidad de Madrid Central	Nivel de aceptabilidad individual de la medida	Escala-Likert de 5 puntos 1-Muy negativamente 5-Muy positivamente
	Impacto de Madrid Central en su viaje habitual	Impacto general sobre el viaje habitual en términos de tiempo, coste, comodidad, etc.	
	Evaluación de Madrid Central como peatón	Satisfacción individual al caminar por Madrid Central	
	Tiempo caminando dentro de Madrid Central	Variación de tiempo caminando en la zona tras la implementación de Madrid Central (reducción, mantenimiento o aumento)	Pregunta multirespuesta
	Aspectos a destacables de la peatonalización en Madrid Central	Aspectos a destacar positivamente como peatón en Madrid Central	
	Desarrollo de Madrid Central para los peatones	Medidas a implementar para mejorar la experiencia caminando en Madrid Central	
	Actividades de compras y ocio dentro de Madrid Central	Impacto sobre las actividades de compras y ocio en Madrid Central (reducción, mantenimiento o aumento)	
	Frecuencia de viaje a Madrid Central	Frecuencia de viaje a Madrid Central como destino (varias categorías)	
	Rol de Madrid Central en la vida del encuestado	Si el individuo vive, trabaja, ambas o ninguna en Madrid Central	
	Día que suele viajar a Madrid Central	Días laborales, no laborales o ambos	
	Principal actividad llevada a cabo en Madrid Central	Actividades diarias realizadas en Madrid Central (trabajo, studio,	

		compras, tiempo de ocio, zona de paso)	
Elección modal en Madrid Central	Cambio en la elección modal tras la implementación de Madrid Central	Si el encuestado ha cambiado (o no) su modo de transporte para acceder a Madrid Central tras la implementación de la ZBE	Pregunta multirespuesta
	Modos de transporte habituales (máx.2) para acceder a Madrid Central antes de implementar la ZBE	Selección de los principales modos de transporte para acceder a Madrid Central antes de implementar la ZBE (solo los 2 modos de transporte más habituales)	
	Modos de transporte habituales (máx.2) para acceder a Madrid Central después de implementar la ZBE	Selección de los principales modos de transporte para acceder a Madrid Central después de implementar la ZBE (solo los 2 modos de transporte más habituales)	
	Factores que determinan su elección modal	Coste; tiempo; comodidad; flexibilidad horaria; posibilidad de carga; otros	

Tabla 3 – Estructura de la encuesta y variables incluidas.

Como se observa en la Tabla 4, la muestra presenta una mayor proporción de hombres (59,1%) y una menor presencia de personas mayores de 65 años (2,4%). Según su situación laboral, el 56,9% de los encuestados son asalariados, destacando la presencia de estudiantes (16,8%) y de asalariados a tiempo parcial que estudian al mismo tiempo (18,8%). Cabe mencionar que el 75,3% de los encuestados tiene estudios universitarios. En cuanto a la estructura del hogar, el 38,3% de los encuestados comparte hogar (compañeros de piso y parejas), el 30,8% son familias con hijos y el 28,4% vive con sus padres. El nivel de ingresos se distribuye uniformemente en la muestra, con un porcentaje representativo de encuestados en todos los subgrupos de ingresos incluidos en el cuestionario. El código postal se ha diseñado como una variable adicional en seis categorías: (i) Dentro de Madrid Central; (ii) Entre Madrid Central y la M-30; (iii) Entre la M-30 y la M-40; (iv) Entre la M-40 y la M-50; y (vi) Sin respuesta. Cabe destacar que todas las categorías incluidas en cada variable están adecuadamente representadas en la muestra.

El segundo bloque de la encuesta se centra en las actitudes personales (Tabla 4). Hay una mayor presencia de la ideología de izquierdas (36,9%) en comparación con otras opciones. Los encuestados también declararon niveles muy altos de concienciación en temas sociales (38,4%), económicos (40,3%) y medioambientales (53,4%).

	N	%		N	%
Características socioeconómicas y demográficas					
Edad			***Estructura del hogar***		
Menor de 25	235	29.4	Vivo solo	77	9.7
26-34	183	22.9	Vivo con mis padres	227	28.4
35-49	211	26.4	Comparto piso	87	10.9
50-64	151	18.9	Pareja sin hijos	148	18.5
Mayor de 65	19	2.4	Familia con niños mayores de 10 años	133	16.6
Género			Familia con hijos menores de 10 años, ancianos y/o discapacitados	127	15.9
Mujer	472	59.1	***Ingresos mensuales***		
Hombre	327	40.9	Sin ingresos	113	14.1
Nivel de estudios			< 800 €	97	12.1
Universitario	602	75.3	800 – 1.000 €	72	9.0
No universitario	197	24.7	1.000 – 1.300 €	109	13.7
Estado de empleo			1.300 – 1.600 €	91	13.7
Estudiante	135	16.9	1.600 – 2.000 €	115	14.4
Trabajador	455	56.9	2.000 – 2.500 €	79	9.9
Trabajador y estudiante	155	18.8	2.500 – 3.200 €	65	9.1
Amo de casa, desempleado o jubilado	59	7.4	> 3.200 €	58	7.3
Residencia					
Dentro de Madrid Central	126	15.8	Dentro de la M-30	123	15.4
Entre M-30 y M-40	197	24.7	Entre M-40 y M-50	163	20.4
Fuera de la M-50	132	16.5	Sin respuesta	58	7.2
Actitudes personales					
Ideología política			***Concienciación social***		
Izquierdas	295	36.9	Muy baja	99	12.4
Derechas	106	13.3	Baja	48	6.0
Centro	202	25.3	Neutra	159	19.9
Sin definir	196	24.5	Alta	186	23.3
Concienciación ambiental			Muy alta	307	38.4
Muy baja	33	4.5	***Concienciación económica***		
Baja	36	4.8	Muy baja	76	9.8
Neutra	109	13.6	Baja	50	6.2
Alta	189	23.7	Neutra	155	19.4
Muy alta	427	53.4	Alta	194	24.3
			Muy alta	322	40.2

Tabla 4 – Información socioeconómica y demográfica y actitudes personales

La Tabla 5 muestra también la información recogida sobre las variables relacionadas con los viajes. La mayoría de los encuestados tiene carnet de conducir (91,9%) y dispone de al menos un coche en su domicilio (79,2%). Sólo el 13,9% tiene un ciclomotor o una motocicleta en casa. La mayoría de los participantes (73,3%) tiene abono de transporte público, y la frecuencia de uso del transporte colectivo se distribuye uniformemente entre todas las categorías incluidas en la encuesta. Por último, los encuestados declaran un uso muy bajo de las formas de movilidad compartida existentes (el 72,2% de los encuestados rara vez utiliza estos servicios), lo que se alinea con los resultados obtenidos por la última Encuesta de Movilidad de Madrid (Monzón et al., 2019).

	N	%		N	%
Variables relacionadas con el tipo de viaje					
Carnet de conducir			***Disponibilidad de vehículo***		
Sí	734	91.9	Coche	633	79.2
Abono de transporte público			Motocicleta	111	13.9
Sí	586	73.3	***Uso de servicios de movilidad compartida***		
Uso de transporte público			Muy bajo	577	72.2
Muy bajo	226	28.3	Bajo	98	12.3
Bajo	122	15.3	Neutro	75	9.4
Neutro	88	11.0	Alto	30	3.7
Alto	108	13.5	Muy alto	19	2.4
Muy alto	255	31.9			

Tabla 5 – Variables relacionadas con el tipo de viaje.

El cuarto grupo de variables contiene las percepciones individuales y los hábitos de movilidad vinculados a Madrid Central (Tabla 6). Más de una cuarta parte de los encuestados (27,3%) mostró que la implantación de Madrid Central ha tenido un impacto muy negativo o negativo en sus desplazamientos habituales, mientras que un total del 23% señaló un impacto positivo o muy positivo. Sólo una pequeña parte de los participantes indicaron una valoración negativa (6,3%) o muy negativa (4,4%) como peatones al caminar dentro de Madrid Central. Además, el 24,7% de los encuestados han aumentado su tiempo de caminar en la ZBE después de la implementación de Madrid Central, pero la mayoría de ellos (71,5%) mantuvo sus hábitos previos. La variación de tiempo dedicado a las actividades de comercio y ocio de los individuos tras la implementación de Madrid Central muestra porcentajes similares entre los encuestados que afirman que han disminuidos dichas actividades (38,2%), las han aumentado (34,9%) o han mantenido constantes sus hábitos (26,9%) en comparación con la situación anterior a la ZBE. La frecuencia y el día habitual de los viajes se distribuyen adecuadamente en la muestra, con un número notable de encuestados para cada categoría. Las actividades realizadas en "Madrid Central" son ocio (32,0%), trabajo (27,9%) y compras (21,8%).

Por último, mostramos las tendencias resultantes en cuanto a la aceptabilidad de los individuos de Madrid Central. El grado de aceptabilidad se divide en cinco categorías utilizando una escala de Likert de cinco puntos (1-muy negativo, 5-muy positivo). Un 36,2% de los encuestados mostró una opinión muy positiva de "Madrid Central", mientras que el 31,7% manifestó una opinión positiva. Por el contrario, sólo el 9,5% de los encuestados señaló una opinión muy negativa hacia "Madrid Central", mientras que un 14,6% señaló una opinión negativa. El 8,3% restante ofreció una evaluación neutra. En general, se observa que Madrid Central parece contar con bastante apoyo por parte de la población.

Percepciones y hábitos de movilidad relacionados con Madrid Central

Impacto de Madrid Central en los viajes habituales			***Evaluación como peatón de Madrid Central***		
Muy negativo	94	11.8	Muy negativo	35	4.4
Negativo	124	15.5	Negativo	50	6.3
Neutro	397	49.7	Neutro	184	23.0
Positivo	99	12.4	Positivo	198	24.8
Muy positivo	85	10.6	Muy positivo	332	41.5
Tiempo caminando en Madrid Central			***Aspectos a destacar como peatón *****		
Aumento	197	24.6	Mejora de la calidad del aire	466	58.3
Mantenimiento	571	71.5	Incremento de espacios públicos	391	48.9
Reducción	31	3.9	Reducción de ruido	437	54.7
Desarrollo de Madrid Central para peatones **			Incremento de zonas de reunión	191	23.9
Preferencia de tráfico peatonal	216	27.0	Mejoras de seguridad para peatones y ciclistas	328	41.1
Calles exclusivamente peatonales	328	41.0	**Actividades de compra y ocio en Madrid Central**		
Aumento de ancho de aceras	412	51.6	Aumento	279	34.9
Total prohibición de vehículos	130	16.3	Mantenimiento	215	26.9
Arboles para sombras	409	51.2	Reducción	305	38.2
Frecuencia de viaje a Madrid Central			***Rol de Madrid Central en el individuo***		
< 1 viaje/mes	75	9.4	Residencia y trabajo	40	5.0
> 1 viaje/mes	133	16.7	Residencia	56	7.0
< 2 viaje/mes	139	17.4	Trabajo	161	20.2
2-5 viaje/mes	179	22.4	Sin relación	542	67.8
5-10 viaje/mes	93	11.6	***Principal actividad realizada en Madrid Central ****		
> 10 viaje/mes	180	22.5	Trabajo	223	27.9
Tipo de día de viaje a Madrid Central			Estudio	67	8.4
Laboral	136	17.0	Compras	174	21.8
No laboral	239	29.9	Ocio	256	32.0
Ambos	424	53.1	Zona de paso	63	7.9
			Otro	16	2.0
Aceptabilidad de Madrid Central					
Muy negativa	115	14.4	Positiva	253	31.7
Negativa	75	9.4	Muy positiva	290	36.3
Neutra	66	8.2			

Tabla 6 – Percepciones y hábitos de movilidad en relación a Madrid Central.

Además, se animó a todos los encuestados a señalar posibles acciones para mejorar la satisfacción con Madrid Central. Los participantes con una aceptación positiva o muy positiva de Madrid Central indicaron principalmente las siguientes acciones: aumentar los servicios actuales de transporte público (80,6%); una mejor promoción del coche compartido (44,7%); apoyo financiero para renovar la flota de vehículos privados (44,1%); y ampliar Madrid Central (31,9%). Los participantes con una aceptación negativa o muy negativa de Madrid Central señalaron: la necesidad de una mayor oferta de servicios de transporte colectivo (49,7%) y de apoyo financiero para renovar la flota de vehículos privados (46,1%). Otras medidas mostradas por este grupo de encuestados fueron permitir que los vehículos de combustión lleguen a Madrid Central durante algunas franjas horarias (34,6%); implantar una tasa para acceder a Madrid Central en vehículo privado (22,8%); y reducir la extensión actual de Madrid Central (22,0%).

El último bloque aborda la elección modal de los individuos antes y después de la implementación de Madrid Central (Tabla 7). La mitad de los encuestados (49,9%) indicaron un cambio modal provocado por la ZBE. Los encuestados también indicaron sus dos modos de transporte más frecuentes para acceder a Madrid Central antes y después de su implantación. El coche privado (solo o con acompañante) y el metro (53,3%) eran la opción más frecuente para viajar a la ZBE antes de la implantación de Madrid Central (50,6%). A estos modos de transporte les seguían el autobús (21,1%), el tren de cercanías (12,5%) y caminar (12,6%). Tras la puesta en marcha de Madrid Central, el metro sigue siendo el modo de transporte más utilizado para acceder a Madrid Central, seguido del autobús (27,4%), el coche privado (solo o con acompañante) (21%), caminar (18,4%) y el tren de cercanías (16,4%). Además, los encuestados indicaron los factores más determinantes para explicar su elección modal. En este sentido, destacaron los siguientes factores: comodidad (55,3%) y tiempo de viaje (53,4%), seguidos del coste (42,9%).

	N	%		N	%
Elección modal en Madrid Central					
Cambio en la elección modal tras implementar la ZBE					
Sí	399	49.9			
Modos de transporte habituales (máx.2) para acceder a Madrid Central antes de su implementación*			***Modos de transporte habituales (máx.2) para acceder a Madrid Central antes de su implementación****		
Vehículo privado solo	251	31.4	Vehículo privado solo	105	13.4
Vehículo privado acompañado	153	19.2	Vehículo privado acompañado	61	7.6
Metro	426	53.3	Metro	495	62.0
Autobús	169	21.1	Autobús	218	27.3
Tren	100	12.5	Tren	131	16.4
Bicicleta	40	5.0	Bicicleta	58	7.3
Caminando	101	12.6	Caminando	147	18.4
Taxi/VTC	32	4.0	Taxi/VTC	66	8.3
Coche compartido	19	2.4	Coche compartido	47	5.9
Patinete compartido	1	0.1	Patinete compartido	10	1.3
Motocicleta compartida	11	1.4	Motocicleta compartida	22	2.8
Influential factors to modal choice **					
Coste	343	43.6	Flexibilidad	261	33.2
Tiempo	427	54.2	Carga	162	20.6
Comodidad	442	56.2			

* Los encuestados podían responder un máximo de 2 categorías
****** Los encuestados podían seleccionar varias categorías
Tabla 7 – Elección modal en Madrid Central

5. METODOLOGÍA: MODELOS DE ELECCIÓN DISCRETA

El enfoque de la investigación se centra en el uso de un marco de elección discreta basado en especificaciones logit. La formulación original de los modelos logit, derivada de la teoría de la maximización de la utilidad y el comportamiento, supone que los responsables de la toma de decisiones son maximizadores de la utilidad. Es decir, los individuos elegirán la opción con la mayor utilidad para ellos. La investigación sobre el transporte ha utilizado previamente los modelos logit (Thrane, 2015; Hammadou y Papaix, 2015; Arbués et al. 2016). En el estudio se realizan tres modelos logit (un logit binario y dos logit ordenados).

El primer modelo explora la aceptabilidad de la población respecto a Madrid Central utilizando un modelo logit ordenado. La variable dependiente es la aceptabilidad individual de Madrid Central, medida mediante una escala Likert de cinco puntos. La aceptabilidad de la ZBE Madrid Central se ha recogido como una variable discreta ordenada (1 = Muy negativa; 2 = Negativa; 3 = Neutral; 4 = Positiva; 5 = Muy positiva).

El segundo modelo analiza los cambios en la elección modal para llegar a Madrid Central, asumiendo dichos cambios desde una lógica binaria (0 = la elección modal no cambia tras implantar Madrid Central; 1 = la elección modal cambia tras implantar Madrid Central). La naturaleza discreta de la variable dependiente ha llevado a la adopción de una especificación logit binaria para este modelo.

El tercer modelo obtiene información sobre los cambios de elección modal entre los individuos que utilizaban el vehículo privado antes de la implantación de Madrid Central.

La variable dependiente se basa en una variable discreta ordenada que capta una graduación de las opciones de cambio modal tras la implantación de Madrid Central. A partir de la información reportada sobre los modos de transporte utilizados antes y después de la implantación de la ZBE, se construyó una variable dependiente con la siguiente codificación: (1) aumento del uso del vehículo privado en comparación con la situación anterior a la ZBE (este grupo de individuos renunció a utilizar otros modos de transporte y sólo utilizó su vehículo privado para llegar a Madrid Central); (2) mantenimiento del hábito de uso del vehículo privado después de "Madrid Central"; (3) reducción del uso del vehículo privado favor del taxi/VTC; (4) reducción del uso del vehículo privado en favor del transporte público o modos activos; (5) abandono del uso del vehículo privado para llegar a Madrid Central. Estas cinco categorías establecen una graduación de la sostenibilidad derivada del cambio modal de los conductores de vehículo privado tras la implementación de Madrid Central.

6. RESULTADOS

Esta sección presenta los principales resultados del análisis realizado en esta investigación.

En primer lugar, la sección 6.1 muestra los resultados obtenidos del modelo logit sobre la aceptabilidad de la ZBE. La sección 6.2 presenta los resultados descriptivos sobre el cambio modal tras la aplicación de Madrid Central, que llevaron al desarrollo del modelo logit binario sobre el cambio modal y al modelo logit ordinario sobre el cambio modal de los antiguos usuarios de vehículo privado, principal grupo afectado por la medida, de los cuales se analizarán sus principales resultados.

6.1 Análisis de la aceptabilidad de Madrid Central

Dado que las variables explicativas utilizadas en el modelo eran en su mayoría categóricas, la interpretación de los resultados de la modelización requería la selección de un caso base. Esto nos permitió determinar si, para cada variable explicativa, las respuestas de los individuos eran estadísticamente significativas entre categorías en comparación con el caso base. Las categorías base elegidas pueden consultarse en la Tabla 8.

Los resultados del modelo logit ordenado que explora la aceptabilidad hacia Madrid Central se muestran en la Tabla 8. El modelo identifica las variables explicativas que desde un punto de vista estadístico (p valor < 0,05) influencian el nivel de aceptabilidad de Madrid. Un signo positivo indica una mayor aceptabilidad hacia Madrid Central en comparación con el caso base. La mayoría de las variables explicativas que resultaron no estadísticamente significativas fueron finalmente eliminadas de la última versión del modelo.

Bloques	Variables explicativas	Coef.	Std. Error	p-valor
SOCIOECONÓMICAS Y DEMOGRÁFICAS	*Estado de empleo*			
	Estudiante y trabajador	0.427	1.192	0.026
	Estructura del hogar			
	Comparto vivienda	0.395	0.168	0.018
ACTITUDES PERSONALES	*Ideología politica (caso base: izquierdas)*			
	Centro	-0.870	0.204	0.000
	Derecha	-1.637	0.249	0.000
	Ninguno	-0.930	0.208	0.000
	Concienciación ambiental	0.464	0.176	0.008
VARIABLES RELACIONADAS CON EL TIPO DE VIAJE	*Disponibilidad de motocicleta propia (caso base: no)*			
	Sí	0.496	0.218	0.023
	Abono transporte público (caso base: no)			
	Sí	0.518	0.172	0.003
	Uso de servicios de movilidad compartida			
	Ato	-0.533	0.205	0.009
PERCEPCIONES Y HÁBITOS DE MOVILIDAD RELACIONADOS CON MADRID CENTRAL	*Impacto general en los viajes habituales (caso base: muy negativo)*			
	Negativo	1.527	0.281	0.000
	Neutral	2.201	0.296	0.000
	Positivo	2.809	0.374	0.000
	Muy positivo	3.567	0.443	0.000
	Tiempo caminando en la ZBE			
	Incremento	0.734	0.191	0.000
	Actividades de compras y ocio en Madrid Central después de las restricciones (caso base: reducción)			
	Mantenimiento	1.380	0.212	0.000
	Aumento	1.930	0.242	0.000
	Frecuencia de viaje a Madrid Central			
	Más de 1 vez al mes y menos de 2 veces por semana	0.438	0.198	0.027
	Tipo de día viajando a Madrid Central (caso base: día laboral)			
	Día no laboral	0.587	0.235	0.013
	Ambos	0.466	0.202	0.021
	Principal actividad llevada a cabo en Madrid Central			
	Compras	-0.503	0.187	0.007
ELECCIÓN MODAL EN MADRID CENTRAL	*Cambio modal (caso base: no)*			
	Sí	-0.567	0.184	0.002
	Vehículo privado solo antes de Madrid Central (caso base: no)			
	Sí	-0.394	0.200	0.049
	Vehículo privado acompañado antes de Madrid Central (caso base: no)			
	Sí	-0.306	0.201	0.128
	Bicicleta tras Madrid Central (caso base: no)			
	Sí	0.681	0.356	0.056
Cut1		-0.024	0.461	
Cut2		1.785	0.474	
Cut3		2.608	0.481	
Cut4		5.341	0.508	
No. obs.		799		
Log-Likelihood		-789.099		
Pseudo R^2		0.315		

Tabla 8 – Nivel de aceptabilidad de Madrid Central: resultados del modelo logit ordenado.

De acuerdo a los resultados del modelo, un pequeño número de variables sociodemográficas han resultado estadísticamente significativas en la explicación de la aceptabilidad pública de Madrid Central (ver Tabla 8). Los individuos que trabajan y estudian simultáneamente presentan una actitud más positiva hacia la ZBE. Los participantes que comparten vivienda también presentan una mayor aceptabilidad. Estos resultados están relacionados con el hecho de que las personas que forman parte de estos dos grupos son jóvenes (el 83,3% de los individuos que simultáneamente trabajan y estudian y el 90,8% de las personas que comparten piso son menores de 26 años), de bajos ingresos (el 70% de los individuos que trabajan y estudian simultáneamente y el 72,4% de los participantes que comparten un hogar tienen unos ingresos mensuales inferiores a 1300 €/mes), y menos dependientes del coche (el 68,6% de las personas que trabajan y estudian y el 86,2% de los individuos que comparten un hogar no utilizan un vehículo privado para acceder a Madrid Central) según los resultados de la encuesta. Por lo tanto, los modos de transporte colectivo son una buena opción para ellos, dadas las características de la red de transporte público de Madrid y el reducido precio de su abono transporte. Estos segmentos de población no parecen tener necesidad de un vehículo privado en casa, lo que supondría además un sobrecoste.

La ideología política y la conciencia medioambiental resultan cruciales para entender la aceptabilidad de Madrid Central por parte de los ciudadanos. La ideología política parece ser un factor muy importante para la aceptación de Madrid Central, siendo todas las categorías de esta variable estadísticamente significativas (valor p = 0,000). Los encuestados con una ideología política de izquierdas muestran una aceptabilidad mucho mayor en comparación con otras ideologías políticas, especialmente los partidarios de los grupos políticos de derechas. En particular, para los individuos que apoyan a los partidos de izquierda, la probabilidad de valorar muy positivamente Madrid Central es cuatro veces mayor en comparación con los individuos que apoyan otras ideologías políticas. Este resultado está alineado con estudios anteriores que correlacionan las políticas restrictivas de transporte implementadas por los gobiernos locales (Christiansen, 2018).

Cabe destacar que la implementación de Madrid Central fue una de las medidas más importantes adoptadas por un gobierno local formado por una coalición de partidos de izquierdas. La medida ha sido objeto de numerosos debates entre partidos políticos de diferentes ideologías sobre su eficacia e influencia en cuestiones económicas y sociales. Nuestros resultados muestran claramente que los participantes con ideología de izquierdas estaban muy a favor de estas medidas, mostrándose en línea con la coalición de izquierdas en el gobierno. No obstante, cabe mencionar que Madrid Central parece ser una medida bastante apoyada por los madrileños, ya que más del 65% de los encuestados declaran tener una opinión positiva o muy positiva hacia la ZBE.

De acuerdo con el objetivo de las ZBE, la conciencia medioambiental de los individuos se relaciona fuertemente con la aceptabilidad. Es lógico que las personas más preocupadas por los problemas medioambientales sean propensas a apoyar iniciativas como Madrid Central" Los encuestados con una conciencia medioambiental alta y muy alta apoyan la implementación de "Madrid Central" (p-valor = 0,008), a pesar de que la eficacia de esta medida en la mejora de la calidad del aire aún no se ha demostrado de forma sólida. Además, cabe destacar que la conciencia social y económica de los individuos no se encontró estadísticamente significativa en la determinación de la aceptabilidad hacia la ZBE, a pesar de los impactos que pueda generar Madrid Central en la sociedad y la economía.

Los atributos relacionados con el viaje también influyen en el nivel de aceptabilidad de la población. La posesión de abono de transporte público o la posesión de una motocicleta privada están relacionadas con una mayor aceptabilidad de Madrid Central (p-valores = 0,023 y 0,003, respectivamente). Los propietarios del abono de transporte público de la muestra son usuarios que realizan una media de más de cuatro viajes al día. No es de esperar que se vean muy afectados por las restricciones del coche para acceder a Madrid Central, donde la accesibilidad y la oferta de transporte público son muy elevadas.

Como se ha demostrado anteriormente, las motocicletas han sufrido menos restricciones que los coches para entrar en Madrid Central, por lo que pueden verse favorecidas en el nuevo escenario de circulación. Esta razón probablemente lleva a tener una actitud más favorable hacia las políticas de movilidad basadas en las restricciones a los coches.

Sorprendentemente, los usuarios frecuentes de los servicios de movilidad compartida muestran un menor grado de aceptabilidad (p-valor = 0,009) en comparación con los usuarios ocasionales de estos servicios. Los usuarios frecuentes pueden temer que Madrid Central aumente el uso general de los servicios de movilidad compartida (por ejemplo, atrayendo a nuevos usuarios), reduciendo así su disponibilidad en el futuro.

Las variables de este grupo tienen un papel importante en la explicación de la aceptabilidad pública hacia Madrid Central. En primer lugar, el nivel de aceptabilidad está directamente relacionado con el impacto positivo o negativo de esta política en los desplazamientos realizados por los encuestados. Razonablemente, los participantes que han mantenido o mejorado su experiencia de viaje muestran una mayor aceptabilidad (valor p = 0,000) que aquellos que la han empeorado. Estos resultados son similares a los de otras políticas de transporte restrictivas, que han recibido valoraciones más bajas por parte de los usuarios perjudicados (Gaunt, 2007). Además, los ciudadanos que han aumentado sus rutinas diarias de caminar dentro de la ZBE también muestran una mayor aceptabilidad hacia "Madrid Central" (p-valor = 0,000). Este efecto se debe probablemente a que las políticas de restricción del uso del coche implican el desarrollo de ciudades más amables y transitables.

Los encuestados que aumentaron o mantuvieron sus actividades comerciales y de ocio en la zona tras la implementación de Madrid Central son más favorables a la ZBE, en comparación con los que redujeron sus niveles de actividad. En cuanto a los patrones de movilidad, los ciudadanos que viajan ocasionalmente a Madrid Central (como máximo dos veces a la semana o durante los fines de semana) muestran un mayor nivel de aceptabilidad. Sin embargo, los individuos cuya actividad principal dentro de la ZBE es ir de compras presentan una menor aceptabilidad, tal vez como consecuencia del impacto negativo que pueden tener las restricciones a los vehículos privados para cargar bolsas pesadas.

Los participantes que cambiaron su modo de transporte tras la implementación de Madrid Central presentan una aceptabilidad más negativa que aquellos que no lo hicieron. Por último, en cuanto al modo de transporte más utilizado antes y después de la implantación de Madrid Central, los ciudadanos que utilizaban su vehículo privado antes y después de la implementación de la ZBE muestran una menor aceptabilidad, mientras que los ciudadanos que se desplazan en bicicleta después de la adopción de Madrid Central tienen actitudes más favorables. Este resultado demuestra que Madrid Central ha sido eficaz para crear un mejor entorno para el uso de los modos activos.

6.2 Resultados descriptivos sobre el cambio modal tras la implementación de Madrid Central

Se observa un cambio relevante hacia patrones de movilidad sostenible tras la implementación de Madrid Central (Figura 1). La mitad de los encuestados (49,9%) ha declarado haber cambiado su modo de transporte habitual para acceder a Madrid Central tras la adopción de la medida.

En cuanto a la elección modal, hay que recordar que los encuestados podían seleccionar sus dos modos de transporte más frecuentes para llegar a Madrid Central. Así, los datos obtenidos indican la cuota modal captada por cada uno de los modos de transporte en relación con el número total de viajeros. Los resultados descriptivos indican un notable descenso en el uso del vehículo privado (-28,5% del total de encuestados), lo que significa que el 60% de los antiguos usuarios del coche han cambiado su modo de transporte habitual. Estos viajeros han cambiado principalmente a modos de transporte alternativos.

En particular, el transporte público y los modos activos son los modos de transporte más beneficiados por la implantación de Madrid Central. El transporte público aumentó su cuota modal del 66,7% al 75,6%. Del mismo modo, los modos activos (viajar a pie y/o en bicicleta) aumentaron del 16,8% al 25,0%. Los modos de transporte minoritarios, como los servicios de movilidad compartida, han duplicado sus usuarios la ZBE. Los servicios de taxi y VTC han aumentado su cuota del 4,0% al 8,3%, mientras que el uso de las opciones de movilidad compartida (carsharing, scooter sharing, etc.) creció del 3,8% al 8,4%.

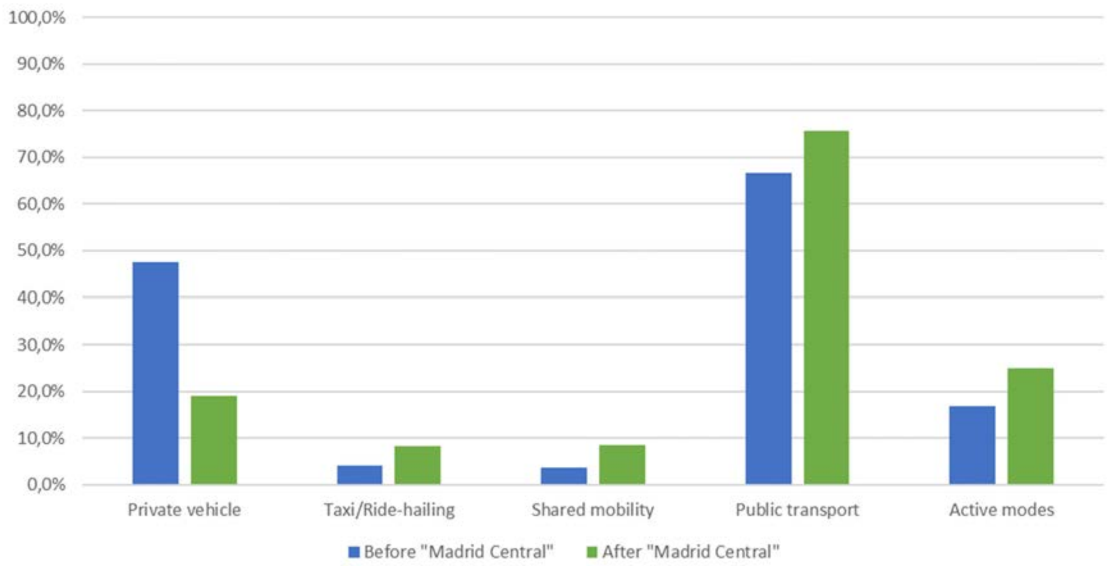

Fig. 1 – Elección modal antes y después de Madrid Central

6.3 Análisis del cambio modal en Madrid Central

Esta sección presenta los resultados del modelo dedicado a la exploración del cambio (o no) de elección modal para acceder a Madrid Central después de aplicar la ZBE. Para ello, se ha desarrollado un modelo logit binario (Tabla 9) que indica, desde un punto de vista estadístico (p-valor < 0,05), las variables que influencian dicha elección. Un signo positivo indica una mayor probabilidad de haber experimentado un cambio modal, mientras que un signo negativo indica una mayor probabilidad de haber mantenido su patrón de viaje.

Bloques	Variables explicativas	Coef.	Std. Error	p-valor
SOCIOECONÓMICAS Y DEMOGRÁFICAS	*Sector de empleo*			
	Sector primario e industria	-0.578	0.339	0.088
	Comercio y hostelería	-0.722	0.333	0.030
	Transporte y logística	-0.774	0.360	0.032
ACTITUDES PERSONALES	*Concienciación social*	-2.114	1.069	0.048
	Concienciación social (2)	0.520	0.256	0.043
VARIABLES RELACIONADAS CON EL VIAJE	*Disponibilidad de coche propio*	0.726	0.272	0.008
PERCEPCIONES Y HÁBITOS DE MOVILIDAD RELACIONADOS CON MADRID CENTRAL	*Impacto de Madrid Central en los viajes habituales (caso base: muy negativo y negativo)*			
	Neutral	-1.877	0.279	0.000
	Positivo	-1.965	0.379	0.000
	Muy positivo	-2.808	0.460	0.000
	Evaluación peatonal de Madrid Central	-0.550	0.109	0.000
	Tiempo caminando en Madrid Central (caso base: reducción y mantenimiento)			
	Incremento	1.110	0.238	0.000
	Frecuencia de viaje a Madrid Central			
	>1/mes y <2/semana	0.422	0.211	0.045
	Principal actividad llevada a cabo en Madrid Central			
	Compras	-0.435	0.243	0.073
ELECCIÓN MODAL EN MADRID CENTRAL	*Vehículo privado antes de Madrid Central*	1.604	0.234	0.000
	Vehículo privado después de Madrid Central	-1.348	0.284	0.000
	Movilidad compartida después de Madrid Central	0.931	0.350	0.008
	Constante	3.739	1.106	0.001
	No. Obs	799		
	Log-Likelihood	-339.757		

Tabla 9 – Cambio modal ocasionado por Madrid Central: resultados del modelo logit binario.

El sector de empleo parece ser la única variable sociodemográfica que influye en el cambio modal tras la implantación de Madrid Central. Hay dos sectores que muestran una influencia significativa (p-valor < 0,05): comercio y hostelería, y transporte y logística. Los individuos que trabajan en estos sectores tienen una menor probabilidad de cambiar su modo de transporte habitual para circular en Madrid Central. Una de las razones sería el uso del vehículo privado o de empresa como herramienta de trabajo con disponibilidad de garaje. En este sentido, cabe destacar que Madrid Central permite la entrada de vehículos siempre que aparquen en garajes privados.

En cuanto a las actitudes personales, la concienciación de los individuos sobre la sostenibilidad, recogida a través de una escala Likert de cinco puntos, es la única variable con un efecto estadísticamente significativo sobre el cambio modal.

Sorprendentemente, la conciencia medioambiental no es estadísticamente significativa para explicar el cambio modal.

En lo que respecta a las variables relacionadas con los viajes habituales, la disponibilidad de coches privados resulta crucial para explicar los cambios en la elección modal tras la implantación de Madrid Central. El principal cambio en la movilidad observado después de Madrid Central ha sido una disminución significativa del uso del coche. Otras variables relacionadas con el transporte, como la posesión de un abono de transporte público o el uso de modos de movilidad compartida, no resultan estadísticamente significativas en este modelo.

Por el contrario, los hábitos de movilidad de los individuos y las percepciones vinculadas a Madrid Central tienen un papel importante a la hora de explicar el cambio modal tras la adopción de la ZBE. En primer lugar, se observa que el impacto de Madrid Central en la movilidad diaria (viajes frecuentes) está inversamente relacionado con el cambio modal.

Razonablemente, las personas que no se han visto afectadas por las restricciones de Madrid Central o que incluso han visto mejoradas sus condiciones de acceso no han cambiado su modo de transporte, en comparación con aquellas personas cuyas opciones de movilidad se han visto limitadas. Además, la situación como peatón en Madrid Central presenta dos conclusiones diferentes. Por un lado, los encuestados que valoran positivamente la peatonalización de Madrid Central no han cambiado su modo de transporte, lo que puede deberse a que ya utilizaban modos de transporte sostenibles. Por otro lado, cabe destacar que los ciudadanos que han experimentado un cambio modal han aumentado su tiempo de paseo en Madrid Central.

Los individuos que viajan ocasionalmente a Madrid Central (más de 1 viaje/mes y menos de 2 viajes/semana) son más propensos a cambiar su modo de transporte habitual para llegar a la ZBE. Estos encuestados probablemente utilizaban el vehículo privado en estos desplazamientos antes de la implementación de Madrid Central, ya que no les resultaba familiar utilizar servicios como el transporte público o la movilidad compartida.

Los resultados del modelo también muestran que los encuestados cuya actividad principal en la zona es ir de compras son significativamente menos propensos a cambiar su modo de transporte. Esto puede estar relacionado con el uso del vehículo privado para facilitar la carga de bolsas.

Por último, es interesante analizar la influencia del modo de transporte utilizado antes de la implementación de Madrid Central en el cambio modal. Como se observa, los individuos que eran usuarios del vehículo privado antes de la ZBE son más propensos a cambiar su modo de transporte (valor $p = 0{,}000$).

En línea con lo comentado anteriormente, podemos concluir que, al menos en el caso de Madrid, el vehículo privado ha sido la opción de transporte más afectada por la implantación de la ZBE, provocando así tendencias positivas de movilidad más sostenible.

Por último, se observa que los individuos que utilizan modos de movilidad compartida tras la implantación de Madrid Central (por ejemplo, carsharing, ciclomotor compartido, etc.) son más propensos a haber cambiado su modo de transporte para desplazarse a Madrid Central. Este resultado puede indicar que los usuarios actuales de estos servicios proceden en su mayoría de otros modos de transporte debido a las restricciones establecidas por la ZBE.

6.4 Análisis del nivel de cambio modal experimentado por los usuarios de vehículo privado

Esta sección muestra los resultados del modelo logit ordenado que explora nivel de cambio modal de los conductores de vehículos privados tras la implantación de Madrid Central. Este modelo se centra exclusivamente en la submuestra de participantes que utilizaban su vehículo privado para acceder a la zona de Madrid Central antes de la implantación de la ZBE (380 encuestados). La tabla 10 resume cómo se codificó la variable dependiente y el número de participantes para cada categoría.

	N	%
Nivel de cambio modal de los antiguos usuarios de vehículo privado (comparados con la situación previa a Madrid Central)		
Incremento del uso de vehículo privado	7	1.8
Uso similar del vehículo privado	112	29.5
Reducción de uso del vehículo privado en favor del uso del taxi o VTC	32	8.4
Reducción de uso del vehículo privado en favor del uso de transporte público o modos activos	33	8.7
Abandono total del uso del vehículo privado	196	51.6

Tabla 10 – Caracterización de los antiguos usuarios de vehículo privado.

Dado que las variables explicativas utilizadas en el modelo eran en su mayoría categóricas, la interpretación de los resultados de la modelización requería la selección de un caso base. Esto nos permitió determinar si, para cada variable explicativa, las respuestas de los individuos eran estadísticamente significativas entre categorías en comparación con el caso base. Las categorías base elegidas pueden consultarse en la Tabla 11.

Un signo positivo en los resultados del modelo indica una mayor probabilidad de reducir el uso del vehículo privado en favor de otro modo de transporte para llegar a Madrid Central. Por el contrario, un signo negativo indica una probabilidad hacia el mantenimiento o el aumento del uso del vehículo privado para acceder a la zona de Madrid Central.

El modelo concluye que, desde un punto de vista estadístico (valor $p < 0,05$), el cambio modal de los antiguos usuarios del vehículo privado (personas que utilizaban el coche antes de la implantación de Madrid Central) está notablemente influenciado por una amplia gama de variables explicativas incluidas en la encuesta.

Bloques	Variables explicativas	Coef.	Std. Error	p-valor
SOCIOECONÓMICAS Y DEMOGRÁFICAS	*Edad (caso base: mayor de 35 años)*			
	Menor de 25	-1.024	0.561	0.068
	26-34	-0.331	0.361	0.360
	Género (caso base: mujer)			
	Hombre	0.430	0.231	0.063
	Nivel de estudios (caso base: no universitario)			
	Universitario	-0.550	0.257	0.032
	Estructura del hogar (caso base: familia con niños mayores de 10 años)			
	Vivo solo	-0.685	0.444	0.123
	Vivo con mis padres	0.396	0.558	0.475
	Comparto piso	0.262	0.637	0.681
	Pareja sin hijos	-0.339	0.377	0.369
	Familia con hijos menores de 10 años, ancianos y/o personas discapacitadas	-0.875	0.335	0.009
	Ingreso mensual (caso base: superior a 2.000€/mes)			
	Sin ingresos propios	0.853	0.590	0.148
	Menor de 1.300 €/mes	0.774	0.325	0.017
	1.300 – 2.000 €/mes	0.410	0.296	0.169
ACTITUDES PERSONALES	*Ideología política (caso base: centro)*			
	Izquierdas	0.097	0.320	0.762
	Derechas	0.796	0.345	0.021
	Ninguno	1.031	0.302	0.001
VARIABLES RELACIONADAS CON EL VIAJE	*Disponibilidad de abono transporte público*			
	Sí	0.451	0.245	0.065
	Uso de servicios de transporte público (caso base: muy bajo o bajo)			
	Medio, alto o muy alto	0.938	0.269	0.000
PERCEPCIONES Y HÁBITOS DE MOVILIDAD RELACIONADAS CON MADRID CENTRAL	*Impacto de Madrid Central en los viajes habituales (caso base: neutro)*			
	Muy negativo	0.057	0.336	0.866
	Negativo	0.648	0.307	0.035
	Positivo	-0.185	0.469	0.694
	Muy positivo	0.643	0.554	0.246
	Tiempo caminando en Madrid Central (caso base: reducción o mantenimiento)			
	Incremento	0.479	0.265	0.070
	Tipo de día de viaje a Madrid Central (caso base: laboral o ambos)			
	No laboral	1.394	0.323	0.000
	Principal actividad llevada a cabo en Madrid Central			
	Compras	-0.945	0.324	0.004
ELECCIÓN MODAL EN MADRID CENTRAL	*Factores que influencian la elección modal*			
	Coste	0.482	0.261	0.065
	Tiempo	-0.822	0.240	0.001
	Comodidad	-0.388	0.234	0.097
	Carga	-1.270	0.243	0.000
Cut1		-5.007	0.697	
Cut2		-1.300	0.571	
Cut3		-0.806	0.569	
Cut4		-0.316	0.568	
No. obs		380		
Log-Likelihood		-382.670		
Pseudo R^2		0.158		

Tabla 11 – Nivel de cambio modal de los antiguos usuarios de vehículo privado: resultados del modelo logit ordenado.

El modelo muestra que las características sociodemográficas juegan un papel importante para entender el cambio modal de los usuarios de vehículo privado. En primer lugar, se observa cómo la edad está cerca de ser estadísticamente significativa (p-valor = 0,068), lo que indica que los menores de 26 años son más persistentes en el uso del vehículo privado tras la implementación de Madrid Central. Tanto el género como el nivel de estudios son estadísticamente significativos a la hora de explicar el abandono del vehículo privado. Los hombres muestran una mayor tendencia que las mujeres (p-valor = 0,063) a reducir y dejar el vehículo privado para ir a Madrid Central. Además, los encuestados con estudios universitarios son más propensos a seguir utilizando el coche para llegar a la ZBE (p-valor = 0,032).

La composición del hogar es otra variable crucial que determina el cambio modal de los antiguos usuarios de vehículos privados. Las familias con personas dependientes (por ejemplo, niños menores de 10 años, personas mayores y discapacitadas, etc.) son más propensas a seguir utilizando sus vehículos privados para acceder a Madrid Central que las familias con niños mayores de 10 años. Esta situación puede asociarse a la necesidad de este tipo de familias de realizar desplazamientos puerta a puerta.

Los resultados del modelo también indican que el nivel de ingresos desempeña un papel importante para explicar el cambio modal de los usuarios de coche. Los individuos con ingresos mensuales inferiores a 1.300 euros son más propensos a reducir el uso del coche privado (p-valor = 0,017) en comparación con la categoría de referencia base (individuos con ingresos superiores a 2.000 euros/mes). Así pues, la población con niveles de ingresos elevados se muestra más reticente a dejar y sustituir sus coches para llegar a Madrid Central, ya que pueden permitirse tarifas de aparcamiento privado dentro de la ZBE y/o comprar un vehículo menos contaminante.

En cuanto a las actitudes personales, la ideología política parece ser estadísticamente significativa para explicar el cambio modal de los usuarios de vehículos privados tras la implantación de "Madrid Centra. Sorprendentemente, los modelos muestran que las personas de derechas y las personas que no revelaron su ideología política son más propensos a reducir y dejar de usar los coches para llegar a Madrid Central en comparación con las personas de centro, mientras que el resultado para las personas con ideología de izquierdas no es estadísticamente significativo.

Este hallazgo, similar al obtenido anteriormente por Tertoolen et al. (1997), parece contradictorio con las ideologías tradicionalmente asociadas a una mayor conciencia medioambiental y social (por ejemplo, la de izquierdas). Esto refuerza el argumento de que las razones personales tienen mucha más relevancia que la ideología para promover el cambio modal.

Asimismo, la posesión del abono de transporte público y hacer un uso intensivo de los sistemas de transporte público son variables estadísticamente significativas para explicar el abandono y la disminución del uso del vehículo privado. Este resultado está fuertemente alineado con el objetivo de las ZBE. El uso del transporte público en general facilita el abandono del coche. Otras variables relativas a los hábitos de movilidad y las percepciones relacionadas con Madrid Central resultaron estadísticamente significativas en el modelo.

En primer lugar, el impacto general de Madrid Central en los viajes regulares de los individuos tiene un efecto significativo en la elección modal actual de los usuarios del coche. Como se esperaba, las personas que perciben que Madrid Central les afectó negativamente tienen más probabilidades de haber reducido el uso del coche. Del mismo modo, los individuos que aumentan el tiempo dedicado a caminar dentro de Madrid Central después de su implantación tienen más probabilidades de haber abandonado y reducido el uso del vehículo privado para llegar a la ZBE.

El tipo de día en que los individuos viajan a Madrid Central también es estadísticamente significativo. Los individuos que acceden a la ZBE en días no laborales son más propensos (p-valor = 0,000) a abandonar o reducir el uso del vehículo privado. Esto puede explicarse por el hecho de que esas personas encuentran una mayor flexibilidad en la organización de sus viajes que las personas que llegan a Madrid Central en días laborales. Esta conclusión subraya la conveniencia para algunos ciudadanos de utilizar el vehículo privado para ahorrar tiempo en la vida cotidiana. Las iniciativas en materia de política de transportes deberían esforzarse por encontrar opciones sustitutivas del coche en términos de ahorro de tiempo en los desplazamientos. La actividad principal realizada en Madrid Central también está fuertemente relacionada con la elección de los individuos de utilizar (o no) vehículos privados tras la implantación de la ZBE. Los encuestados que declararon que su actividad principal era ir de compras presentan una mayor tendencia (p-valor = 0,004) a seguir utilizando sus vehículos privados. Esto está probablemente relacionado con el hecho de que el uso de vehículos privados facilita la carga de bolsas, como se ha comentado con anterioridad.

Por último, se estudia la influencia de los factores clave de los individuos (como el coste, el tiempo, la comodidad, etc.) para seleccionar su modo de transporte habitual. Como parece razonable, las personas con alta sensibilidad al coste del viaje son más propensas a reducir o abandonar el uso de su coche privado para llegar a Madrid Central.

Esto puede deberse a que llegar a Madrid Central en coche implica pagar un garaje privado, que es muy caro en la zona, mientras que el transporte público es asequible. Por otro lado, las personas sensibles al ahorro de tiempo, a la comodidad y muy preocupadas por la posibilidad de cargar peso son tienden a persistir en el uso de sus vehículos privados para llegar a Madrid Central. Estos tres factores están muy asociados a los atributos que suelen destacarse en os vehículos privados.

7. CONCLUSIONES

Este artículo aborda el necesario estudio sobre la aceptabilidad y el impacto en la elección modal del transporte consecuencia de la implementación de una ZBE. Tomando datos de una ZBE recientemente implementada en Madrid (llamada Madrid Central), se ha realizado un análisis de elección discreta para: i) determina los factores clave para explicar la aceptabilidad pública, ii) identificar los factores clave que explican el cambio modal después de implementar la medida, y iii) explorar los cambios en la elección modal entre los conductores de vehículos privados, lo cual es particularmente interesante dado que la reducción de vehículos privados es uno de los principales objetivos de las ZBE. Los resultados obtenidos pueden ser una plataforma interesante para que los responsables políticos consigan una mejor comprensión de las características de las personas que se sienten perjudicadas por las ZBE y determinar las variables clave para comprender mejor la elección modal y su efecto múltiple tras la aplicación de una ZBE. De esta manera, se pueden reorientar los impactos negativos y maximizar los beneficios sociales de las políticas de restricción de vehículos. Además, los resultados obtenidos podrían alimentar los procesos de planificación participativa, en los que se pueden seleccionar y comprometer diferentes perfiles de ciudadanos con respecto a la aceptabilidad de las ZBE (May e Isson, 2008; Whitmarsh et al., 2009; Soria-Lara et al., 2019)

Un hallazgo interesante es que la aceptabilidad de las ZBE en áreas urbanas, al menos en el caso de Madrid Central, está débilmente relacionada con aspectos socioeconómicos como el género, la edad, la educación o el nivel de ingresos. Por el contrario, la aceptabilidad se explica mucho mejor por la ideología política, la conciencia medioambiental y el impacto de las restricciones al uso del coche en los hábitos de movilidad individuales. En general, la aceptabilidad de Madrid Central es bastante positiva entre los madrileños, dada su alta conciencia medioambiental (77,1% de la muestra). Estos resultados están en consonancia con los obtenidos por Oltra et al. (2021) en el contexto de Barcelona, donde las personas con una alta conciencia medioambiental mostraron un mayor nivel de aceptación de las políticas de restricción del uso del coche. La fuerte relación entre ideología política y aceptabilidad es razonable, ya que la implementación de Madrid Central ha estado en el punto caliente del debate político en la región durante 2018, generando confrontación entre los partidos políticos.

En este sentido, aunque no se puede evitar cierta influencia política, las autoridades públicas deberían trabajar para ofrecer una mejor información a la comunidad basada en estudios de investigación cuantitativos que demuestren su impacto en aspectos como la contaminación atmosférica, el cambio modal y los impactos económicos y sociales. Eso contribuirá a que la gente obtenga un juicio objetivo, en lugar de pensamientos basados en la alineación ideológica con los partidos políticos.

Un resultado relevante es que la aceptabilidad de Madrid Central se asocia en gran medida con el impacto que esta política tiene en los hábitos de los individuos, especialmente en lo que se refiere al comportamiento de los viajes en movilidad. Los ciudadanos que han mejorado la calidad de sus viajes muestran una mayor aceptabilidad hacia Madrid Central. Los usuarios frecuentes del transporte público, los motociclistas y los usuarios ocasionales de servicios de movilidad compartida están a favor de Madrid Central, probablemente porque la medida les beneficia o al menos no les perjudica. Además, Madrid Central es más apoyado por aquellas personas que aprovecharon la medida para desarrollar una actividad comercial y de ocio más intensa, para disfrutar de los paseos a pie, o para empezar a ir en bicicleta hacia o dentro de la ZBE.

Sin embargo, Madrid Central es menos apoyado por las personas influenciadas negativamente por la ZBE. Los encuestados que se vieron obligados a cambiar su modo habitual para llegar a Madrid Central, especialmente las personas que utilizaban el vehículo privado, se oponen a las restricciones de automóviles. Este es un tema controvertido en la planificación del transporte, donde estudios anteriores (Szarata et al., (2017)) subrayan el rechazo inicial de los usuarios de automóviles y de los grupos locales a políticas similares que restringen el acceso en coche. Madrid Central tampoco es apoyado por las personas que van a comprar, probablemente porque el coche es la forma más cómoda para ellos de llevar bolsas pesadas. Finalmente, los usuarios frecuentes de servicios de movilidad compartida no están muy a favor de Madrid Central, probablemente porque pueden acabar experimentando una mayor competencia para alquilar estos servicios en la zona.

Para mejorar la aceptabilidad sin comprometer los estándares de sostenibilidad, las autoridades locales deberían centrarse en promover esquemas políticos que minimicen los impactos negativos sobre aquellos que se sienten perjudicados por las ZBE. En la encuesta, los autores del trabajo dejaron un texto libre a los encuestados para que sugirieran acciones que pudieran mejorar o complementar las políticas de restricción de coches dentro de Madrid Central. Una gran parte de los encuestados sugirió aumentar la frecuencia de los servicios de transporte público en la zona, proporcionar apoyo financiero a la renovación del parque de vehículos y promover enfoques de movilidad compartida. Ofrecer soluciones dentro de un marco sostenible puede contribuir, sin duda, a mejorar la aceptación de ciertos grupos de población.

En cuanto a la influencia sobre los patrones de movilidad, parece evidente el notable poder de Madrid Central para provocar cambios en la elección modal hacia medios más sostenibles. Según las respuestas de la encuesta, se produjo una reducción importante del uso del coche (-28,5% del total de encuestados), así como un aumento del uso del transporte público (+8,9%) y de los modos activos (+8,2%). Adicionalmente, cabe destacar el notable crecimiento observado en los servicios de transporte colectivo (+4,3%) y en las opciones de movilidad compartida (+4,6%) para desplazarse a Madrid Central.

Para ello será necesario aumentar la frecuencia y disponibilidad de los servicios de transporte público, así como la cantidad de puntos de recarga eléctrica.

Otro conjunto de conclusiones relevantes se refiere al cambio modal después de la ZBE, que se asocia en gran medida con las percepciones de los individuos y los hábitos de movilidad relacionados con Madrid Central. Por ejemplo, la frecuencia de los viajes y el tipo de actividad que suelen realizar los encuestados dentro de Madrid Central influyen enormemente en el cambio modal. Las personas que viajan a Madrid Central menos de dos veces por semana y más de una vez al mes son más propensas a cambiar de modo para acceder a la ZBE, mientras que los individuos cuya actividad principal realizada en Madrid Central es ir de compras son significativamente menos propensos a cambiar su modo de transporte. Esto revela un punto interesante para la elaboración de políticas: los viajeros no frecuentes son más propensos a cambiar su modo de transporte. Sin embargo, la zona tiene muchos viajes regulares ya que Madrid Central tiene una importante concentración de puestos de trabajo que obliga a muchas personas a desplazarse diariamente. Un problema similar se observa en los viajes de compras, ya que el comercio minorista es una de las principales actividades económicas dentro de Madrid Central. Las políticas futuras deberían explorar medios para contribuir a mejorar la accesibilidad de esas personas a Madrid Central en modos sostenibles sin comprometer el potencial comercial y laboral de la zona.

Un último nivel de conclusiones se centra en el impacto de Madrid Central en el cambio modal entre los usuarios de automóviles. Los encuestados con ingresos mensuales bajos (<1.300€/mes) tienden a dejar o reducir el uso de su vehículo privado más que las personas con ingresos altos.

Sin embargo, las familias con familiares dependientes (niños, ancianos y discapacitados) siguen utilizando su vehículo privado, dadas sus limitaciones de movilidad. Esta situación podría comprometer el carácter inclusivo y los efectos sociales de Madrid Central, ya que los ciudadanos con altos ingresos que se desplazan en su vehículo privado pueden permitirse aparcar en garajes y es más posible que puedan comprarse vehículos de menores emisiones.

Además, los factores clave para las opciones de movilidad de los individuos (como el coste, el tiempo, la comodidad, etc.) resultan ser cruciales para explicar el cambio modal. Es particularmente notable cómo las personas que se desplazan para hacer compras tienden a seguir eligiendo sus vehículos privados a pesar de la aplicación de la ZBE. En este sentido, el documento muestra que las razones personales parecen ser más importantes para la elección modal que la ideología o la concienciación. Este resultado se ve corroborado por el primer modelo, en el que variables como la conciencia medioambiental no tienen una influencia significativa.

Los resultados son especialmente útiles para el diseño de futuras estrategias políticas para la aplicación y el funcionamiento de las ZBE, de acuerdo con los objetivos ambientales, económicos y sociales. Se pueden señalar algunos aspectos para una mayor investigación.

Las futuras contribuciones deberían profundizar en múltiples aspectos derivados de la implantación de una ZBE: la optimización de los sistemas de transporte público para que se conviertan en una alternativa real a los vehículos privados en la zona afectada, las desigualdades sociales generadas por las ZBE, los efectos de dichas ZBE sobre el comercio minorista y otras actividades relevantes situadas en el centro de la ciudad, etc.

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ATTITUDES TOWARDS THE ENVIRONMENT RELATED TO TRAVEL AND PERSONAL MOBILITY

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ABSTRACT

The objective of this paper is to study the relationship between personal mobility and attitudes towards the environment related to travel behavior considering sociodemographic characteristics.

The dataset used for this study was collected through a web-based survey carried out in Valencia (Spain) during 2017 and 1684 valid responses were obtained. In this research a subpart of the survey is used, including 5 items which measure attitudes towards the environment related to travel and 5 items to measure personal mobility. The items were measured using a 5 points Likert Scale. Additionally, individual and household demographic characteristics are considered.

The methodology of this research consist on descriptive analysis and frequency distributions. Factor Analysis (Exploratory and Confirmatory) is used to construct the latent variables which measure attitudes and Mann-Whitney U is test are assessed to find significant differences among the variables of the study.

Preliminary results show that environmental concerns are taken into account by women as a factor to decrease their car use, while men do not consider this factor that relevant. Next, young people and men carry our more activities while traveling in public transport, for instance: reading, listening to music or checking social networks. The results of this research are useful for the development of transport policies to promote sustainable transport.

1. INTRODUCTION

This research is part of a wider project, called MINERVA, which is funded by the I+D+i National Program of Society Challenges of the Spanish Ministry of Economy and Finance of Spain). The aim of MINERVA is to study the influence of personal values, attitudes and perceptions and social interactions on travel behavior.

This paper aims to study attitudes towards personal mobility and attitudes towards the environment related to travel considering sociodemographic characteristics.

1.1. Explicative factors of travel behavior

The prediction of individual's travel behavior is an essential component of transportation planning and policy analysis. The ultimate mission of travel demand forecasting research is to develop the capability to predict how individuals respond to changes in their travel environment (Kitamura, 1988). Such predictions are based on a set of factors that influence travel behavior. For this reason it is relevant to identify and characterize such factors.

Among the factors that influence travel behavior, one of the main objectives of the Minerva Project is to collect information regarding attitudes towards the environment and attitudes towards personal mobility.

The displacement of people towards their usual places generates a demand for modes of transport, which are largely related to certain factors that make the individual decide one or another type of transport. In this line, people's attitudes are strongly influenced for beliefs as well as individual travel behaviors. A person's intention is a function of two basic determinants; one personal in nature and the other reflecting social influence (Ajzen, 1991).

Travel behavior research has long recognized the role of attitudes and preferences in influencing mobility. Even though attitudes are often included as control variables for self-selection, many studies have concluded that they play a significant role in influencing travel behavior (Hunecke et al., 2010; Bopp et al., 2011; Spears et al., 2013; Runing Ye et al, 2017). The measurement of attitudes is carried out using scales that involve the application of standardized questionnaires to enable individuals to be placed on a dimension indicating degree of favorability towards the object in question.

This research contributes to gain more knowledge about these factors taking into account also demographic and socioeconomic characteristics.

2. OBJETIVE AND RESEARCH QUESTIONS

2.1 Objective

The aim of this paper is to study the relationship between personal mobility and attitudes towards the environment related to travel behavior considering sociodemographic characteristics.

2.2 Research questions

Main research questions are presented below:

- To what extent personal mobility and attitudes towards the environment can contribute to travel behavior analyses and how to measure these variables.
- How demographic factors and socio economic characteristics might influence personal mobility.
- How demographic factors and socio economic characteristics might influence attitudes towards the environment.

3. DATA COLLECTION

3.1 Instrument design and recruitment

The dataset used for this research is part of the data collection developed for MINERVA research. For this project, a web based survey was developed ad-hoc to gather information regarding attitudes and perceptions, personal values, social interactions and travel behavior. In this study, a subpart of this survey is used (Arroyo et al, 2017).

The web-based survey was distributed mainly online and several organizations, public administration and companies contributed with the dissemination of the survey. Data collection took place between May and October 2017, excluding August in order to avoid non-recurrent mobility and long-distance trips executed during summer holidays. The main area of the study was Valencia (Spain) and its metropolitan area, although different residential locations were also accepted.

The survey is composed by 5 parts. Firstly, a brief questionnaire gathers information about demographics and socio-economic characteristics (both at personal and household level), as well as transport accessibility and built environment attributes of the residence area. Secondly, a two-day activity-travel diary collects all the activities and trips performed during a week day and a week-end day, including characteristics of the companions of each episode. Next section collects information regarding social interactions, for this purpose the list of the companions already defined is displayed and a brief questionnaire of each person should be complimented, including: gender, age, type of relationship, closeness degree, approximate residential location distance from the respondent, frequency of face to face meetings, frequency of communication and degree of influence of the companion in the respondent’s mobility. The fourth part is the Values survey, based on Schwartz theory of human values (Schwartz, 1994).

The last step consists on a survey regarding cognitive, affective and behavioral attitudes towards transport modes, attitudes towards innovative travel modes, use of ICTs and personal mobility and perceptions of the built environment. Additionally, the on-line questionnaire collects intentions to use travel modes; semantic differential towards travel modes, which measures mental representations of travel modes through certain adjectives.

Further details of the questionnaires analyzed in this paper are provided later, including individual items and constructs to measure attitudes towards the environment and personal mobility.

3.2 Sample characteristics

After data cleaning and validation, the sample is composed by 1684 individuals (Table 1). The distribution according to gender reasonably balanced. However, considering age, those over 50 years old are under-represented in the sample. Participants are mainly employed individuals, followed by students and other occupations are including in "other", for instance retired and unemployed people.

	Respondents	Percentage
GENDER		
Male	774	46 %
Female	910	54 %
AGE		
16-25	471	28 %
26-35	385	23 %
36-50	522	31 %
>50	306	18 %
OCCUPATION		
Student	398	23 %
Employed	1022	61 %
Other	264	16 %

Table 1 – Sample characteristics

4. METHODOLOGY AND ANALYSIS

4.1 Variables: description and measurement

- Demographic and socio-economic characteristics

Several demographic and socio-economic characteristics were considered both at individual and house hold level (Table 2).

- Attitudes towards the environment and personal mobility

Three latent constructs were developed in order to measure attitudes towards the environment and personal mobility. Details and validation are described in the next section.

DEMOGRAPHICS		
Gender	0 = male; 1 = female	Categorical
Age	Age of the respondent	Continuous
Transport Pass	1 = respondent has an integrated public transport pass; 0 = otherwise	Categorical
Car	Bike availability (0 = low to 5 = high)	Continuous
Bike	Car availability (0 = low to 5 = high)	Continuous
Motorbike	Motorbike availability (0 = low to 5 = high)	Continuous
Bikes in HH	Number of bikes available in the household	Continuous
Cars in HH	Number of cars available in the household	Continuous
Marital status	1 = single; 2 = married; 3 = civil partner; 4 = couple; 5 = widow; 6 = divorced; 7 = others	Categorical
Education level	1 = no studies; 2 = primary level; 3 = vocational training ; 4 = secondary level; 5-6 = higher education; 7 = university degree or higher	Categorical
Occupation	1 = student; 2 = employed; 3 = self-employed; 4 = student and employed; 5 = unemployed; 6 = retired; 7 = housekeeper; 8 = others	Categorical
Income (net monthly)	1 = any income; 2 = less thant 500€; 3 = 500-1000€; 4 = 1000-1500€; 5 = 1500-2000€; 6 = 2000-2500€; 7 = 2500 - 3000; 8 = more than 3000	Categorical

Table 2 – Definition of variables

4.2 Scale reliability and validity of constructs

Attitudes towards environment and self-mobility were measured using 10 item (5 items for each type of attitude):

<u>Attitudes towards the environment</u>

- Item 130. I try to use less the car to improve air quality.
- Item 131. If I had to buy a car, or replace the current one, I would choose a more energy efficient one, even if it was smaller or more expensive.
- Item 132. We should increase the price of fuel to invest in improving public transport.
- Item 133. I support restricting the use of the car in the city to reduce congestion.
- Item 134. In my city, air quality is a major problem.

<u>Attitudes towards personal mobility</u>

- Item 135. I usually make arrangements online or by phone to avoid trips.
- Item 136. When I need to buy something, I prefer to go to the nearest shop as possible.
- Item 137. When I travel, I usually do other activities (reading, listening to music, checking social networks online, etc.)
- Item 138. I try to walk or cycle as much as possible and only use a motor vehicle for long distances.

- Item 140. I plan my trips and choose the mode of transport considering my daily schedule of activities.

Firstly, descriptive analysis were carried out and basic statistics and measures of normality, symmetry and kurtosis were obtained. Some of the items presented slightly signs of asymmetry and non-normality, which lead us to select robust estimators for Confirmatory Factor Analysis.

Cronbach’s alpha was used to measure internal consistency which indicates how closely related a set of items are as a group. It was observed that item 130 did not show a strong correlation with the construct and it was deleted. The obtained measures (attitudes towards the environment = 0.751; attitudes towards personal mobility = 0.713) point out an adequate value for Cronbach’s alpha for both latent constructs, thus, the scale reliability can be assumed.

The Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) is used to determine the proportion of variance in the variables that might be caused by underlying factors. High values are obtained (>0.9) which indicate that factor analysis technique may be appropriate with the data. Bartlett's Test of Sphericity tests the hypothesis that the correlation matrix is an identity matrix, which would indicate that variables are unrelated and therefore unsuitable for structure detection. Null value is obtained, which also supports the use of factor analysis with the data.

Pearson correlation matrix shows strong correlation among the items belonging to each construct, as it was expected.

4.3 Exploratory Factor Analysis (EFA)

In order to evaluate the scales and validate the latent variables generated, Exploratory Factor Analysis (EFA) was conducted based on the proposed theoretical constructs: attitudes towards the environment and attitudes towards personal mobility.

The results of EFA, using Varimax rotation and a factor loading of 0.40 as the threshold to maintain items in a factor, led to two independent factors as shown in Table 3.

Variable	Mean	SD	Median	Mode	EFA (Factor loading)
Attitudes towards the environment					
a131	3.72	1.280	4.00	5.00	0.553
a132	2.51	1.427	2.00	1.00	0.735
a133	3.02	1.303	3.00	3.00	0.629
a134	3.56	1.369	4.00	5.00	0.730
Attitudes towards personal mobility					
a135	3.79	1.334	4.00	5.00	0.712
a136	3.69	1.245	4.00	4.00	0.657
a137	3.76	1.297	4.00	5.00	0.629
a138	3.74	1.332	4.00	5.00	0.478
a140	3.90	1.274	4.00	5.00	0.688

Table 3 – Exploratory factor analysis

4.4 Confirmatory Factor Analysis (CFA)

Next, Confirmatory Factor Analysis (CFA) was conducted. Unlike EFA, in this method the posited relationships of the observed indicators to the latent variables are specified previously. The following goodness of fit indices were obtained: Chi square/df = 2701.721 (36), Comparative Fit Index (CFI) = 0.958, Tucker Lewis Index (TLI) = 0.935, Standarized Root Mean Square Residual (SRMR) = 0.035 and Root Mean Square Error Of Approximation (REMSEA) = 0.031. These statistics support the validity of the constructed scales. As shown in Table 4, all coefficients exceed 0.4, and most of them are higher than 0.5. It is confirmed that all statements are strongly correlated with the latent variables defined.

Variable	STDYX Standarized Loadings (S.E.)
Attitudes towards the environment	
a131	0.650 (0.023)
a132	0.673 (0.027)
a133	0.515 (0.023)
a134	0.500 (0.031)
Attitudes towards personal mobility	
a135	0.697 (0.020)
a136	0.408 (0.042)
a137	0.489 (0.038)
a138	0.479 (0.039)
a140	0.607 (0.029)

Table 4 – Confirmatory factor analysis

Results of Exploratory and Confirmatory Factor Analyses confirm the validity of the construct and reliability of the scales employed to measure the variables of the study.

This, it can be assumed that attitudes that the items developed to measure attitudes towards the environment and attitudes towards personal mobility can be used for this purpose after this validation process.

5. RESULTS

5.1 Frequency distributions

Firstly, frequency distributions are obtained for each item individually (Figure 1) in order to explore how participants perceive each factor in general, considering the entire sample of the study.

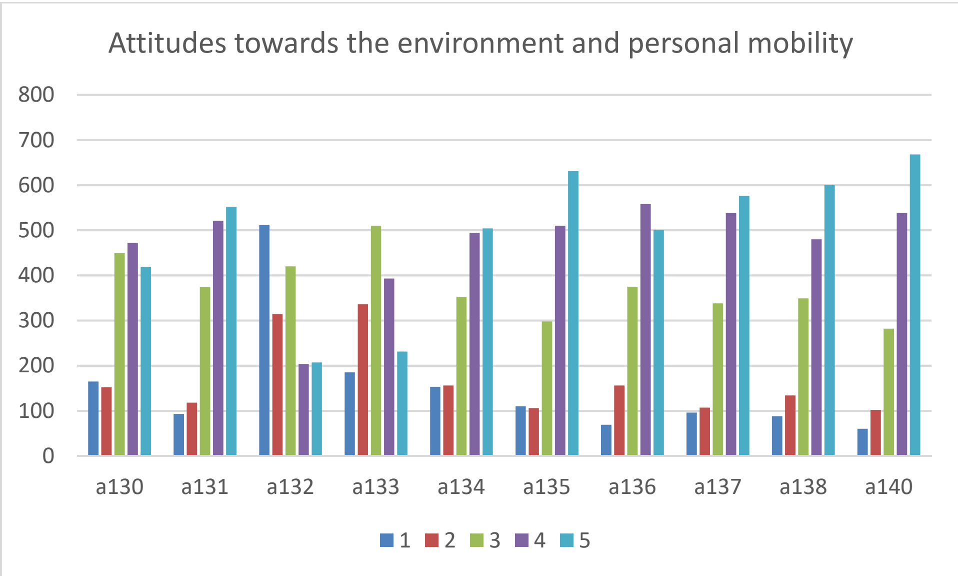

Figure 1. Attitudes towards the environment and personal mobility. Frequency Distribution.

In general, items which represent environmental concern issues related to travel (a130-a134) present lower scores that those regarding personal mobility. For instance an extended rejection to price increase of fuel is observed (item a132). The restriction of the use of private vehicle in order to reduce congestion seems controversial, with a relevant number of participant who support and who reject this measure simultaneously (a133). A higher amount of respondents reported their intention to choose a more energy efficient (a131) and a smaller part of the participants agreed with the intention to use less their cars to improve air quality.

Higher scores are observed for the items regarding personal mobility. In general, participants reported their willingness to avoid unnecessary trips which can be easily replaced with ITCs (a135), a high multitasking while traveling (a137), elevated preference for active transport for short distances (a138) and a high level of planning of their daily schedule when choosing their transport mode (a140). The item 136 was scored slightly lower, which represents the preference of buying as closest to home as possible.

5.2 Mann-Whitney test

The Mann-Whitney U test is a nonparametric test that allows two groups or conditions or treatments to be compared without making the assumption that values are normally distributed. The two independent samples are combined and ordered together, to notice if they mix randomly in the rank order or if they are grouped in opposite ends. In the first case it would indicate that the two samples are not different, while in the second it would indicate a difference between them.

In this research, Mann-Whitney U test is used to explore differences between attitudes towards the environment and attitudes towards personal mobility and sociodemographic characteristics.

The p-value chosen as a threshold to reject the null hypothesis that imply that both samples are equal in the population of the study was 0.005. Hence, p-value minor to 0.05 are taken into account. Two items related to attitudes towards the environment (a130 and a132) provided significant differences when gender is considered. Similar results were obtained for attitudes towards personal mobility, where other two items were found significant for gender (a137 and a140) (Table 5).

	Gender			
	U Mann-Whitney	W Wilcoxon	Z	p
a130	327447	625053	-2.313	0.021*
a131	347124	644730	-0.266	0.791
a132	327475.5	739253.5	-2.304	0.021*
a133	346235	758013	-0.354	0.723
a134	344477	756255	-0.540	0.589
a135	346559.5	644165.5	-0.327	0.744
a136	330770.5	628376.5	-1.984	0.047
a137	308381	605987	-4.352	0.000*
a138	338749.5	636355.5	-1.148	0.251
a140	315024	612630	-3.690	0.000*

Table 5 – Mann-Whitney U test. Gender

The items aforementioned which provided significant differences are considered now. Table 6 shows the percentage of frequency distribution of responses for each factor and score (1 to 5) considering gender. As it can be seen, women score higher than men in most of the responses (a130, a137 and a140). This means that women try to use less the car to improve air quality, usually do other activities while travelling (reading, listening to music, checking social media, etc.) and try to use active transportation as much as possible. It should be taken into account that women use more public transport and active modes than men in general in the area of the study. Contrary to that, men seem slightly less reactive than women to the increase of carburant prices to invest it on public transport improvements. However, in this case the general reaction to this measure is negative.

	1		2		3		4		5	
	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
a130	11%	9%	9%	9%	28%	26%	27%	29%	23%	27%
a132	30%	32%	17%	20%	25%	26%	12%	12%	16%	10%
a137	6%	5%	7%	6%	23%	18%	34%	31%	29%	40%
a140	4%	3%	8%	5%	19%	16%	33%	33%	36%	44%

Table 6 – Distribution of responses. Significant variables. Gender

In order to study how age is related to the variables of the study, percentiles of the sample were obtained. None of the items related to attitudes towards the environment provided significant differences among participants under 25 years and those over 47. Thus, no conclusions can be obtained according to age. On the other hand, three of the five factors which measure attitudes towards personal mobility (a135, a136 and a137) resulted significant when both age groups are taken into account (Table 7).

Age				
	U Mann-Whitney	W Wilcoxon	Z	p
a130	99487	212537	-0.875	0.382
a131	99967.5	193928.5	-0.758	0.449
a132	99398	193359	-0.896	0.370
a133	96518	190479	-1.643	0.100
a134	102667.5	215717.5	-0.044	0.965
a135	91427	204477	-3.002	0.003*
a136	94020	207070	-2.325	0.020*
a137	69718	163679	-8.755	0.000*
a138	102320	215370	-0.137	0.891
a140	99951	193912	-0.774	0.439

Table 7 – Mann-Whitney U test. Age

Following the same methodology as in the previous case, the next step consists in the analysis of responses distribution of the variables that provided significant differences. As it is shown in Table 8, respondents over 47 seem more inclined to make arrangements online/ by phone in order to avoid unnecessary trips (a135) and prefer to do the shopping as close to their home as possible. In this case the differences observed are smaller. On the other hand, a relevant contrast if found for item a137. Younger individuals of the sample (those under 25) seem more inclined to multitask during their trips. This could be related to a higher use of ICTs of those under 25 who use their phones for multiple purposes while traveling.

	1		2		3		4		5	
	AgeQ1	Age Q3	Age Q1	Age Q3	Age Q1	Age Q3	Age Q1	Age Q3	Age Q1	Age Q3
a135	9%	6%	10%	5%	22%	19%	28%	32%	32%	38%
a136	4%	3%	11%	9%	22%	20%	34%	35%	29%	34%
a137	2%	11%	4%	10%	14%	25%	31%	30%	49%	24%

Table 8 – Distribution of responses. Significant variables. Age

Similar results are obtained for different occupation status (Table 9). In this case, the differences between the variables of the study are assessed considering students and employed individuals. Although attitudes towards the environment did not provided significant differences, much more interesting results are obtained for attitudes towards personal mobility, with four significant factors: a135, a137, a138 and a140.

	Occupation			
	U Mann-Whitney	W Wilcoxon	Z	p
a130	177099.5	255309.5	-0.688	0.492
a131	177935	599756	-0.557	0.578
a132	172816	251026	-1.383	0.167
a133	173810	252020	-1.222	0.222
a134	179719	601540	-0.260	0.795
a135	155877.5	234087.5	-4.222	0.000*
a136	180235	258445	-0.176	0.860
a137	138018	559839	-7.188	0.000*
a138	167844	589665	-2.223	0.026*
a140	164422.5	586243.5	-2.823	0.005*

Table 9 – Mann-Whitney U test. Occupation

Next, the significant factors for occupation are explored (Table 10). Participants with employment reported a highest inclination to make arrangements online in order to avoid trips (a135). This could be explained by a better time management of those who work.

Next, students tend to multitask more that employees during their trips (a137) which is in line with previous results related to age. Last, students seem to plan their trips considering their daily schedule slightly more than employees. However, it should be taken into account that high scores are observed in the whole sample for this factor.

	Students	Employees	Students	Employees	Students	Employees	Students	Employees	Students	Employees
a135	11%	5%	10%	6%	19%	16%	26%	33%	34%	40%
a137	2%	6%	5%	7%	12%	23%	30%	36%	51%	29%
a138	5%	6%	9%	8%	16%	24%	30%	30%	41%	32%
a140	4%	3%	6%	6%	13%	19%	29%	36%	48%	36%

Table 10 – Distribution of responses. Significant variables. Occupation

6. CONCLUSIONS AND FUTURE RESEARCH

This research aims to study attitudes towards personal mobility and attitudes towards the environment. The latent variables constructed to evaluate these attitudes have been validated and the scale reliability is confirmed in this research. Thus, it can be assumed that the instrument developed to measure these factors is adequate and could be used in future research.

Results of this study reveal interesting conclusions which could be useful for policy making in order to promote sustainable travel modes. For instance, the increase of fuel price and restriction of private vehicle use are perceived as controversial measures by the participants of this research with divided opinions. On the other hand, respondents are inclined to avoid unnecessary trips which can be easily replaced with ITCs. Multitasking (reading, listening to music, checking social media, etc.) while traveling was also evaluated positively.

Considering gender, it was found that women try to use less the car to improve air quality, usually do other activities while travelling and try to use active transportation as much as possible. Taking into account that women use more public transport and active modes than men in general in the area of the study, more gender perspective studies are encouraged to better plan and design public transport systems as well as pedestrian and cyclist infrastructures.

Older respondents were more inclined to make arrangements online/ by phone in order to avoid unnecessary trips and prefer to do the shopping as close to their home as possible.

On the other hand, younger individuals prefer multitasking during their trips. The different use of ICTs for traveling should be considered for the promotion of sustainable travel.

Specific campaigns should be addressed to each cohort of the population. Additionally, special attention should be paid to design of public transport systems so as to facilitate multitasking, i.e. charging station for devices, wifi connection, comfortable spaces, etc.

Participants with employment reported a highest inclination to make arrangements online in order to avoid trips. Further cooperation among public administrations is still needed to enhance online services.

These results suggest interesting relationships between attitudes towards personal mobility and attitudes towards the environment. In order to confirm how this variables can explain travel behavior further analyses will be conducted based on Structural Equation Modelling.

Additionally, similar analyses will be assessed for the subsample of the survey which includes information about the activity and travel diary to include observed mobility.

Limitations of this study include sample size and underrepresentation of the older population cohort, which is a common limitation in web-based surveys. Additional attention should be paid in the future in order to enlarge participation of older respondents.

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INTERMODALIDAD EN LAS ESTACIONES DEL FUTURO

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RESUMEN

El presente artículo muestra los resultados de los estudios realizados en las estaciones de Cercanías situadas en los municipios de Jerez de la Frontera, Reus, Benalmádena y Dos Hermanas. En estos estudios se calcularon matrices de movilidad en las áreas de influencia de las estaciones, a partir de datos georreferenciados de telefonía móvil y se realizaron encuestas de preferencias declaradas y reveladas y aforos vehiculares que permitieron caracterizar la movilidad en la situación actual y estimar la demanda futura.

El presente artículo tiene como objetivo revisar el concepto de la intermodalidad dentro del modelo “movilidad como servicio” y analizar los factores que influyen, en este aspecto, en la demanda de estaciones de Cercanías.

Uno de los factores principales que afectan a la demanda de las estaciones es el tiempo de acceso y dispersión de éstas desde/hasta el origen o destino final del viaje. Cómo se resuelve esta etapa de viaje de “última milla”, tanto desde el punto de vista de la oferta como de la gestión público-privado son claves para aumentar la demanda de las estaciones en un contexto de liberalización de los servicios de cercanías sujetos a Obligaciones de Servicio Público (OSP) en 2027.

1. INTRODUCCIÓN

En el contexto actual, los servicios de cercanías de los núcleos están sujetos al Contrato entre la Administración General del Estado y la sociedad mercantil estatal Renfe Viajeros SME, S.A. para la prestación de los servicios públicos de transporte de viajeros por ferrocarril de cercanías, media distancia convencional, alta velocidad media distancia

(AVANT) y ancho métrico competencia de la Administración General del Estado, sujetos a Obligaciones de Servicio Público (OSP) en el periodo 2018-2027.

El contrato firmado entre la A.G.E y Renfe Viajeros determina el régimen de derechos y obligaciones al que queda sujeta Renfe como operadora de los servicios ferroviarios de los núcleos de cercanías de Asturias, Bilbao, Cádiz, Madrid, Málaga, Murcia, San Sebastián, Santander, Sevilla, Valencia y Zaragoza.

La trasposición al ordenamiento jurídico español del llamado “cuarto paquete ferroviario” de la Unión Europea, dibuja un escenario futuro que liberalizará los servicios de cercanías sujetos a OSP en 2027.

Este artículo revisa la movilidad de los servicios ferroviarios de cercanías de cuatro corredores y reflexiona sobre el papel de las estaciones de cercanías en el futuro próximo, alineado con la Estrategia de Movilidad Segura, Sostenible y Conectada (EMSSC) del MITMA. La visión de dicha Estrategia es la de “hacer de la movilidad un derecho, un elemento de cohesión social y de crecimiento económico”, en base a tres principios básicos, seguridad, sostenibilidad y conectividad.

2. SERVICIOS DE CERCANÍAS

El presente artículo muestra el análisis de la accesibilidad y movilidad global de las estaciones actuales de cercanías de Reus, Jerez de la Frontera, Dos Hermanas y Torremuelle (Benalmádena) pertenecientes a los núcleos de servicios ferroviarios de Tarragona, Cádiz, Sevilla y Málaga respectivamente. Los datos utilizados para el análisis de movilidad de las estaciones han sido obtenidos a partir de encuestas de preferencias reveladas (EPR) y encuestas de preferencias declaradas (EPD) a usuarios de las estaciones.

Por otro lado, el análisis de la movilidad global muestra las matrices calculadas en las áreas de influencia de las estaciones de los corredores estudiados; obtenidas mediante datos de telefonía móvil, encuestas y aforos realizados durante el año 2018.

En la siguiente tabla se muestran las estaciones en la que se ha estudiado la movilidad global, así como el núcleo y la línea de cercanías a la que pertenecen.

Estación de Cercanías	Reus	Jerez de la Frontera	Dos Hermanas	Torremuelle
Núcleo de Cercanías	Rodalies de Tarragona Rodalies de Catalunya	Cádiz	Sevilla	Málaga
Línea de Cercanías / Servicios de Media Distancia	RT-1 Tarragona-Reus R-14 Barcelona Estació de França-Lleida R- 5 Barcelona Estació de França-Reus-Riba-roja d´Ebre	C-1 Cádiz-Jerez de la Frontera-Aeropuerto de Jerez	C-1 Lebrija - Utrera - Santa Justa - Lora del Río	C -1 Málaga Centro - Fuengirola

Tabla 1 – Características de las estaciones estudiadas. Fuente: Renfe

2.1 Demanda de las estaciones y ordenación del territorio

Las estaciones analizadas presentan una demanda entre 500 y 5.000 viajeros diarios (subidos+ bajados) para valores de 2018 (según los datos de los aforos realizados por RENFE en día medio laborable de otoño). Las líneas a las que pertenecen las estaciones presentan una demanda entre 20 y 25 mil viajeros diarios para el caso de Dos Hermanas y Torremuelle, en torno a 10 mil para Reus y cerca de 7 mil viajeros diarios para Jerez de la Frontera.

	Demanda de viajeros diarios 2018 (subidos + bajados) (1)			
	Reus	Jerez de la Frontera	Dos Hermanas	Torremuelle
Estación de Cercanías	2.644	3.266	4.630	763
Núcleo de Cercanías	Rodalies Tarragona: 811 Rodalies Catalunya: 34.906 Total: 35.717	6.901	27.919	26.985
Línea de Cercanías	RT1: 301 R14: 2.252 R15: 7.938 Total: 10.491	C-1: 6.678	C-1: 23.242	C-1: 25.040
Servicios hora punta AM	5	5	5	5

(1) Los datos del núcleo y de las líneas corresponden a viajeros subidos

Tabla 2 – Demanda diaria de las estaciones objeto de estudio (2018). Fuente: Renfe

Atendiendo a la ordenación del territorio, las estaciones de Dos Hermanas y Jerez de la Frontera se encuentran situadas en el centro urbano con una población atendida superior a los 35 mil habitantes en un radio de captación de 1.000m, mientras que Reus y Torremuelle se encuentran en áreas perimetrales al núcleo urbano y por lo tanto la población atendida de la estación se reduce a 18,3 mil y 4,7 mil habitantes respectivamente.

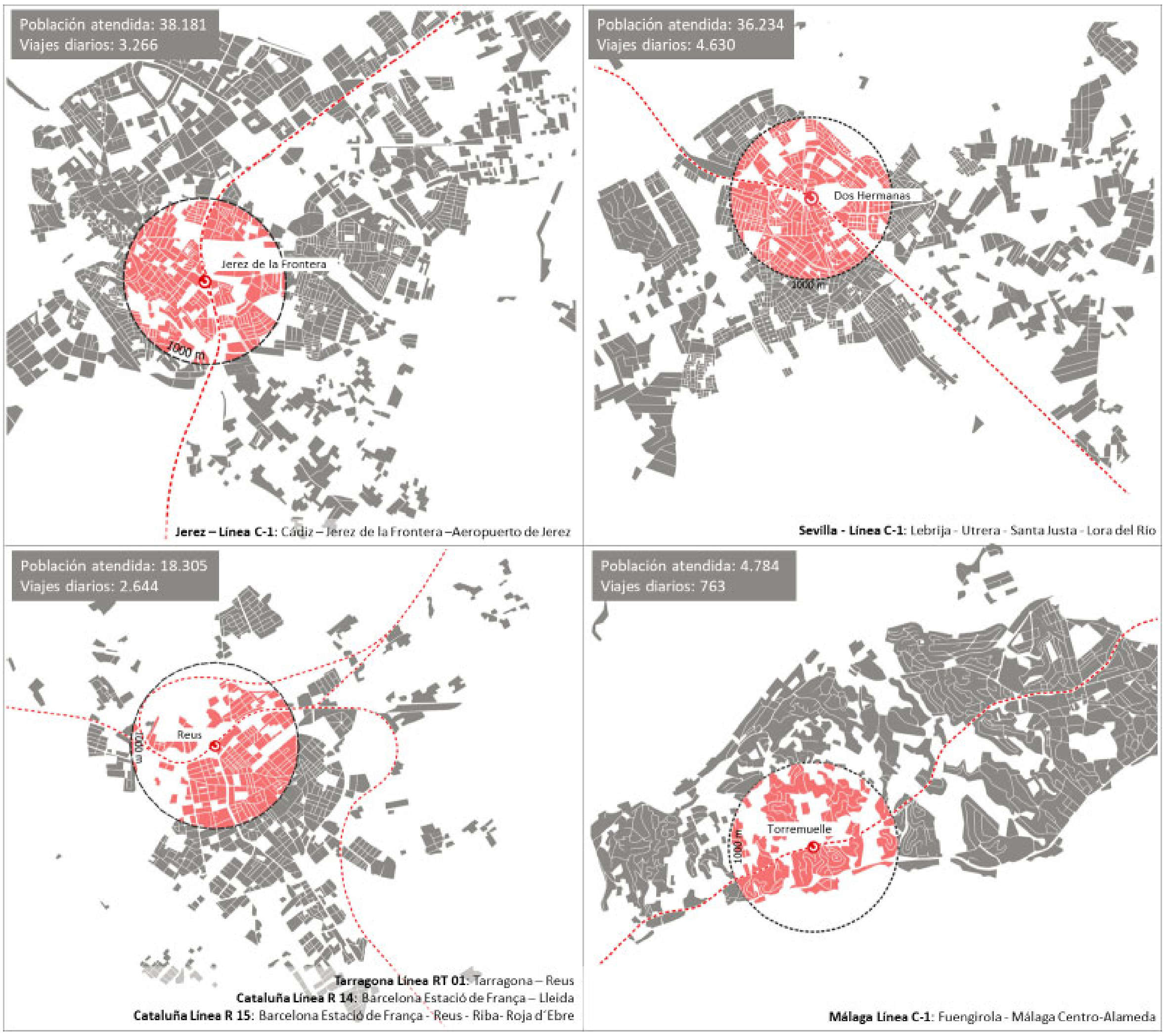

Fig. 1– Población atendida en el ámbito de influencia (1.000m) de las estaciones. Fuente: Elaboración propia.

2.2 Accesibilidad a las estaciones

En lo referente a la accesibilidad, los resultados de las encuestas de preferencias reveladas realizadas a los viajeros actuales de las estaciones de Reus, Jerez de la Frontera, Torremuelle y Dos Hermanas reflejan los siguientes resultados:

-Motivo de viaje: Tal como se muestra en la siguiente figura, estudios y trabajo es el principal motivo de viaje para los viajeros de los servicios ferroviarios de cercanías. Torremuelle al situarse en un entorno turístico con mezcla de usos muestra un mayor porcentaje de viajes asociados al ocio o al turismo.

En el caso de la estación de Jerez de la Frontera el más del 50% de los viajeros presentan como motivo de viaje estudios.

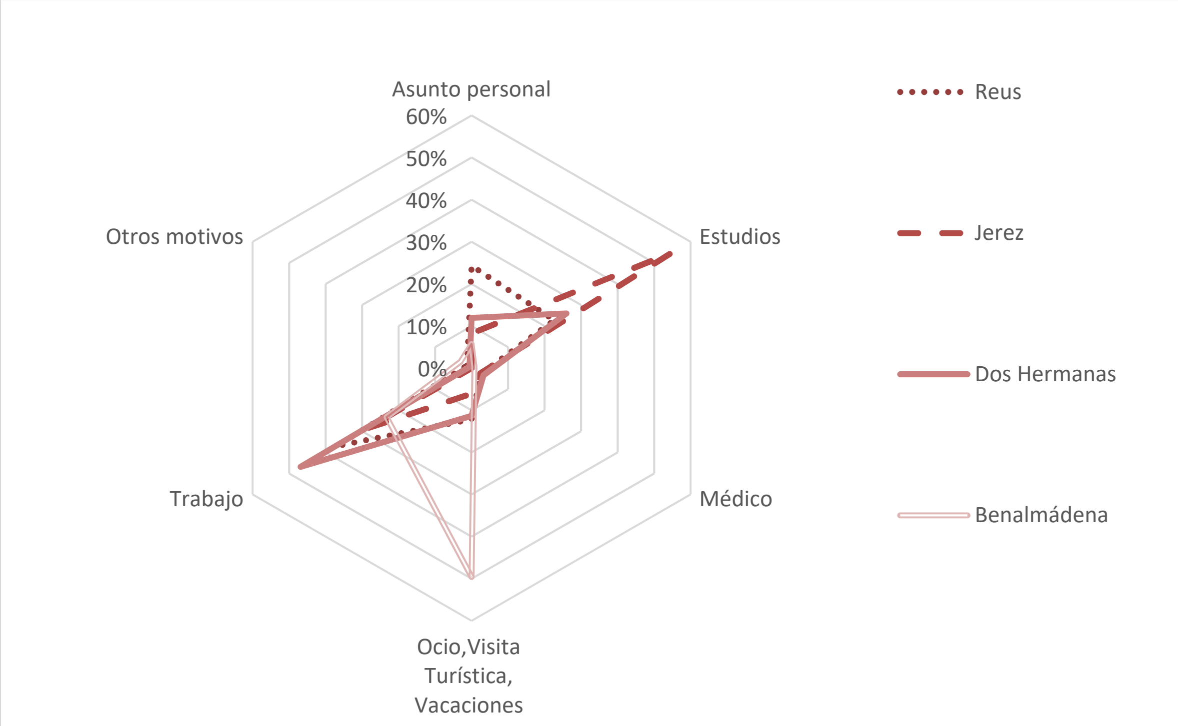

Fig. 2– Motivo de viaje de los viajeros de las estaciones de Reus, Jerez, Dos Hermanas y Torremuelle. Fuente: Campaña de encuestas de preferencia revelada, Ineco 2019.

-Modo de acceso: Más del 50% de los viajeros que acceden a las estaciones de Cercanías de Reus, Dos Hermanas, Jerez de la Frontera y Torremuelle lo hacen a pie (ver Figura 3). El segundo modo de acceso más frecuente es como acompañante en vehículo privado. En Dos Hermanas el porcentaje de viajeros que acceden en bicicleta y los que acceden como acompañantes en vehículo privado es similar, un 12 y un 16% respectivamente. En Jerez de la Frontera destaca la accesibilidad en autobús con un porcentaje significativo del 11%.

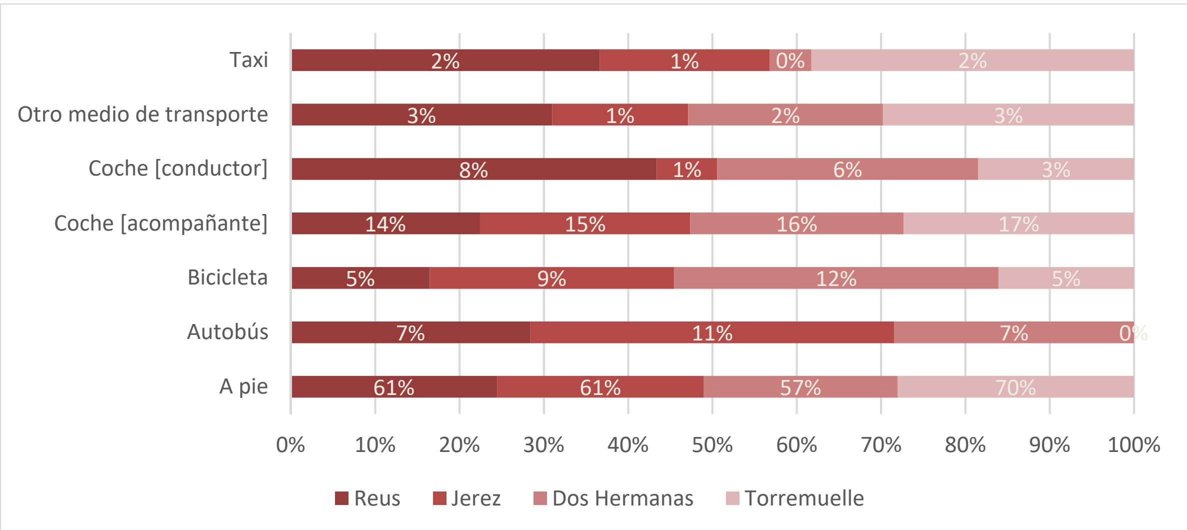

Fig. 3– Modo de acceso las estaciones de Reus, Jerez, Dos Hermanas y Torremuelle. Fuente: Campaña de encuestas de preferencia revelada, Ineco 2019.

-Frecuencia: Respecto a la frecuencia de acceso a la estación, en el caso de Jerez de la Frontera y Dos Hermanas, el mayor porcentaje de viajes se realiza con una frecuencia de cinco o más días, representando este segmento el 48% en el caso de Jerez y el 61% en el caso de Sevilla. En Reus, el 47% se reparte entre una frecuencia de 1-2 veces por semana y una de 5 días a la semana, mientras que en Torremuelle la frecuencia de viaje está muy repartida, destacando con un 26% la frecuencia de viaje ocasional seguida de una frecuencia de más de 5 días a la semana (22%).

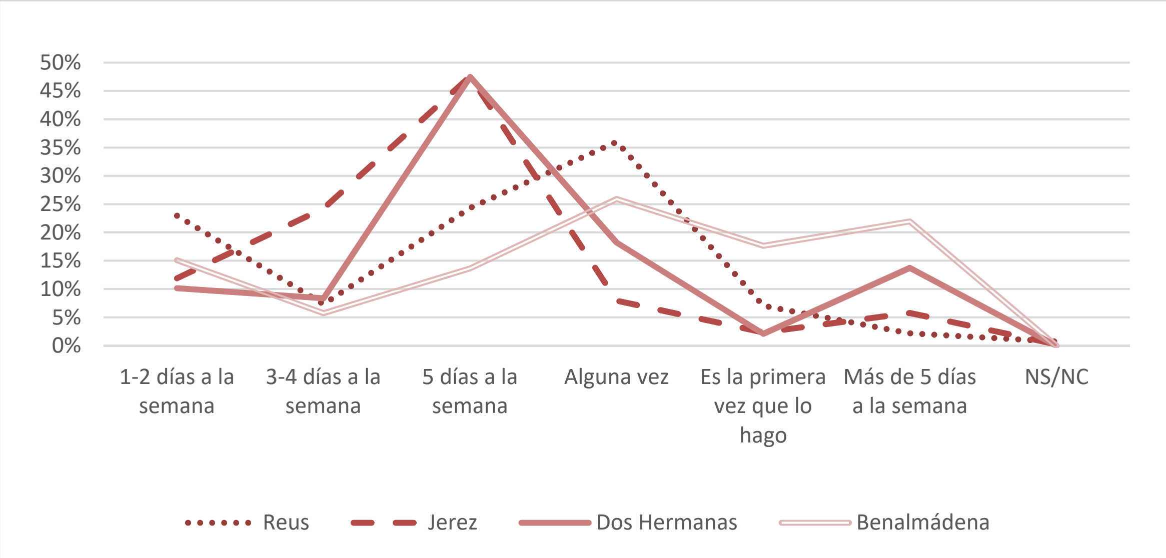

Fig. 4– Frecuencia de viaje de las estaciones de Reus, Jerez, Dos Hermanas y Torremuelle. Fuente: Campaña de encuestas de preferencia revelada, Ineco 2019.

Considerando que el principal modo de acceso a las estaciones es “a pie”, resulta interesante pone el foco en la distribución territorial. En el siguiente gráfico se puede observar la población atendida en las estaciones de Cercanías en un área de captación de 1.000 m y la demanda correspondiente en términos de viajeros diarios (subidos + bajados).
Jerez de la Frontera y Dos Hermanas se localizan en áreas urbanas consolidadas con una captación de población elevada, aunque en términos de viajes/habitantes destaca sobre el resto Jerez de la Frontera con mayor ratio de captación.

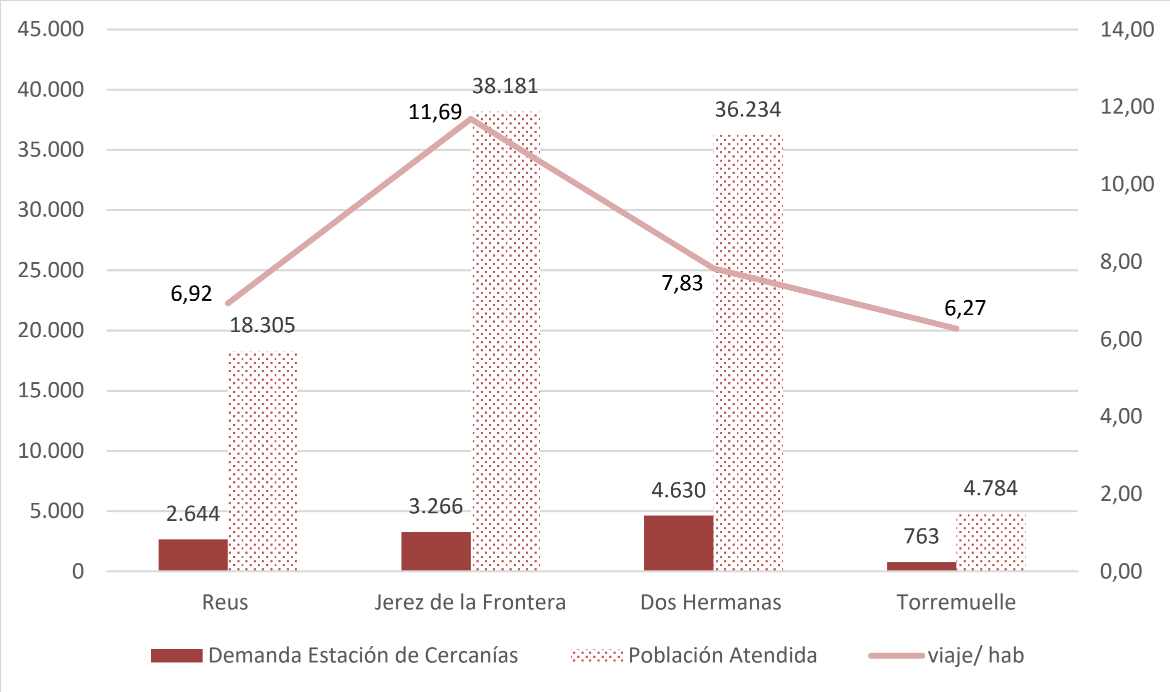

Fig. 5– Frecuencia de viaje de las estaciones de Reus, Jerez, Dos Hermanas y Torremuelle. Fuente: Elaboración propia, Ineco 2019.

2.3 Principales orígenes/destinos

En las siguientes figuras se muestran los principales orígenes y destinos obtenidos a partir de las encuestas de preferencias reveladas (ERP) realizadas en las estaciones objeto de estudio.

Los viajeros encuestados en Dos Hermanas presentaron como principales orígenes/destinos las estaciones de Sevilla San Bernardo, Sevilla Santa Justa y Virgen del Rocío con un 29%, un 19% y un 14% respectivamente, resultando también significativa la atracción y generación de viajes con la estación de Utrera (15%).

En el caso de Jerez de la Frontera, los principales orígenes y destinos se agrupan en las estaciones de Cádiz (25%), San Fernando (16%), El Puerto de Santa María (13%) y Universidad (11%).

La estación de Reus muestra una atracción más polarizada que el resto de las estaciones analizadas. Los resultados de las EPR muestran una atracción y generación viajes centrada en Barcelona Sants (28%) y Tarragona (24%). Del mismo modo, los viajeros de la estación de Torremuelle presentan como principales orígenes y destinos las estaciones de Málaga María Zambrano y Málaga Centro Alameda con porcentajes del 18% y la estación de Benalmádena-Arroyo de la Miel con un 15%.

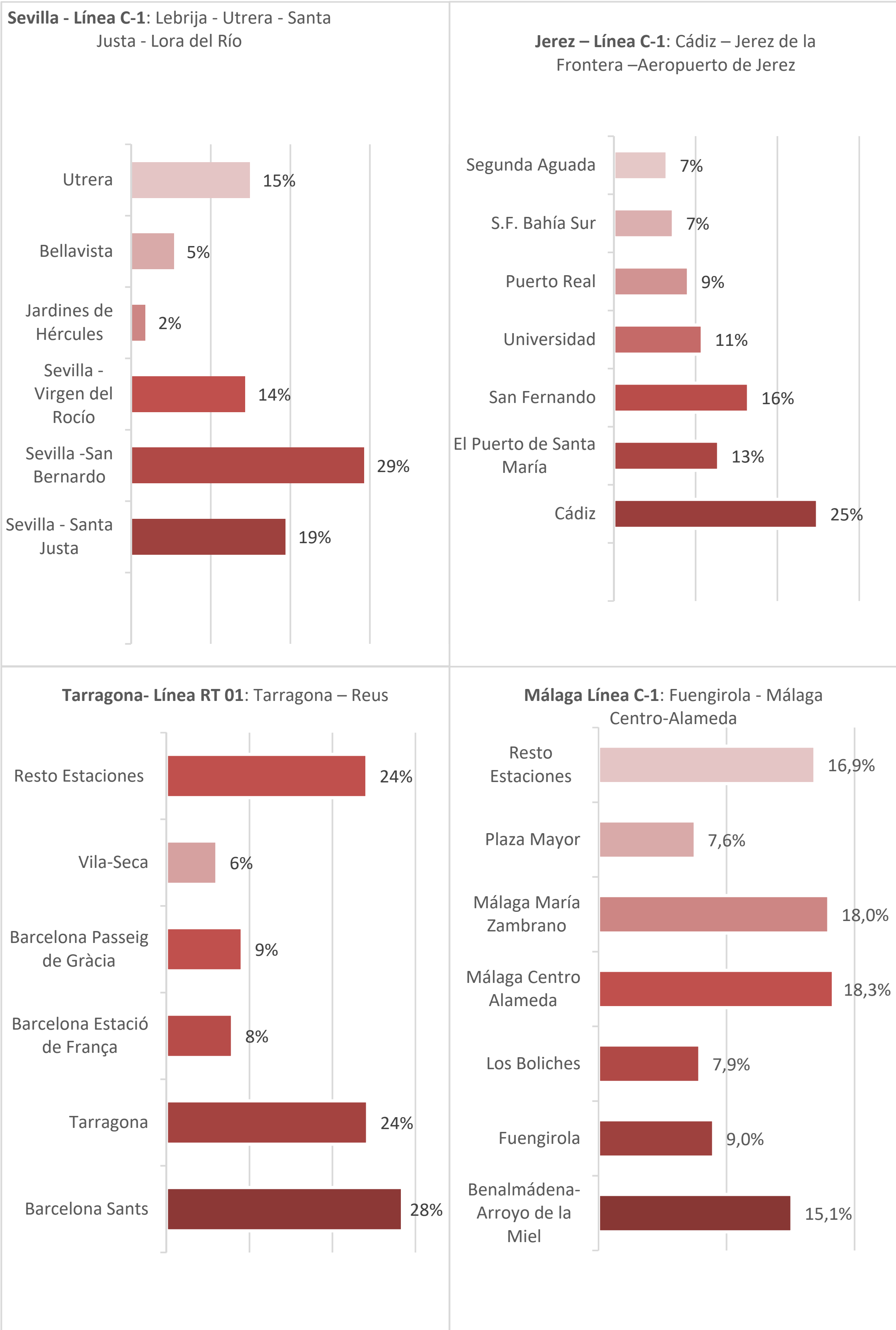

Fig. 5– Principales destinos de las estaciones de Reus, Jerez, Dos Hermanas y Torremuelle. Fuente: Elaboración propia, Ineco 2019.

2.4 Potenciales de demanda de las estaciones

La estimación de los potenciales de demanda de las estaciones ferroviarias de Cercanías en los corredores de los núcleos de estudio (Tarragona, Cádiz, Sevilla y Málaga), se ha obtenido a partir de un modelo general de movilidad.

Para la aplicación del modelo se han calculado matrices de viajes (origen/destino) por modo de transporte a partir de datos de telefonía móvil, aforos automáticos de vehículos, aforos manuales de viajeros de tren y autobús y datos de origen destino de encuestas de preferencias declaradas.

La caracterización de la movilidad en la situación en el escenario base (datos de movilidad de 2018) permite analizar los potenciales de demanda global (viajes diarios en carretera+ferrocarril) de los principales orígenes y destinos de las estaciones analizadas.

2.4.1 Potenciales de demanda estación Dos Hermanas (Sevilla)

En el siguiente gráfico se muestran los potenciales de demanda del área de influencia de la estación de Dos Hermanas (Zona 1) con las áreas de influencia de las estaciones con las que hay mayor relación de movilidad. Es decir, el área de influencia de las estaciones de Sevilla-Santa Justa-San Bernardo-Virgen del Rocío (Zona 5), estación de Bellavista (Zona 4) y estación de Utrera (Zona 6).

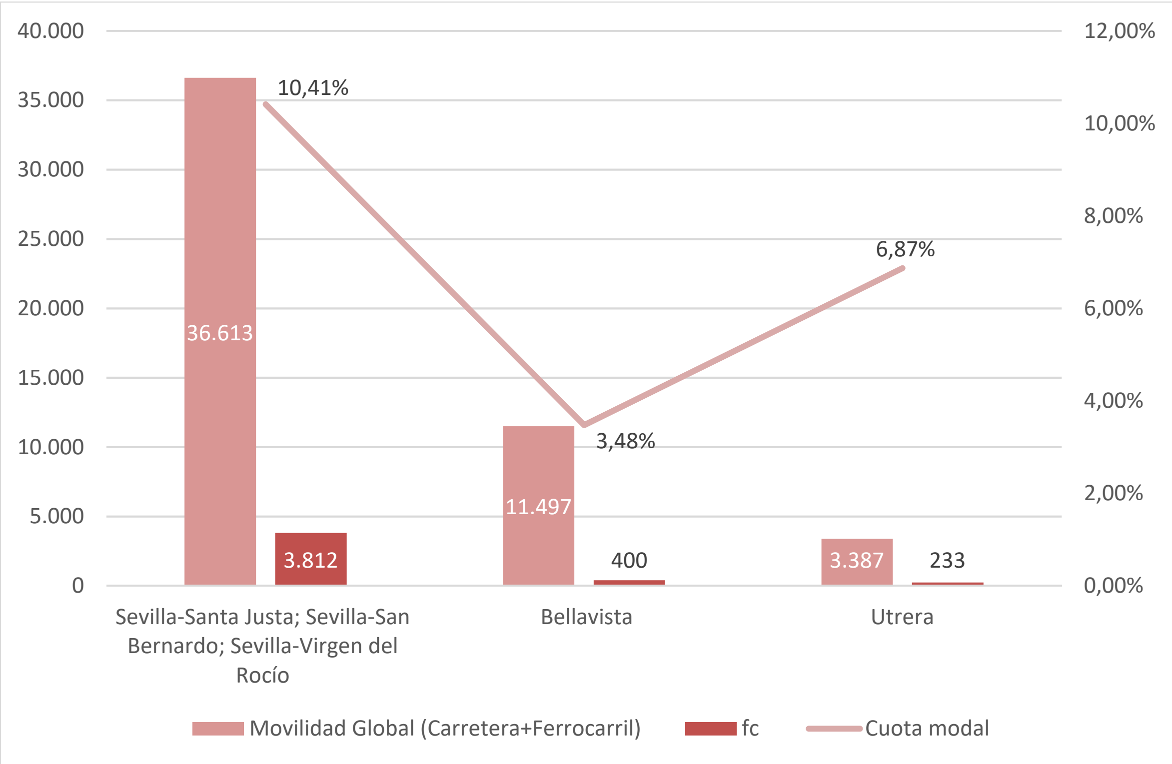

Fig. 6– Potenciales de demanda diaria desde/hacia la zona de influencia de Dos Hermanas (Zona1) hacia/desde las zonas de Sevilla (Zona 5), Bellavista (Zona4) y Utrera (Zona 6). Fuente: Elaboración propia, Ineco 2019.

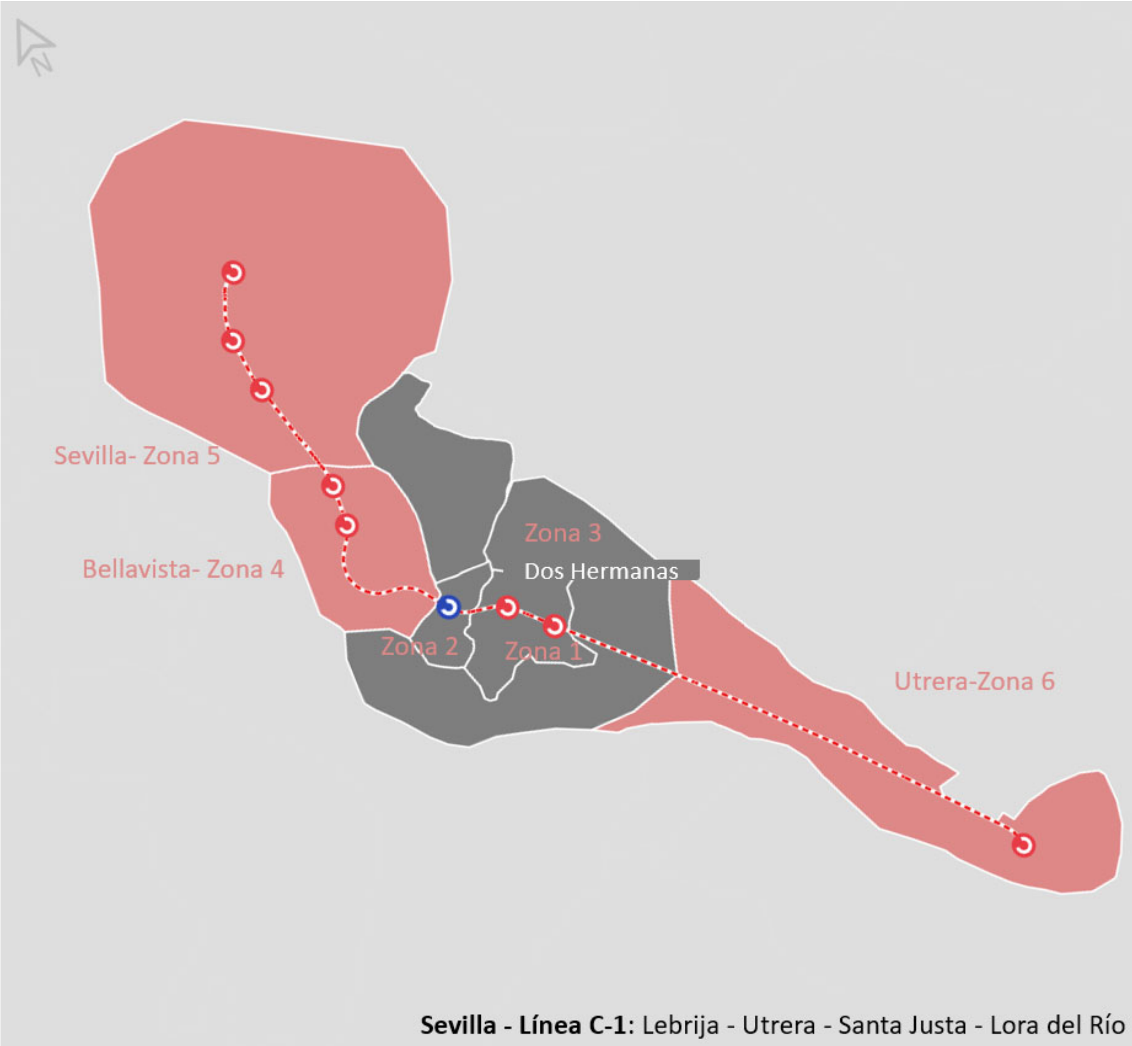

Fig. 7– Zonificación ámbito de estudio del corredor de la Línea C-1: Lebrija-Utrera-Santa Justa-Lora del Río. Fuente: Elaboración propia, Ineco 2019.

El potencial de demanda de la zona de influencia de la estación la estación de Dos Hermanas (Zona 1) hacia/desde las zonas de influencia de las principales relaciones (Zonas 4-5-6) muestran un total de 51,5 mil viajes diarios en términos de movilidad global (carretera y ferrocarril).

Sin embargo, este potencial de demanda aumenta un 50,19% si se amplía el área de influencia a las áreas adyacentes al área de influencia de Dos Hermanas (Zona 2 y Zona 3).

Zonas	Potenciales de demanda (viajes diarios)	Incremento
Movilidad Global Áreas Adyacentes (Zona 1, Zona 2 y Zona 3)	77.343	50%
Movilidad Global Dos Hermanas (Zona 1)	51.497	

Tabla 3 –Potenciales de demanda de las áreas de influencia de la estación de Dos Hermanas. Fuente: Elaboración propia, Ineco 2019

2.4.2 Potenciales de demanda estación Jerez de la Frontera (Cádiz)

A continuación, al igual que en el caso anterior, se expone el potencial de demanda del área de influencia de la estación de Jerez de la Frontera (Zona 3) con las áreas de influencia de las estaciones reflejadas en las encuestas de preferencias reveladas como principales nodos de atracción y generación de viajes.

En el siguiente gráfico se muestra que la relación de movilidad global desde/hacia Jerez de la Frontera con el área de influencia de las estaciones de Cádiz; S.F. Bahía Sur; Segunda Aguada; Puerto Real; Universidad; San Fernando (Zona 6) es de más de 19 mil viajes diarios (carretera + ferrocarril) mientras el potencial de demanda del Puerto de Santa María (Zona 4) es de unos 7,5 mil viajes diarios (carretera + ferrocarril).

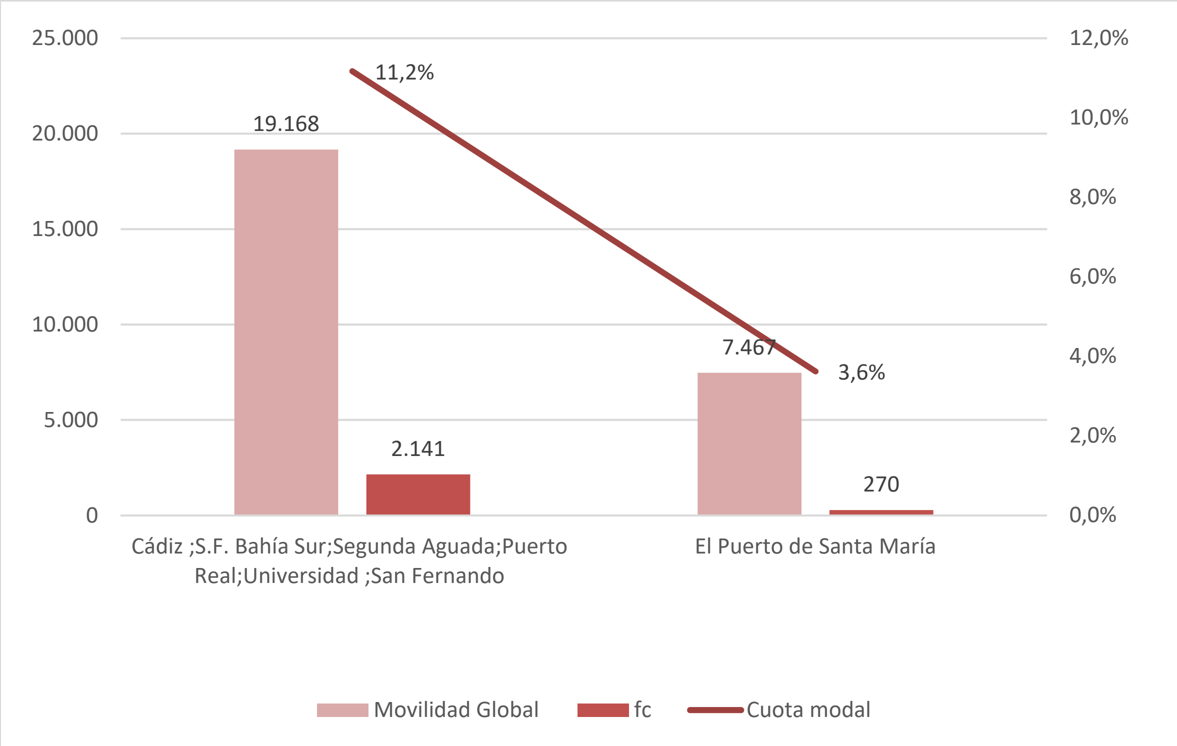

Fig. 8– Potenciales de demanda diaria desde/hacia la zona de influencia de Jerez de la Frontera (Zona 3) hacia/desde las zonas de Puerto de Santa María (Zona 4) y Cádiz-San Fernando (Zona 6). Fuente: Elaboración propia, Ineco 2019.

Las matrices de movilidad muestran la demanda de viajes en carretera y ferrocarril para cada una de las zonas en las que se ha dividido el corredor de la Línea C-1: Cádiz – Jerez de la Frontera –Aeropuerto de Jerez.

Este cálculo permite comparar el potencial de demanda de la estación de Jerez de la Frontera (Zona 3) con las zonas de mayor demanda ferroviaria (Zona 4 y Zona 6), este potencial de demanda es de 26.635 viajes diarios en ambos sentidos.

Ampliando la cobertura a las áreas adyacentes a la estación de Jerez de la Frontera (Zona 2, Zona 3 y Zona 7), tal y como se observa en la siguiente tabla, se produce un incremento del 33%.

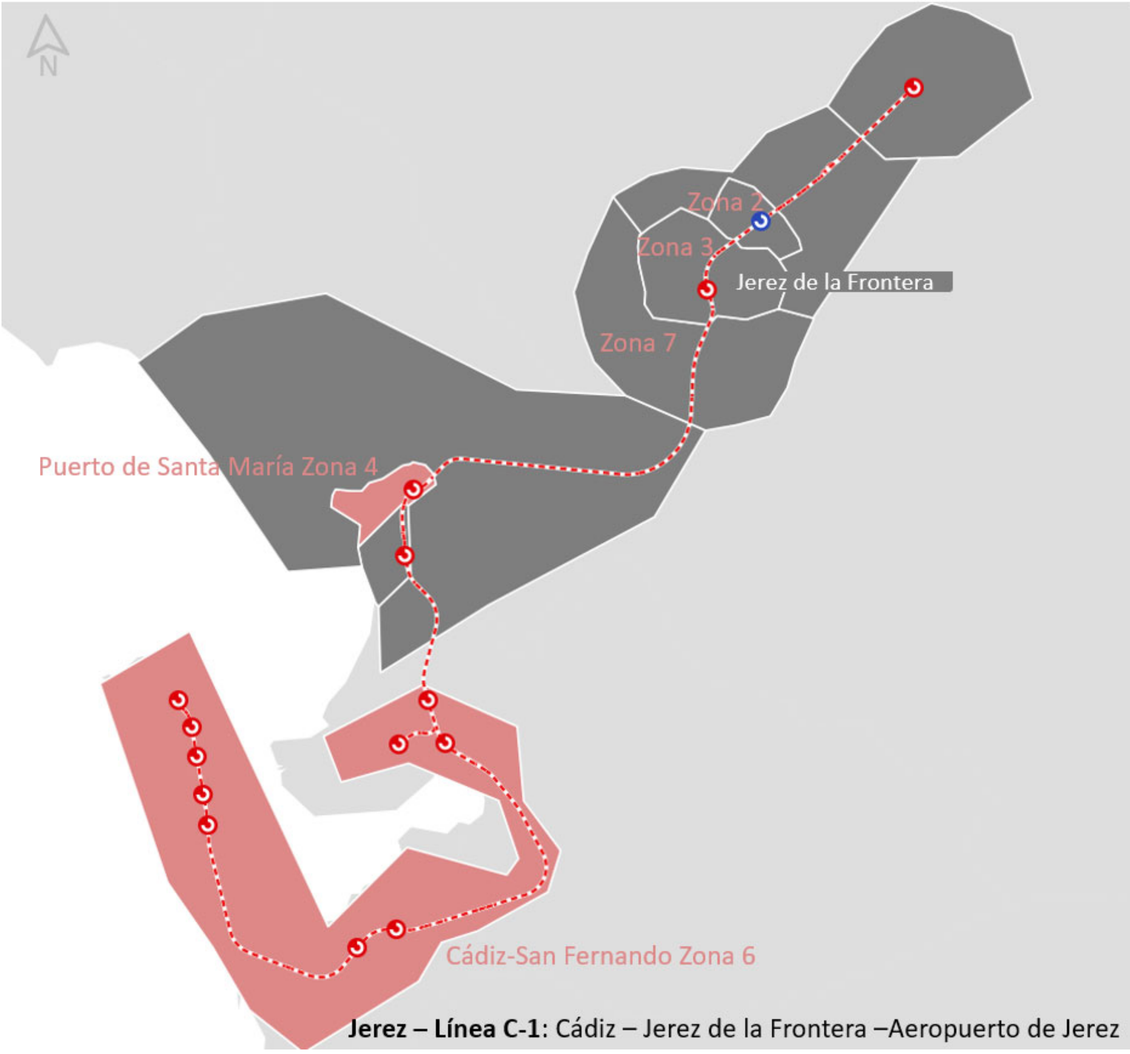

Fig. 9– Zonificación ámbito de estudio del corredor de la Línea C-1: Cádiz-Jerez de la Frontera-Aeropuerto de Jerez. Fuente: Elaboración propia, Ineco 2019.

Zonas	Potenciales de demanda (viajes diarios)	Incremento
Movilidad Global Áreas Adyacentes (Zona 2, Zona 3, Zona 7).	35.423	33%
Movilidad Global Jerez de la Frontera (Zona 3)	26.635	

Tabla 4 –Potenciales de demanda de las áreas de influencia de la estación de Jerez de la Frontera. Elaboración propia, Ineco 2019

2.4.3 Potenciales de demanda estación Reus (Tarragona)

El potencial de demanda de movilidad global (ferrocarril+carretera) del área de influencia de la estación de Reus (Zona 2) con las áreas de influencias de las principales estaciones reflejadas en las encuestas de preferencias reveladas, es de 12 mil viajes diarios con el área de influencia de la estación de Tarragona (Zona 6), 1,79 mil viajes diarios con el área de influencia de las estaciones que pertenecen Barcelona (Zona 10) y cerca de 3 mil con el área de influencia de la estación de Vila-Seca (Zona 5).

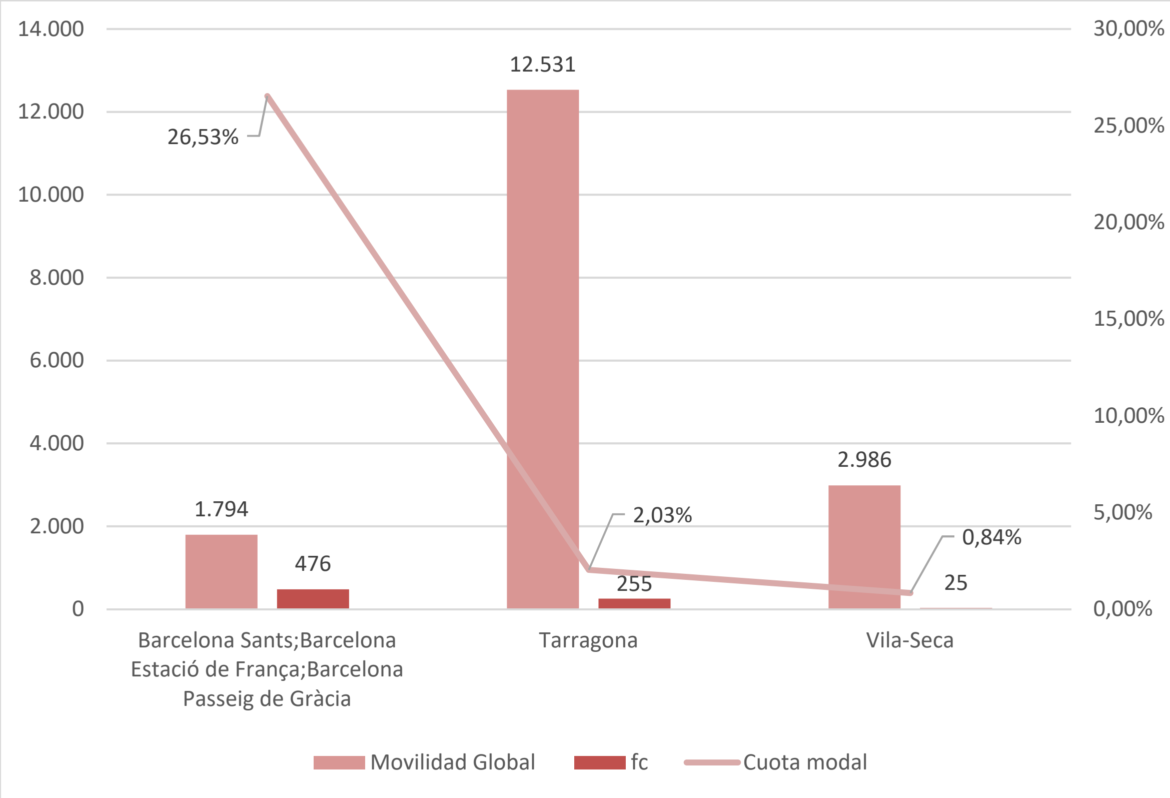

Fig. 10– Potenciales de demanda diaria desde/hacia la zona de influencia de Reus (Zona 2) desde/hacia Barcelona (Zona 10), Tarragona (Zona 6) y Vila-Seca (Zona 5) Fuente: Elaboración propia, Ineco 2019.

El potencial de demanda global diaria desde/hacia el área de influencia de la estación de Reus (Zona 2) con las zonas de influencia de las estaciones de Vila-Seca (Zona 5), Tarragona (Zona 6) y Barcelona (Zona 10) asciende de 17,3 mil viajes.

Sin embargo, si se amplía el ámbito de influencia a las zonas adyacentes a la estación de Reus (Zonas 1-2-3-4) el potencial de demanda asciende a 63,4 mil viajes diarios hacía/desde las zonas de mayor demanda del corredor (Zonas 5-6-10).

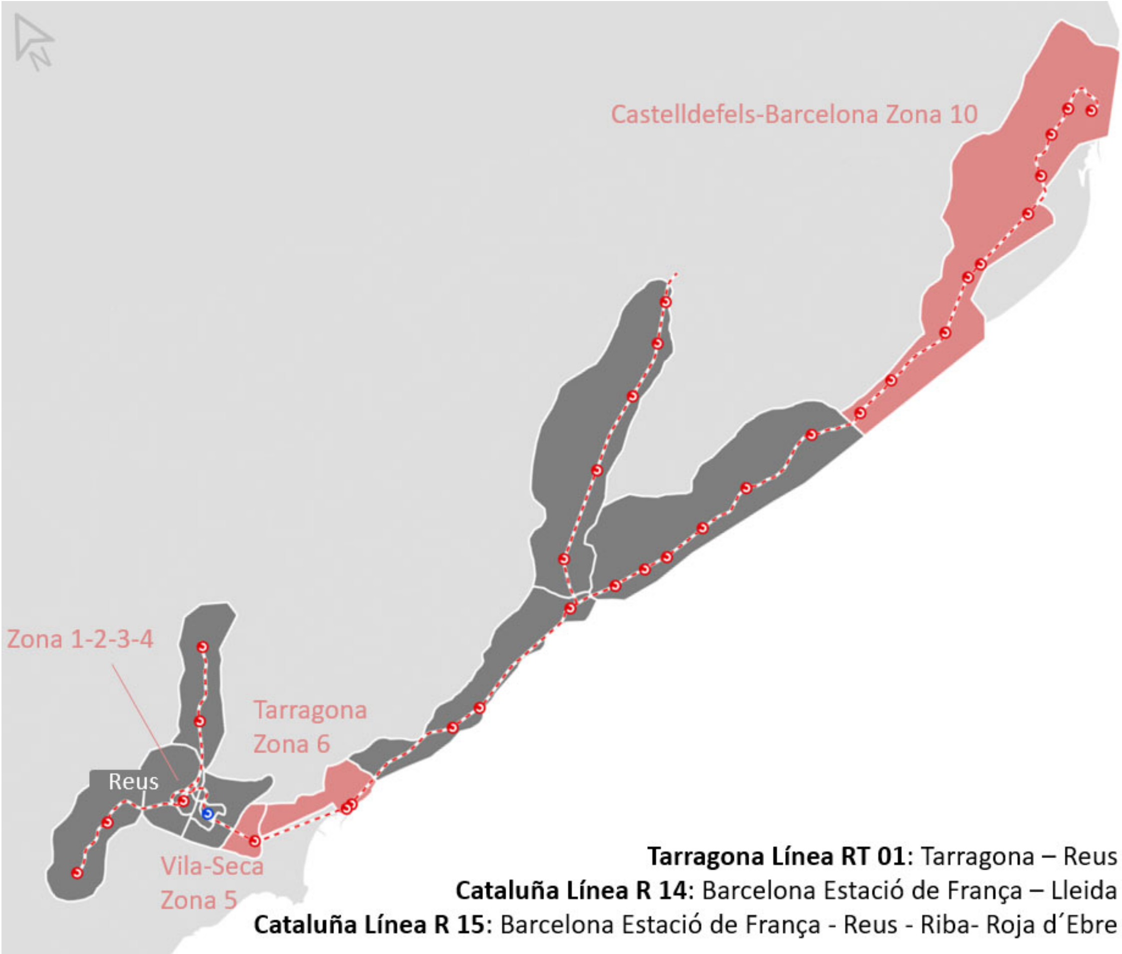

Fig. 9– Zonificación ámbito de estudio del corredor de las líneas RT 01, R 14 y R 15. Fuente: Elaboración propia, Ineco 2019.

Zonas	Potenciales de demanda (viajes diarios)	Incremento
Movilidad Global Áreas Adyacentes (Zonas 1-2-3-4)	63.456	266%
Movilidad Global Área Reus (Zona 2)	17.330	

Tabla 5 –Potenciales de demanda de las áreas de influencia de la estación de Reus. Elaboración propia, Ineco 2019

2.4.4 Potenciales de demanda estación Torremuelle (Benalmádena)

La estación de Torremuelle no presenta una relación de movilidad polarizada como en los casos anteriores, estas relaciones principales se reparten entre las áreas de influencia de Benalmádena-Arroyo de la Miel (Zona 8), Málaga (Zona 7), Fuengirola (Zona 5) y Plaza Mayor (Zona 12).

La principal relación potencial de demandada (3,6 mil viajes diarios) se produce con el área de influencia del núcleo urbano de Benalmádena.

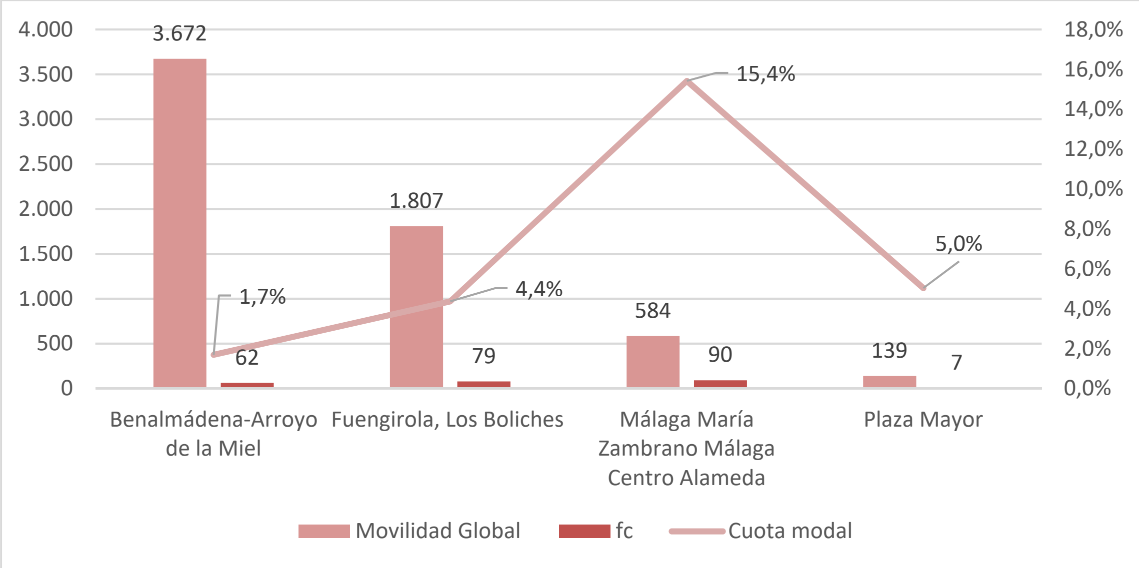

Fig. 10– Potenciales de demanda diaria de la zona de influencia de Torremuelle (Zona 2) con Benalmádena-Arroyo de la Miel (zona 8), Fuengirola (Zona 5), Málaga (Zona 7) y Plaza Mayor (Zona 12). Fuente: Elaboración propia, Ineco 2019.

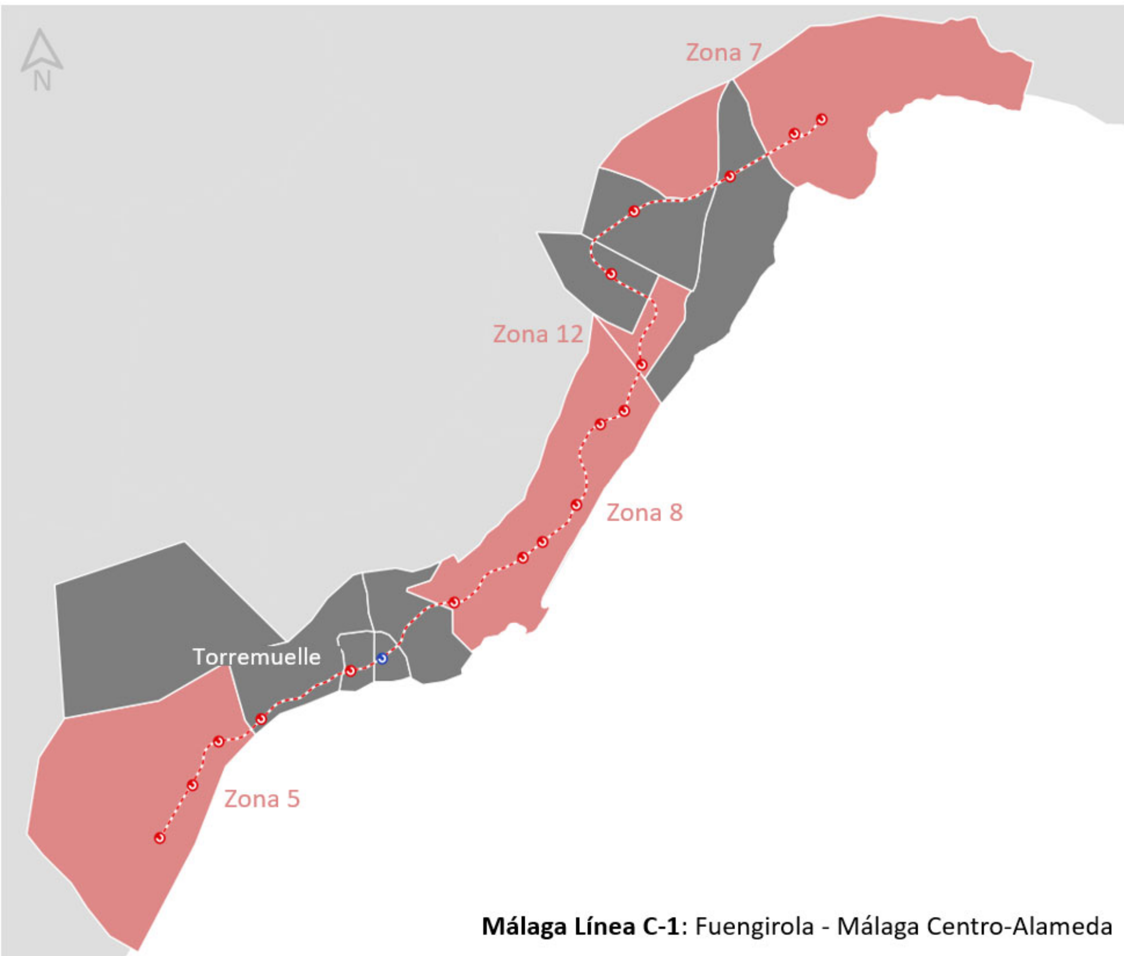

Fig. 11– Zonificación ámbito de estudio del corredor de la Línea C-1: Fuengirola-Málaga Centro-Alameda. Fuente: Elaboración propia, Ineco 2019.

Zonas	Potenciales de demanda (viajes diarios)	Incremento
Movilidad Global Áreas Adyacentes (Zonas 1-2).	13.256	114%
Movilidad Global Área Torremuelle (Zona 1)	6.202	

Tabla 5 –Potenciales de demanda de las áreas de influencia de la estación de Torremuelle. Elaboración propia, Ineco 2019

El potencial de demanda la zona de la estación de Torremuelle (Zona 1) con las zonas de influencia de las estaciones las áreas de Benalmádena - Arroyo de la Miel (Zona 8), Málaga (Zona 7), Fuengirola (Zona 5) y Plaza Mayor (Zona 12) asciende a 6,2 mil viajeros diarios (movilidad global). Ampliando la zona de cobertura de Torremuelle a la zona adyacente (Zona 2) el potencial de demanda se incrementa de 6,2 mil a 13,2 mil viajeros diarios (ferrocarril + carretera).

3.RESULTADOS

Los resultados del análisis realizado exponen un perfil de usuario de Cercanías de las estaciones de Reus, Jerez de la Frontera, Dos Hermanas y Torremuelle. El principal motivo de viaje es estudios o trabajo con valores entre el 60 y 83% de los viajeros en Reus, Jerez de la Frontera y Dos Hermanas, mientras que esta cifra en los viajeros de Torremuelle, situada en un entorno turístico y residencial de vacaciones, desciende hasta el 25%.

Respecto a la frecuencia de viaje, cerca del 50% los viajeros de las estaciones de Jerez de la Frontera y Dos Hermanas acceden a la estación 5 días a la semana, mientras que en el caso de Reus se reduce al 24% y en Torremuelle desciende esta cifra al 14%.

	Demanda de viajeros diarios 2018 (subidos + bajados)			
	Reus (Tarragona)	Jerez de la Frontera (Cádiz)	Dos Hermanas (Sevilla)	Torremuelle (Málaga)
Estación de Cercanías	2.644	3.266	4.630	763

Tabla 6 –Demanda de viajeros diarios (subidos y bajados) en 2018. Renfe

Por lo tanto, se observa que las estaciones de mayor demanda responden principalmente a un perfil de viajeros de movilidad obligada y uso frecuente en días laborales, por lo que son determinantes las características del servicio en las horas punta donde el valor subjetivo del tiempo es mayor.

Las variables que determinan la elección modal de los servicios de cercanías serán aquellas asociadas con las características particulares del viaje en ferrocarril (fiabilidad, regularidad y puntualidad del servicio, así como confort de este) y coste del viaje.

Además, es determinante para la elección modal del viajero, en el ámbito de influencia de los corredores de los núcleos de Cercanías, dónde las congestiones por carretera son menores que en un ámbito urbano y los tiempos de viaje son relativamente ajustados; que el acceso y dispersión a las estaciones esté integrado con otros modos de transporte.

La movilidad global desde/hacia las estaciones de estudio presenta siempre un máximo de demanda con un principal polo de atracción y generación de viajes, en el caso de Reus con Tarragona, Jerez de la Frontera con Cádiz, Torremuelle con Benalmádena y Dos Hermanas con Sevilla; observándose que los potenciales de demanda aumentan significativamente al ampliar las conexiones entre las zonas de influencia del área adyacente de la estación.

Para resolver las conexiones en los corredores ferroviarios de Cercanías se puede optar por nuevas estaciones cuando las distancias entre dichas áreas son suficientes y los planes generales de ordenación urbana contemplan desarrollos urbanísticos con mezclas de usos en el entorno de las potenciales estaciones que garanticen la demanda. Es el caso de las potenciales estaciones en estudio en Jerez de la Frontera, Dos Hermanas y Reus, donde además su puesta en servicio no perjudique a la funcionalidad de la línea ni al resto de usuarios de las líneas de Cercanías donde se ubican.

En otras ocasiones, sin embargo, implantar nuevas estaciones de Cercanías atienden a menor población y pueden restar funcionalidad a la línea actual.

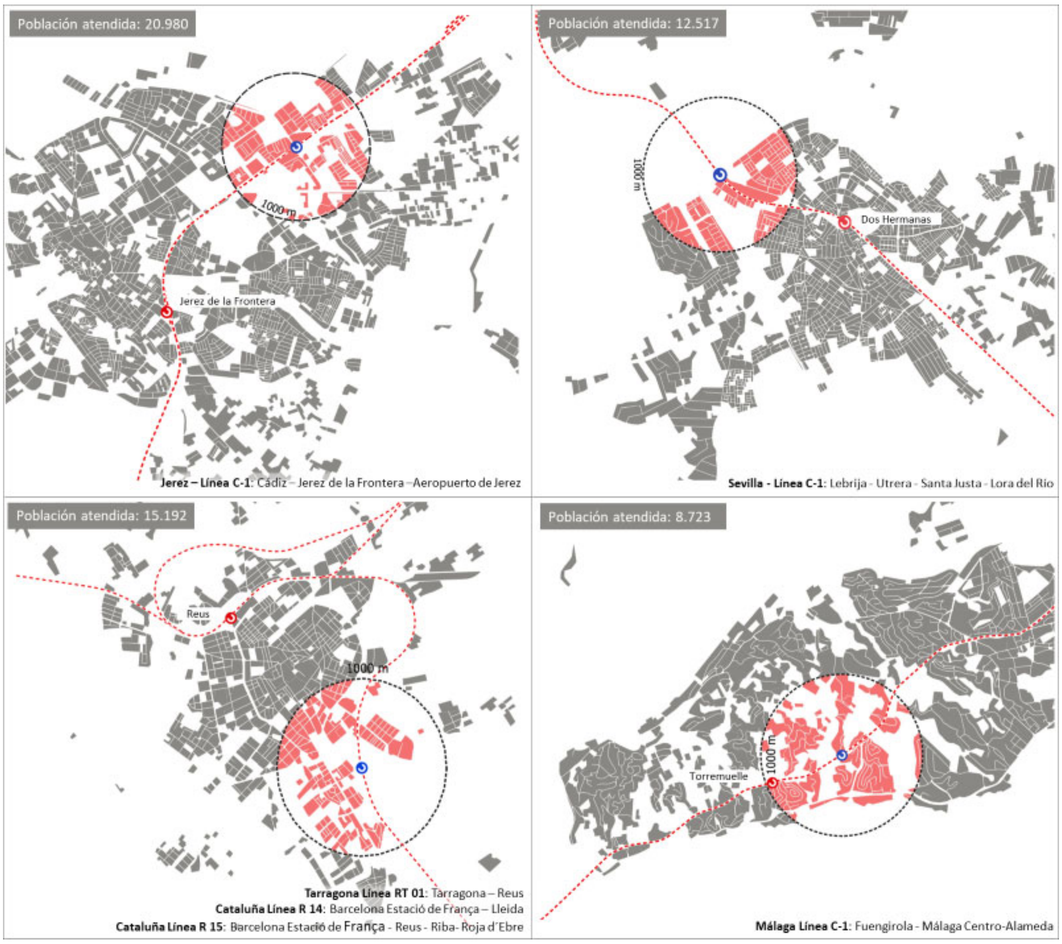

Fig. 11– Población atendida de nuevas estaciones en estudio en el ámbito de influencia de las estaciones de Jerez, Sevilla, Reus y Torremuelle. Fuente: Elaboración propia, Ineco 2019.

4. CONCLUSIONES

La reducida demanda de viajeros de las estaciones de los servicios de cercanías sujetos a OSP analizados (Jerez de la Frontera, Dos Hermanas, Reus y Torremuelle) en comparación con los potenciales de demanda de movilidad global sugieren nuevas medidas que aumenten la demanda de viajeros en estas estaciones y mejoren la calidad y la percepción del servicio por parte de los usuarios potenciales.

Para ello, es necesario actuar en todas las etapas del viaje en Cercanías. Claramente, las mejoras previstas en las inversiones en infraestructura, material rodante y personal repercutirán en mejoras de tiempo de viaje, confort, fiabilidad y regularidad del servicio, y aumentarán las demandas actuales. Sin embargo, las etapas de acceso y dispersión pueden ser tan determinantes para la elección modal como el propio tiempo de viaje en ferrocarril.

Por lo tanto, es necesario redefinir el papel de las estaciones de Cercanías en la red ferroviaria con acciones que aporten a estos servicios de una herramienta de conexión eficiente y vertebración del territorio.

Se proponen a continuación algunas acciones y requisitos de las estaciones de Cercanías del futuro:

- Mejora de la intermodalidad: Adaptación de los servicios de transporte público a la red ferroviaria, potenciando la complementariedad e intermodalidad entre modos, aprovechando la mayor capacidad de transporte del sistema ferroviario.
- Movilidad como servicio: Método de pago integrado con las redes de transporte locales, coordinación entre modos y digitalización de los sistemas de información al viajero en tiempo real. Se reducirán así los tiempos de espera y, en consecuencia, supondrá un ahorro del tiempo de viaje del usuario, disminuyendo también su percepción del tiempo.
- La estación como destino de viaje: optimización de la infraestructura de la estación mediante la generación espacios destinados a co-workings, salas de reuniones, unidades sanitarias bibliotecas, puntos de recogida de paquetería de última milla.
- Desarrollos orientados al transporte de Cercanías: implementar en los P.G.O.U la ubicación de las estaciones vinculados a desarrollos urbanos con mayor densidad y con mezclas de usos que garanticen una distribución mayor del perfil del viajero y una mayor potencialidad de su uso.

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LOS PLANES DE ACCIÓN PARA LA MOVILIDAD DE GRANDES EVENTOS DEPORTIVOS

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RESUMEN

Los grandes eventos deportivos, como los Juegos Olímpicos o los Mundiales de Fútbol, se enfrentan a importantes retos organizativos: desde garantizar unas infraestructuras deportivas adecuadas, hasta asegurar una oferta hotelera suficiente u ofrecer una oferta cultural y de ocio alternativa o complementaria.

Entre estos retos, sin duda, cabe señalar el objetivo de garantizar una oferta de movilidad eficiente y atractiva para todos.

Este reto se soporta en varios objetivos, entre los que cabe destacar:

1. Minimizar el impacto de la movilidad generada por los eventos deportivos en la movilidad diaria de las ciudades que acogen dichos eventos.
2. Garantizar un adecuado funcionamiento de la movilidad asociada a las distintas actividades de los eventos deportivos en cuestión, siempre desde un enfoque que prime la sostenibilidad del sistema.
3. Aprovechar el legado de las inversiones realizadas en el sistema de transporte para el desarrollo de la movilidad diaria una vez finalizado el evento deportivo.

Dentro del segundo punto, en la organización de la movilidad asociada al evento, hay que tener en cuenta las necesidades y condicionantes de un amplio abanico de usuarios: deportistas y equipo técnico, autoridades, medios de comunicación, cuerpos de seguridad y, por supuesto, los espectadores.

También cobran especial interés otros aspectos como la información a los usuarios, la seguridad vial o la seguridad personal en el transporte.

Por último, cabe señalar las distintas necesidades de eventos como los Juegos Olímpicos, que se desarrollan en su mayoría en una sola ciudad o área metropolitana, o los Mundiales de Fútbol, que distribuyen su actividad en varias ciudades.

Una excepción a este hecho puede ser el futuro Mundial de Catar que, debido a los condicionantes territoriales del país, se desarrollará prácticamente en su totalidad en el área metropolitana de Doha.

1. OBJETIVOS Y RESPONSABILIDADES

Un evento deportivo como los Juegos Olímpicos, el Mundial de Fútbol, o una final de competiciones europeas son eventos que se caracterizan por la concentración de un gran volumen de personas en un limitado espacio de tiempo y con una gran repercusión social.

Esta concentración de participantes y visitantes se superpone a la actividad habitual de las ciudades que acogen estos eventos.

Como criterio general, para gestionar las condiciones especiales de movilidad derivadas de estas situaciones, se debe potenciar el transporte público, y una de las medidas es limitar el acceso en vehículo privado en las inmediaciones. Por ello el sistema de transporte ha de ayudar a que el evento se celebre sin ningún contratiempo.

En consecuencia, los objetivos del sistema de transporte para un evento deportivo son:

- Proporcionar transporte seguro, inclusivo, rápido y confiable para todos los asistentes y grupos de clientes.
- Proporcionar una oferta de transporte suficiente, accesible, respetuosa con el medio ambiente y sencilla para espectadores y visitantes, tanto de las ciudades donde se celebran las competiciones, como de otras regiones.
- Respetar la actividad diaria de las ciudades organizadoras, sin producir grandes cambios ni restricciones en el servicio ofertado.
- Dejar un legado positivo, así como facilitar la integración y el uso del transporte público durante y después del evento.
- Lograr el mayor aprovechamiento de los recursos asignados a transporte.

2. ÁMBITO TERRITORIAL Y CALENDARIO DEPORTIVO

La concentración de actividades derivadas de un gran evento deportivo en una misma ciudad o país es un reto para el transporte y para el éxito de asistencia a la competición. En competiciones donde los eventos tienen lugar en una misma ciudad o ciudades cercanas entre sí se suelen vender entradas por días, o por competencias deportivas, como es el caso de los Juegos Olímpicos.

Las fases finales de los Mundiales de Fútbol o las Eurocopas suelen repartir los partidos entre distintos estadios de diversas ciudades, diluyendo parcialmente los efectos sobre la movilidad si se compara con unos Juegos Olímpicos, que concentran la mayor parte de la actividad en una sola ciudad o área metropolitana. Pero cuando estas fases finales de Mundiales o Eurocopas se celebran en países pequeños, el problema es más complejo.

Una práctica habitual es que las entradas a los diferentes eventos deportivos vayan asociados a un título de transporte que permita el acceso ilimitado al mismo durante los días que dura la competición, o para los días en los que es válida la entrada adquirida.

Por ejemplo, en Londres se vendieron las entradas por días, junto con un título de transporte válidos para los días de entrada. En competiciones de Champion que se han celebrado en Europa en los últimos años, la venta de entradas ha llevado asociado un título de transporte válido desde que el visitante llega al lugar de la competición, que suele ser un día antes de la misma

3. STAKEHOLDERS Y MODELO DE GOBERNANZA.

En la organización del sistema de transporte suelen estar involucrados los siguientes organismos y autoridades:

- Comité Organizador del evento deportivo
- Ministerio de Transportes
- Autoridades de transporte metropolitano
- Autoridades locales
- Operadores
- Vigilancia y policía
- Voluntarios

El proceso habitual para organizar la movilidad durante estos eventos es que Comité organizador exponga las necesidades de transporte de los grupos de interés, así como la afluencia de participantes y de visitantes esperados en cada una de las sedes de competencia y entrenamiento, y dimensione, de forma conjunta con el Ministerio de Transportes y las autoridades locales, el sistema de transporte necesario, teniendo siempre como punto de partida la oferta y características del sistema existente. Las autoridades de vigilancia y los voluntarios se encargan de que el sistema sea seguro y confiable para todos los asistentes, y contribuya al éxito de la celebración de la competición.

4. NECESIDADES DE TRANSPORTE POR TIPO DE USUARIO

A continuación, se incluyen los tipos de usuarios habituales de las grandes competiciones deportivas, el tipo de transporte más habitual en cada caso y el tiempo con el que cada tipo de usuario debe estar previo y después de las competiciones. Mención especial tienen las ceremonias de apertura y clausura de la competición.

USUARIO	TIPO DE TRANSPORTE	TIEMPO PREVIO A LA COMPETICIÓN
Deportistas y equipo técnico	Autobús discrecional	2h
Staff Estadios	Transporte público	3-4h
Prensa	Autobús discrecional	3h
Retransmisión del evento	Autobús discrecional	3h
Autoridades	Vehículo privado	30 min
Espectadores	Transporte público	2,5h

Tabla 1 – Tipo de transporte por tipo de usuario y tiempo de estancia previo a las competiciones

USUARIO	TIPO DE TRANSPORTE	TIEMPO DESPUÉS DE LA COMPETICIÓN
Deportistas y equipo técnico	Autobús discrecional	1h
Staff Estadios	Transporte público	2h
Prensa	Autobús discrecional	2h
Difusión del evento	Autobús discrecional	2h
Autoridades	Vehículo privado	30 min
Espectadores	Transporte público	Desde que finaliza el evento hasta 1,5h

Tabla 2 – Tipo de transporte por tipo de usuario y tiempo de estancia después de las competiciones

4.1 Jugadores y cuerpos técnicos

Se requiere diseñar rutas a los estadios y hacer una correcta planificación de itinerarios y horarios.

4.2 Espectadores

Los espectadores se desplazarán preferentemente en transporte público. Para lograrlo, es necesario un plan de comunicación específico. La movilidad será diferente para los estadios que tengan estación de Metro/Cercanías, o no. Si es necesario crear un servicio especial, se hará mediante autobuses lanzadera que conecten con los centros neurálgicos de las ciudades.

4.3 Autoridades

Se requiere diseñar rutas a los estadios donde la seguridad es un criterio fundamental.

Suelen requerir escolta policial y prioridad de paso en todo el recorrido. Es necesaria una adecuada planificación y gestión de los itinerarios en los últimos metros de aproximación a los estadios, donde las aglomeraciones de espectadores pueden comprometer la agilidad (y la seguridad) de los trayectos.

5. CALENDARIO DEL EVENTO. FECHAS CLAVE y ESTIMACIONES DE VISITANTES

5.1 Inauguración y clausura

El calendario de competición es diferente en función del tipo de evento deportivo.

En los Juegos Olímpicos, tras el pico de asistencia a la jornada de inauguración, la demanda es más estable, y sufre un descenso progresivo hasta la clausura de los mismos. En el caso de los Mundiales de Fútbol, son las semanas de la fase de grupos, donde hay un elevado número de partidos diarios, y llevan asociado un elevado volumen de público. Las semanas previas a la final son más variables en función de los países que lleguen a la final, y la proximidad al lugar de competición de estas regiones.

Como ocurre con los Juegos Olímpicos, las ceremonias de apertura y clausura o final son eventos clave de la competición y generalmente tienen una afluencia de asistentes importantes. En los Mundiales de Fútbol se estima que la afluencia a los estadios en estos eventos es en torno a un 20% mayor que en otros partidos en sedes de dimensiones similares. Por ello, deben tener un sistema de transportes reforzado estos días.

5.2 Tipología del evento.

Aunque la accesibilidad universal del transporte ha de garantizarse siempre, es importante tener en cuenta los clientes de la competición. En el caso de los Juegos Olímpicos, se celebran a continuación los Juegos Paraolímpicos, de menor repercusión en cuanto a número de visitantes, pero más exigente en cuanto a los criterios de accesibilidad universal. Por ello, deberá ponerse más hincapié en que el sistema de transporte sea accesible para todos los asistentes.

5.3 Sedes de competencia y entrenamiento

Por último, en los eventos deportivos como Juegos Olímpicos, o Mundiales de Fútbol, son igual de importantes las sedes de competencia como las sedes de entrenamiento. Estas sedes más pequeñas generan también demandas de movilidad, aunque más reducidas, por parte de deportistas, prensa, aficionados, etc. Es posible que estas sedes de entrenamiento no dispongan de una oferta adecuada de transporte público con el sistema de transporte habitual de la ciudad, por lo que será importante dotarlos de autobuses lanzadera desde puntos estratégicos de las diferentes ciudades, con unos horarios suficientes para que los asistentes tengan flexibilidad suficiente para acceder a dichas sedes.

6. ESTRATEGIAS DE TRANSPORTE

6.1 La gestión de la movilidad

En el diseño y gestión de la estrategia de movilidad es necesaria la coordinación efectiva de todos los organismos y agentes implicados. El reparto de competencias entre distintas Administraciones suele hacer recomendable la creación de un comité específico para la gestión de la movilidad durante el evento. Entre las funciones de este comité pueden plantearse:

- La planificación, regulación, mejora y gestión de todas las formas de transporte durante la duración del evento.
- La planificación de la infraestructura para el transporte público realizadas con ocasión del evento.
- Planificación y coordinación de las medidas de gestión de circulación asociadas.
- La gestión de los contratos de transporte público de pasajeros y sus modificaciones temporales vinculadas al evento.
- El diseño, aprobación y gestión de la política tarifaria asociada al evento, así como la puesta en funcionamiento de la billética especial.
- Información a los usuarios.
- Seguimiento de la calidad de los servicios.

6.2 Acciones en los diferentes modos de transporte

6.2.1 Metro y Cercanías

El Metro y las Cercanías deben ser los modos de transporte prioritarios en este tipo de eventos. Se trata de modos de transporte de alta capacidad, rápidos, confiables y seguros en los casos en los que las sedes tienen acceso al mismo en las inmediaciones. En los casos en los que no sea así, será necesario complementar estos modos de transporte con un sistema de autobuses que alimente a la red de Metro o la red de Cercanías desde las ciudades.

6.2.2 Autobuses

Se intentarán respetar los horarios de los servicios habituales para interferir lo menos posible en la rutina de la población que residen en la ciudad o ciudades donde se están celebrando las competencias.

La flexibilidad que otorga el autobús, en cuanto a número de vehículos y creación de rutas nuevas debe aprovecharse para la implantación de un sistema de lanzaderas en los casos en los que la red de Metro no llegue a todas las sedes de competencia, y autobuses alimentadores a la red de transporte de Metro.

6.2.3 Bicicletas

En el caso de las bicicletas, su uso va a depender de muchos factores.

El factor principal será la existencia de una infraestructura ciclista amplia y segura junto con una cultura del usos de la bicicleta. También pueden tener incidencia las fechas de celebración de la competición y la climatología asociada a las mismas. Aunque la mayoría de las veces suelen celebrarse en época estival, esto no siempre es así. También pueden influir la orografía de la ciudad donde tenga lugar la competición, la existencia de un servicio de bicicleta pública o la existencia de empresas de alquiler de bicicletas. En cualquier caso, se deberán reservar espacios en las zonas próximas a las sedes para aparcar las mismas, y carriles reservados para bicicletas en el viario urbano.

6.2.4 Vehículo privado y carriles reservados

El vehículo privado debe reservarse para los tipos de usuarios en los que este tipo de transporte es necesario. Se asume que las autoridades accederán , en la mayoría de los casos, en vehículos oficiales con fuertes medidas de seguridad. Por ello, es necesario que el aparcamiento en las sedes de competencia y entrenamiento este fuertemente limitado, incluso prohibido, para el público general y los trabajadores.

Además, resulta especialmente importante no colapsar la ciudad por un aumento de tráfico en las inmediaciones ya que esta congestión compromete la llegada y circulación de los autobuses que llevan a los deportistas, personal técnico, y a todo el personal de trabajo necesario para el desarrollo de la competición.

Se puede plantear la reserva provisional de carriles específicos para transporte público, para el acceso de deportistas o para vehículos de autoridades.

6.2.5. Accesos peatonales y última milla

En el diseño de las sedes de competencia, se deben recoger un determinado número de espacios para los asistentes previstos considerando el aforo de cada una dichas sedes. Así cada una de las sedes debe contemplar zonas de:

- Drop on-drop off: zonas de embarque y desembarque de autobuses y taxis
- Bolsa de taxis: que permitan asegurar una oferta adecuada de este servicio cuando finalice la competición.
- Front of house: zonas libres en el entorno del estadio para la libre circulación de personas. En ella se suele instalar las fans zone, food trucks o zonas con espacios publicitarios con sponsors de la competición.
- Back of house: zonas en la parte trasera del estadio para prensa, broadcasting, salas VIP, otros.

Además, se deben diseñar itinerarios peatonales desde las estaciones próximas y zonas de drop on-drop off hasta el recinto de la sede de competencia. Estos itinerarios deben ser seguros para el peatón y con la señalética especifica de la competición.

Desde el punto de vista de la seguridad, también es importante guiar a los asistentes hasta el perímetro y zona de front of house.

Se deben crear mapas de última milla, que pueden ser descargados y consultados por los espectadores. En las áreas de drop off y drop on conviene que haya voluntarios repartiendo estos mapas que faciliten el conocimiento del entorno, o desde las estaciones de Metro y Cercanías más próximas.

6.2.6 Sistemas Park&Ride

En la medida de lo posible, y con la finalidad de limitar el uso del vehículo privado en las inmediaciones de las sedes de competencia y entrenamiento, otra de las medidas a implantar es la implantación de sistemas Park&Ride en puntos estratégicos de la ciudad o en las proximidades de las estaciones de la red de Metro.

6.2.7 Sistema de tarifas. Billete único

Como se ha comentado anteriormente, en este tipo de eventos es habitual que el billete de transporte público se facilite con la entrada al evento y que tenga validez variable, normalmente cubriendo desde un día antes del evento hasta el mismo día en el que se tenga entrada. Esto favorece que los asistentes, desde el momento en el que llegan a la ciudad a las estaciones de tren o aeropuerto, usen el transporte público.

6.3 Información al usuario

Es necesario crear un plan de comunicación sobre la movilidad para dar a conocer las posibilidades del sistema a los visitantes y que dar a conocer a los residentes las modificaciones implantadas con motivo de la celebración del evento deportivo.

El plan debe incluir una página web que centralice toda la información señalada anteriormente.

También puede contemplarse el despliegue de voluntarios en puntos clave (aeropuerto, estaciones, proximidades del estadio) con dispositivos móviles para que puedan dar respuesta a las consultas de transporte realizadas por los usuarios.

El plan de comunicación debe tratar de informar a los usuarios de la importancia de iniciar el viaje con tiempo, para poder disfrutar de las actividades que se ofrecerán en los alrededores del estadio (música, deportes, actividades culturales, etc.). Esto permitirá una mejor gestión de la demanda en momentos clave antes del inicio de los partidos, evitando el colapso del sistema de transporte.

6.3.1 Llegadas y salidas al país

Los grandes eventos deportivos atraen participantes, periodistas y espectadores de todo el planeta. Un aspecto a analizar es la capacidad de los infraestructuras de transporte de entrada al país anfitrión, en especial los aeropuertos y su conexión con las ciudades.

En grandes ciudades con aeropuerto internacionales importantes o en países con una fuerte oferta turística, como España, Italia o Francia, la capacidad de acogida de los aeropuertos no suele ser un problema. Además, en Europa, la proximidad entre países permite diversificar los modos de entrada al posible país anfitrión.

En otros casos puede ser necesario analizar la capacidad de estas infraestructuras y, sobre todo, reforzar la oferta de transporte entre las terminales aéreas y las ciudades destino de los visitantes.

7. LEGADO Y BUENAS PRÁCTICAS

7.1 Legado

A la hora de elegir una ciudad anfitriona para un gran evento deportivo, una de los condicionantes es, entre otras, el legado que le puede traer la celebración de la competición a la ciudad. En algunos casos, la utilización posterior de la infraestructura deportiva es importante, pero resulta igual de importante dotar a la ciudad de una buena experiencia en el sistema de transporte y aprovechar el desarrollo de la competición para implementar medidas que hagan que una vez la competición finalice, siga siendo el modo elegido por la población residente, en caso de que no lo sea antes de la competición.

Por ello, es importante dotar al sistema de transporte de un aporte presupuestario suficiente que permita el desarrollo de la competición de forma segura y exitosa como hemos mencionado anteriormente, y que permita desarrollar medidas que, si bien son necesarias para la ciudad, la celebración de la competición en la misma las acelera.

7.2 Medidas temporales limitadas

Por el contrario, deberá limitarse el número de medidas que sean necesarias para el desarrollo de la competición, pero no encajen con la configuración de ciudad y no sean necesarias una vez finalizada la misma, con el objetivo de lo incurrir en un coste que posteriormente no tendrá un legado definido.

EXPLORING THE SPATIO-TEMPORAL DYNAMICS OF MOPED-STYLE SCOOTER SHARING SERVICES IN URBAN AREAS.

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RESUMEN

Spain is one of the countries with the highest shared mobility fleet in the world. The shared use of motorcycles, also known as moped-style scooter sharing, has spread far and wide throughout the country at a dramatic pace in recent years. Despite its increasing popularity and impact on urban mobility, efforts devoted to the study of its spatio-temporal travel patterns are still scant.

Based on the analysis of GPS records of an operator present in seven Spanish cities, this study aims to contribute to this research gap by analysing mopeds' location patterns over time and assessing how different dynamics influence its usage level and self-balance potential. Our study is replicable to different cities and different shared modes, since we propose a methodology to identify the most important origins and destinations over time and analyse the system's self-balance capacity based on spatial autocorrelation tools. These insights are useful for operators to adjust and optimise vehicle distribution routes and maintenance/recharge tasks, decreasing congestion and increasing efficiency. The results may also be helpful for policy makers when planning and offering effective policies and infrastructure to encourage shared mobility.

1. INTRODUCTION

In recent years, shared mobility has grown in many cities around the world. It has been defined as the short-term access to shared vehicles (cars, bicycles, moped-style scooters, and scooters), according to the user's needs and convenience, instead of requiring vehicle ownership (Shaheen et al., 2016). More specifically, the term micromobility was coined to refer to low-speed shared vehicles like bicycles and scooters (moped and kick-style) that have recently drawn more attention (Shaheen & Cohen, 2019). Micromobility offers a flexible transport option capable of avoiding road congestion, reducing the required parking space, lowering noise/air pollution, since all vehicles are hybrid-electric/electric, and last but not least, encouraging intermodality with mass transit. Additionally, mopeds particularly provide faster speeds than bicycles, and this is a very attractive mode for non-flat cities (Aguilera-García et al., 2020).

Studies regarding micromobility essentially focus on docked and dockless bike-sharing systems (for example, Gu et al., 2019; Ji et al., 2020; Lazarus et al., 2020), comparing bike-sharing to scooter-sharing services (McKenzie, 2019) or analysing scooter-sharing travel patterns (Feng et al., 2020; McKenzie, 2020), but there is almost nothing to be found related to moped-style scooter sharing particularly. Most contributions regarding mopeds are related to accidents and safety issues (Aare & von Holst, 2003; R. A. Blackman & Haworth, 2013; Haworth, 2012; Huang & Wong, 2015) or riders' attributes, but they only consider those *who own* a motorcycle (R. Blackman & Haworth, 2010; Jamson & Chorlton, 2009; Rose & Delbosc, 2016; Yannis et al., 2007). As a clean alternative to the car and as a growing shared mobility sector, we consider this effort to be worthwhile. The few studies that exist on shared mopeds focus on user characteristics and preferences (Degele et al.,2018; Aguilera-García et al., 2020).

Our study will focus not on users, but rather of their trips. Our objective is to analyse and visualise mopeds' urban footprint and compare its spatio-temporal dynamics in different cities. The research aims to fill a knowledge gap related to the spatio-temporal patterns of shared mopeds. It proposes an original methodology that uses spatial autocorrelation tools to analyse travel patterns and visualise spatio-temporal behaviour over time, identifying the spots where most trips begin or attend, and assessing to which extent the system is self-balanced, obtaining insights from different dynamics. We based our analysis on a dataset provided by an operator present all throughout Spain called Muving.

These kinds of data-sharing initiatives have grown increasingly popular in recent times and will continue to do so, especially with the institutional support that they are attracting; an example of this is the recent proposal to build the European Common Mobility Data Space (European Commission, 2020) as a strategy to enable data availability, access, and exchange between different stakeholders.

Our findings are useful for authorities to understand the mobility patterns of this important sector, plan and offer strategies or public policy, design infrastructure to promote their use, and regulate accordingly.

They are also important for shared mobility operators, adding value to raw datasets and using insights to improve everyday operational tasks (maintenance, recharging, and distribution of vehicles). The rest of the article is divided into four sections. Following the introduction, Section 2 summarises the related literature. Section 3 describes the study context, data, and methods used for the research. Results are presented in Section 4, and lastly, the main conclusions are outlined in Section 5.

2. RELATED LITERATURE

Urban mobility technologies have undergone substantial and increasingly rapid change over the past two decades, especially in relation to shared mobility services (Pangbourne et al., 2020; Shaheen & Cohen, 2018). The rapid development of social media, Information and Communication Technologies (ICT), and new business models based on the sharing economy have enabled these new services to appear in many cities, changing the transport supply and causing an important impact on travel behaviour. The European Commission has highlighted the importance of multimodality and new shared mobility solutions that take advantages from each mode and are proving crucial to improve the transport system's resilience (especially during the COVID-19 pandemic) (European Commission, 2020).

Some even consider shared mobility development as one of the three revolutions in urban transportation, along with vehicle electrification and automation (Fulton, 2018).

Shared mobility and micromobility are still relatively recent topics because the technology that allowed them to arise in many cities only occurred about a decade ago. Nevertheless, many studies related to bike-sharing (Eren & Uz, 2019; Ricci, 2015) have been published.

This was not the case for the scooter sharing sector (kick or moped-style), which is understandable, since it mostly started running operations only a few years back (in the case of Spanish cities, around 2017). Given the recent nature of their worldwide expansion, to our knowledge, only two studies have been found regarding moped-style scooter sharing. With the data provided by a German operator, Degele et al.,(2018) developed a cluster analysis to segment users according to their age, time between rides, distance driven, and revenue per customer.

They identified four types of moped users (power users, generation-X casual users, generation-Y casual users, and one-time users), analysed which type provided the most revenue, and proposed strategies to retain and promote their usage.

On the other hand, (Aguilera-García et al., 2020) conducted a generalised ordered logit model to identify the key drivers determining the adoption and frequency of use of mopeds in Spanish urban areas. They found that both personal socioeconomic characteristics and trip-related attributes played a major role in explaining the adoption of scooter-sharing services. Young and highly-educated people proved to be the segment of the population with the highest probability of using mopeds, but they also found a considerable amount of people in middle-aged groups.

None of the previously mentioned studies examined the spatial distribution patterns of moped trips. However, bikeshare-related studies can offer some lessons on travel behaviour associated with these systems. Temporal usage patterns show a morning and an evening peak, especially for commuting (Wang et al., 2018). Spatial analyses show that bikes are commonly taken from residential areas to travel to commercial zones, central business districts (CBDs), employment centres, and train stations in the morning, and back to residential areas during evenings (Caspi et al., 2020). In addition, it has been found that the temporal and spatial concentrations of dockless bikes are mainly influenced by the built environment, particularly density and street connectivity (Xu et al., 2019), and that most riders cycle short distances in urban centres (Li et al., 2018). Bicycle travel times are especially competitive compared to other transport modes for short trips in the city centre during peak periods (Romanillos & Gutiérrez, 2019). Most of these papers used GPS datasets collected by operators.

Studies regarding micromobility and the analysis of spatial patterns using spatial autocorrelation tools are particularly scarce. An exception is the study on shared e-scooters by Jiao & Bai (2020) which uses univariate LISA to identify areas of high demand (hot spots) as a preliminary step before applying regression models. We elaborate on this research line and use the most common spatial autocorrelation tools to explore micromobility trips, making use of univariate and bivariate Global Moran's I and LISA statistics and including the temporal component (time bands) in order to capture the dynamics of the system. Univariate analysis allows us to answer the questions of when and where demand is more clustered, and bivariate analysis allows us to answer the question of when and where demand is more self-balanced. Both issues (demand concentration and self-balance potential) are key elements for good management and planning of micromobility services.

3. STUDY CONTEXT, DATA, AND METHODOLOGY

3.1 Study context

Spanish city centres are generally characterised by old historic urban structures, with narrow streets and recurrent congestion problems, which could positively influence the use of shared mopeds. Whatever the reason, the country is one of the hubs with the highest shared moped fleet in Europe, resulting in approximately 9,000 motorcycles (Aguilera-

García et al., 2020; Howe, 2018). This research was conducted with a dataset provided by one of the most important operators present in seven Spanish cities in 2019: Madrid, Valencia, Seville, Saragossa, Malaga, Cordova, and Cadiz. Table 1 summarises some of their relevant characteristics for the study. As can be seen, Madrid and Valencia are the most important cities in terms of population; however Saragossa, Seville, and Cadiz also show high density (Inh/km^2) which is an important factor influencing the adoption of shared services (Munkácsy, 2017; Velázquez Romera, 2019).

Three of them are coastal cities, which usually have higher tourist activities promoting the use of mopeds. Warmer cities are mostly within the Andalusia Region in the south of Spain (Seville, Malaga, and Cadiz). Annual precipitation level is low in the seven cities analysed, which is also important to consider, as rainfall may reduce the use of micromobility in general.

Attribute		Madrid	Valencia	Seville	Saragossa	Malaga	Cordova	Cadiz
Population (municipality)		3,174,000	791,413	688,711	666,880	571,026	325,701	116,027
Average annual temperature (ºC)		15.0	18.3	19.2	15.5	18.5	18.2	18.6
Average annual precipitation (mm)		421	475	539	322	534	605	523
Coastal city		No	Yes	No	No	Yes	No	Yes
Modal split (%)	Public transport	24	21.8	26.2	24	13.2	12.04	7
	Car	39	21.5	35	28	37	44.15	48
	Active**	37	56.7	38.8	48	49.8	43.81	45
Moped-style scooter-sharing operators	Number of operators	4	3	2	2	1	1	1
	Name of companies	Acciona, Movo, Ecooltra, Muving	Acciona, Ecooltra, Muving	Acciona, Muving	Acciona, Muving	Muving	Muving	Muving
Topography		Hilly	Flat	Flat	Flat	Flat	Flat	Flat

Table 1 -Summarised characteristics of the seven cities analysed. Source: the authors with data from Greenpeace, (2019). *updated with results from the last Mobility Survey in 2018 (Comunidad de Madrid, 2018). ** Active = walk + bicycle + other low-speed mode. Data for Cordova and Cadiz was extracted from official reports (ETRALUX, 2011; Junta de Andalucía, 2018).

Only Valencia and Madrid have three or more moped-style scooter sharing operators. In the case of Madrid alone, some studies point to its role as one of the most important shared mobility labs in Europe, with an estimated fleet of more than 20 thousand vehicles (Arias-Molinares & García-Palomares, 2020a; Granda & Sobrino, 2019). These operators usually manage and maintain a fleet offered through an application where individuals access and subscribe to their service. Users pay a fee every time they use a vehicle, while operators are in charge of energy consumption and maintenance. In Spain, electric vehicles do not have parking restrictions in city centres and generally benefit from free on-street parking, providing an attractive alternative for inner districts (for example, in the case of Madrid, within the M-30 highway) (Aguilera-García et al., 2020).

3.2 Data

The dataset for the study contains data collected by the GPS devices installed on mopeds owned by Muving. The data was provided in CVS format, including all trips made between 13 February 2019 and 31 December 2019, and the following information:

- *Id_vehicle:* an identification number for each motorcycle.
- *Id_customer:* an identification number for each user.
- *Start_time:* trip starting timestamp (format: yy-mm-dd hh:mm:ss).
- *Start_latitude and longitude:* xy coordinates where the motorcycle was picked up.
- *End_time:* trip ending timestamp (format: yy-mm-dd hh:mm:ss)
- *End_latitude and longitude:* xy coordinates where the motorcycle was left.
- *Trip time:* trip duration in minutes.
- *Travelled distance:* travelled distance in km of the real trajectory by the street network.

3.3 Methodology

The data workflow covered entering, cleaning, transforming, describing, analysing, and visualising data. Given the size of the dataset (almost two million entries), we processed it using Python (vs 3.8) programming language. A script performing all steps was created: to load the CSV files, extract the day and hour of the trip in the timestamp information, and obtain a new output table. This output table was then imported to a GIS environment (ArcGIS Pro vs. 2.5.2) to display coordinates, geolocate points, and create a new column with the city name. An outlier cleaning process followed, using travelled distances, which in some cases went unrealistically higher than average. In order to discard these outliers, boxplots were made for each city and the final valid dataset included 1,797,2228 trips (see Table 2).

City	Trips with outliers	Distance (km) from which outliers were identified (boxplot)	Trips without outliers
Madrid	307,876	9.3	298,031
Valencia	437,795	8.1	425,683
Seville	477,424	8.4	463,825
Saragossa	201,294	8.6	195,942
Malaga	135,626	9.8	131,940
Cordova	126,061	6.4	121,034
Cadiz	163,616	6.7	160,773
Total	**1,849,692**		**1,797,228**

Table 2 -Dataset without outliers. Source: the authors.

Since time and distance travelled were provided, we calculated average speed, as well as some other indicators, like average usage (trips/customers) and average vehicle rotation per day (trips/vehicles/365days per year). Consequently, a model builder was created in ArcGIS to split the dataset by city, day of the week, and time band. We decided to aggregate the days of the week into two groups: working days (from Monday through Thursday) and weekends (Saturday and Sunday).

We excluded Friday from working days because in Spain, as described by Romanillos (2018), it is common to finish work earlier on Fridays, with particular travel patterns that could influence the normal working-day dynamic.

Regarding time bands, we selected four different hour periods: from 07 to 10 to evaluate the morning peak, especially for obligatory trips (commuting to work/study), 13 to 16 to analyse midday behaviour (lunchtime or midday activities), then 19 to 22 for after-work activities and/or return-to-home trips, and finally, from 23 to 02 hours to evaluate nightlife patterns. After splitting the dataset by time bands, the different layers according to each scenario (city, day of the week, and time band) were spatially aggregated into a hexagonal grid, obtaining the number of starting/ending trips by hexagon. Studies focusing specifically on walking distances to pick up shared mopeds were not found, but (Aguilera-García et al., 2020) found that users were willing to walk up to 500m. Hence, we determined 200 meter-sided hexagons with a surface area of 10,3923048 Has as the optimal size to aggregate our data, since 200m appears to be an acceptable walking distance to pick up a motorcycle.

Lastly, the hexagonal grids were used to perform location patterns analysis using ESDA tools. To this end, we used GeoDa software (vs 1.16.0.16) to calculate two different Global Moran's Indices (Anselin, 1995). The first one was univariate Global Moran's I statistics for origins and destinations separately. This helped us to study the level of concentration or dispersion of the origins and destinations of moped trips, and their variation over the course of the day. This insight could be of interest to inform operators as to the most optimal time and location to carry out operational tasks, like vehicle redistribution, recharging, and maintenance, and to know when/where demand is coming from. In addition, bivariate Global Moran's

I was calculated to measure the spatial association between the destinations and origins of trips. Insights from this statistic served to analyse whether the system is self-balanced throughout the day by answering the question: "*are users ending their trips near where others are starting theirs?*" If the system is balancing itself, then the locations where users are arriving at a certain time are also the locations where other users are starting their trips, allowing for higher vehicle rotation. Both univariate and bivariate Global Moran's I statistics were calculated using a contiguity weight matrix of 1st order. The resulting univariate and bivariate Global Moran Indices and their z-score were graphed, and symbology was applied to the hexagonal grids, generating maps by time bands.

Figure 1 illustrates the conceptual framework of the different Global Moran's Indices calculated, in relation to expected origin-destination location patterns. Our hypothesis predicts that origins are more dispersed than destinations in the early morning band (predominance of trips from residential areas to the city centre), while the opposite should occur in the last bands of the day (predominance of return-to-home trips).

It also expected that the system will tend to balance itself during the middle bands, since, at those hours, the population tends to be concentrated in the city centre, which produces a greater proximity between origins and destinations.

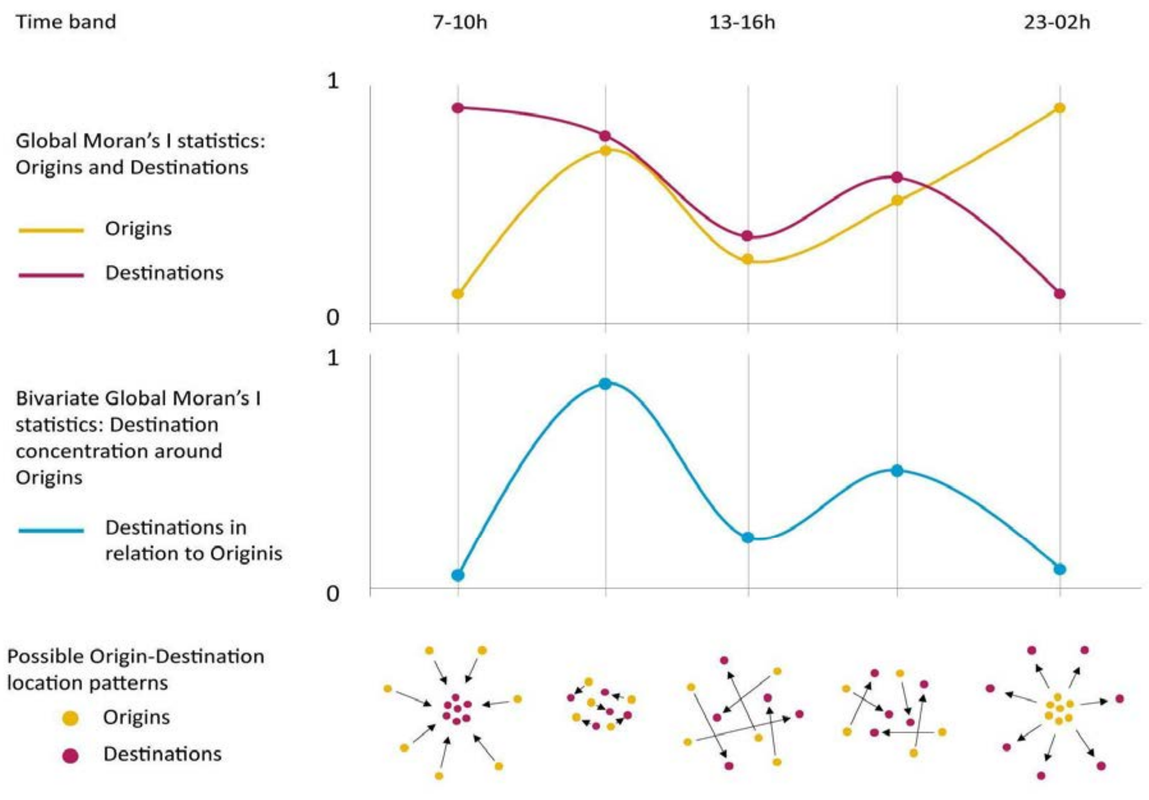

Fig 1- Conceptual framework of the different Global Moran's Indices calculated. Source: the authors.

In addition, univariate Anselin Local Moran's I (LISA statistic) was used in order to identify and map local tendencies (clusters and outliers) related to the location of origins and destinations by time bands. With LISA statistics, it is possible to distinguish High-High clusters (a high value surrounded primarily by high values), Low-Low clusters (a low value surrounded primarily by low values), and spatial outliers, either High-Low (high values surrounded primarily by low values) or Low-High (low values surrounded primarily by high values) (Anselin, 1995). Lastly, bivariate LISA cluster maps for origins and destinations, by time bands, and on working days, were graphed in order to identify areas with a high concentration of both origins and destinations (HH clusters) in which the system self-balances, or other areas with imbalances between origins and destinations (HL and LH outliers).

4. RESULTS

4.1 Service characteristics and performance

Table 3 shows the descriptive characteristics of the dataset analysed. Seville and Valencia generated the greatest number of trips during 2019, with 463,825 and 425,683 trips respectively, while Madrid, the most populated city, generated 298,031.

In relation to this fact, it is important to consider that large metropolitan areas usually have more operators, so competition is a crucial factor that determines their market share. In addition, Madrid is one of the cities with the highest shared mobility fleet, not only of mopeds, but also of other modes like bicycles, cars, kick-scooters, etc.

This context could also explain why, although Madrid has more deployed vehicles, Valencia and Seville show a higher number of trips and more trips per customer throughout the year, with 13.87 and 12.92 respectively, in comparison with Madrid, with 9.33 trips per customer. The average vehicle rotation per day results in 2.04. Cities above this average, like Cadiz, Saragossa, Seville, and Valencia, are more attractive for companies (as the system is more profitable) than, for instance, Madrid, which bears the minimum value with just 1.08 vehicle rotations per day.

City	Trips	Vehicles	Customers	**Usage** (trips by customers)	**Veh. rotation/day** (trips/vehicles/365 days)	**Average trip time** (min)	**Average trip distance** (km)	**Average Speed** (km/hr)
Madrid	298,031	755	31,934	9.33	1.08	11.48	3.49	18.24
Valencia	425,683	578	30,692	13.87	2.02	10.28	3.18	18.56
Seville	463,825	591	35,902	12.92	2.15	10.40	3.23	18.63
Saragossa	195,942	240	15,313	12.80	2.24	10.53	3.42	19.49
Malaga	131,940	196	12,613	10.46	1.84	10.86	3.68	20.33
Cordova	121,034	184	9,715	12.46	1.80	9.06	2.67	17.68
Cadiz	160,773	186	10,755	14.95	2.37	9.05	2.73	18.1
Total	**1,797,228**	**2,414** (316 vehicles duplicated in different cities)	**129,384** (17,540 users duplicated in different cities)	**13.89**	**2.04**	**10.24**	**3.20**	**18.72**

Table 3 -Descriptive characteristics of the dataset analysed. Source: the authors.

Average trip time, distance, and speed prove relatively homogenous across the different cities, with a trip time of around 10 minutes, a 3 km distance, and an 18km/hr speed. The city with the highest trip time is Madrid (11.48 minutes), which could be expected since it is the capital of Spain and is a more congested urban area.

However, this 12-minute ride is still relatively fast compared to other services, such as bike-sharing, which displays trip times of 15 minutes or more (Romanillos, 2018). In any case, travel time and distance may be highly influenced by the size of the company’s service area. Certainly, future expansions of these areas could allow users to travel longer distances. Regarding distances travelled, mopeds are mostly used for short urban trips between 1 and 3 km (see Figure 2). Madrid, Valencia and Seville, which are large metropolitan areas, display a considerable number of trips with longer distances.

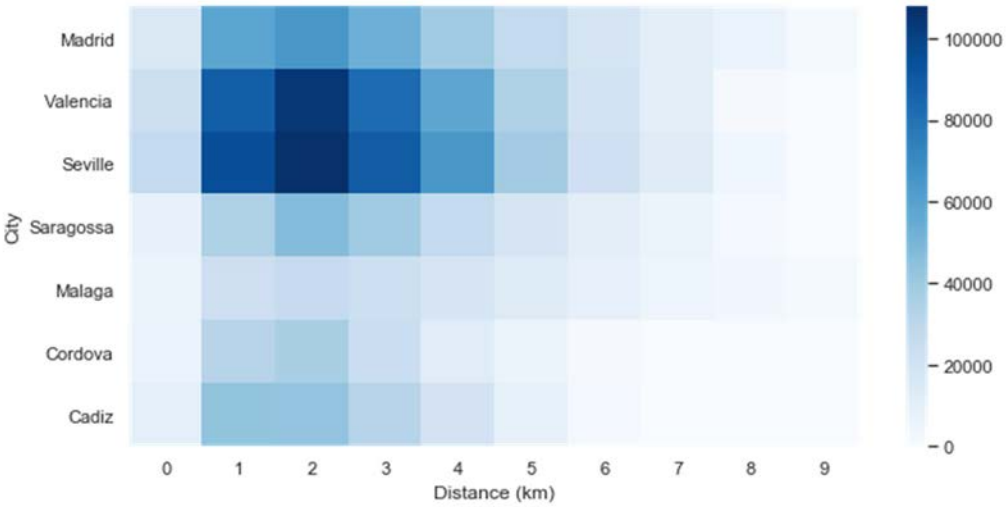

Fig 2 - Number of trips by distance travelled and city. Source: the authors.

In addition to this comparative analysis between cities, when it comes to general fleet and customers, we found that 2,414 mopeds were operating in Spain during 2019 and almost 130,000 clients used one (of which 17,540 made trips in more than one city). The fact that some customers use the app in different cities could demonstrate their intention to use this kind of platform when travelling to different areas, which is an important insight, especially with the introduction of new concepts like Mobility as a Service (MaaS) (Arias-Molinares & García-Palomares, 2020b; Jittrapirom et al., 2017).

4.2 Temporal patterns

When analysing average daily trips by month, we identify a general trend for Spanish cities, with high peaks in March, May and October, and valleys in April and August (see Figure 3). Peaks are related to the beginning of spring season, when the temperatures rise and shared mobility becomes more attractive. High trip counts in September and October correspond to the return from summer holidays when users begin their daily routines again.

The valley seasons (April and August) concentrate most holidays (especially the summer season), when most Spaniards travel for holiday; this is very notorious in the case of Madrid, where the trip count drops considerably. Cities that follow a different trend are, for example Seville, which shows a high peak in April. This is probably due to the increase in tourist and local activity during the Holy Week and Seville’s Fair.

Other cities that follow different patterns are Malaga and Cadiz, which display high number in August, possibly related to the fact that these cities are summer tourist destinations. In these latter cities, trip counts are homogenous throughout the year, increasing notoriously only during the summer season, from which we might infer that many of the moped users during those months are tourists.

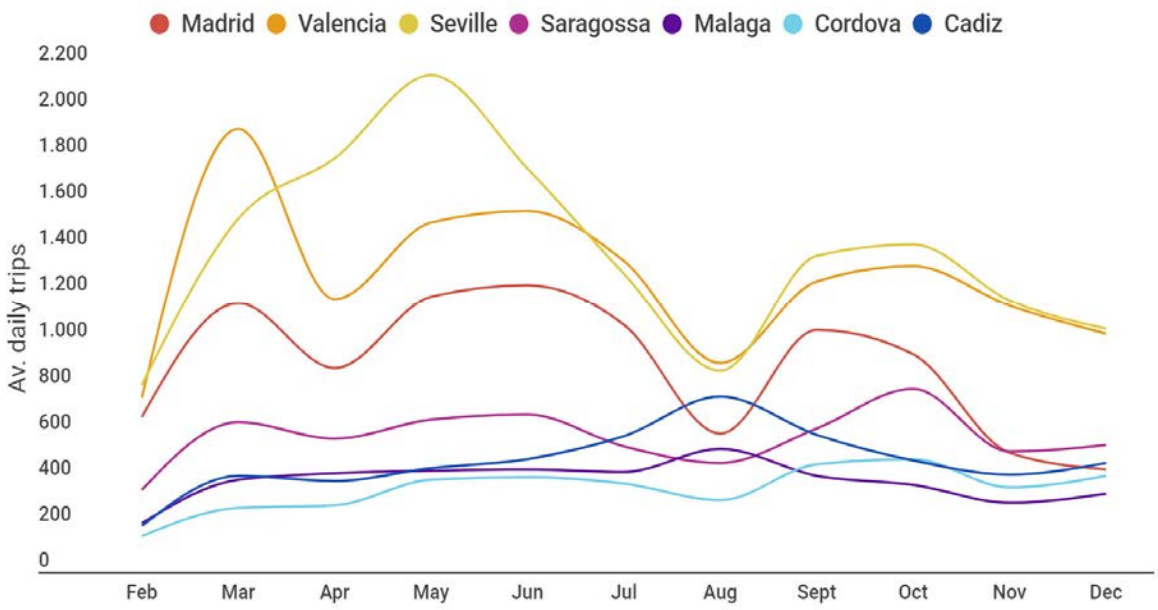

Fig 3 - Average daily trips by month (2019). Source: the authors.

When aggregating data by day of the week, Table 4 shows that in general, 72% of the trips are made on working days and 28% over weekends. These results lead us to infer that mopeds are not only used for recreational trips, but also for other purposes, like commuting or running errands. Figure 4 shows that the distribution of trips is quite homogeneous throughout the week in greater detail.

City	Working days (M-T)	Friday	Weekends (S +D)	Total
Madrid	169,425	45,773	82,833	298,031
Valencia	240,681	62,587	122,415	425,683
Seville	262,801	71,843	129,181	463,825
Saragossa	107,846	29,684	58,412	195,942
Malaga	73,771	20,030	38,139	131,940
Cordova	67,629	18,869	34,536	121,034
Cadiz	90,363	24,037	46,373	160,773
Total	**1,012,516**	**272,823**	**511,889**	**1,797,228**

Table 4 -Trips by day of the week. Source: the authors.

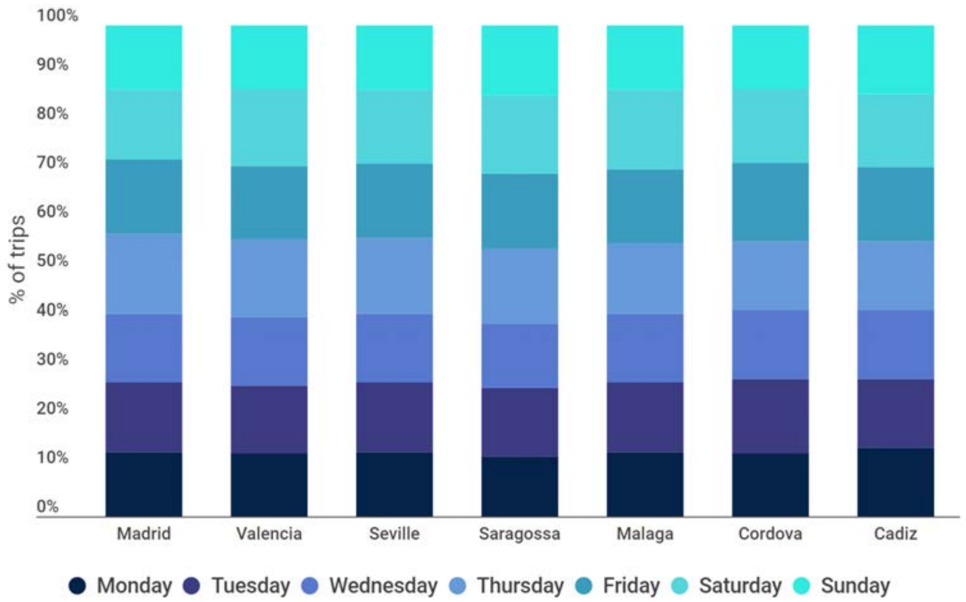

Fig 4 -Percentage of trips by day of the week. Source: the authors.

When exploring hourly patterns, Figure 5 shows the average daily trips on working days and weekends. Relatively homogeneous temporal behaviour is revealed with trips increasing toward the afternoon. We noticed three different peaks: the smallest one from 8 to 9 for commuting, a medium one from 13 to 14 related to midday activities (i.e., lunchtime), and the greatest one from 18 to 20 related to after-work activities and/or returning home. On the other hand, over weekends, the early morning rush hour disappears, and the midday peak (13-14 hrs) becomes as great as the night-time period (19-20 hrs), since many people start doing their activities from late morning onward. And lastly, over weekends, a significant percentage of trips is observed in the early hours (dawn), when customers use mopeds to return home from their night-life activities, given that the subways or public transport options are more limited. Given the lower usage over the weekend and the greater diversity in purpose, the spatial analysis was performed only for working days.

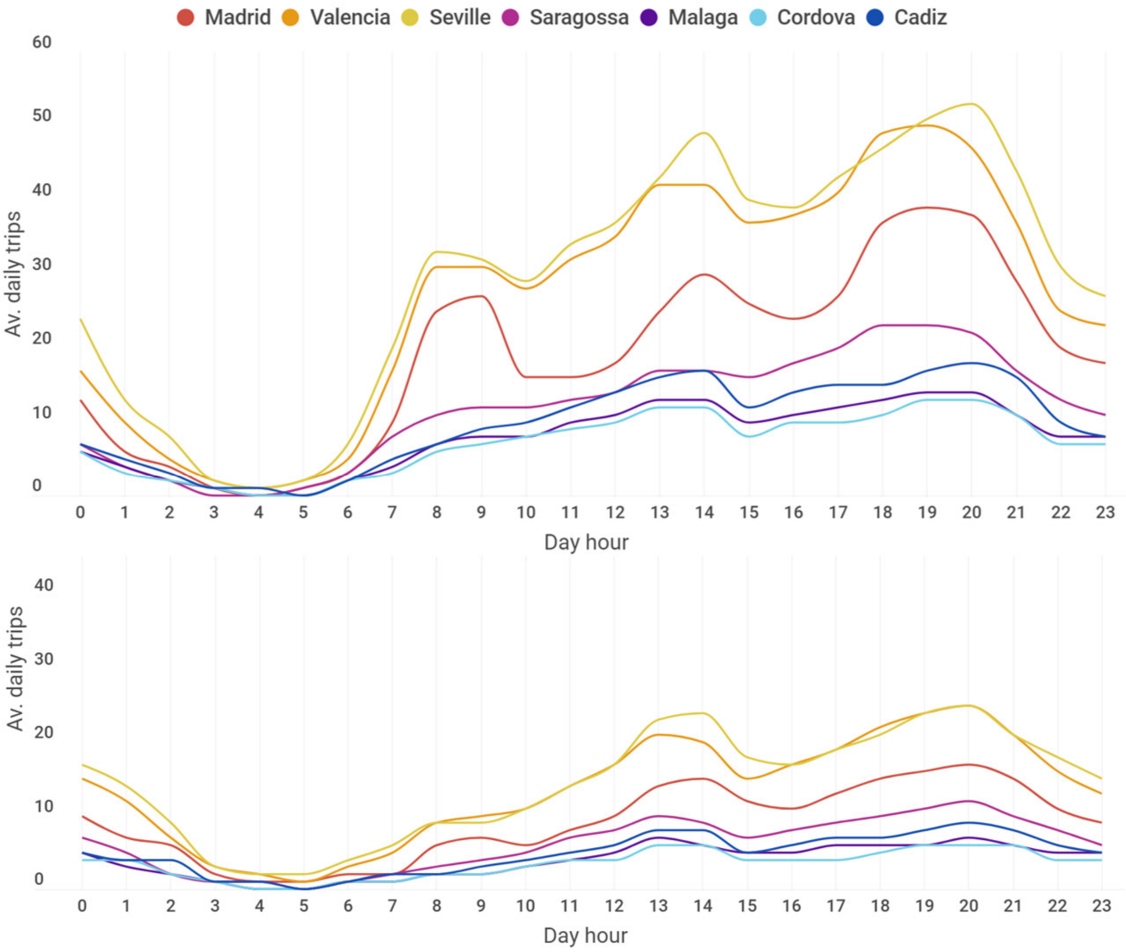

Fig 5- Average daily trips by hour of the day (top: working days, bottom: weekends). Source: the authors.

4.3 Mapping origins and destinations of trips over time

Visualisation of the spatial distribution of trip origins and destinations over the course of a working day is shown in Figure 6. In general terms, it reveals that, in the first band (07-10), origins are more dispersed than destinations, while in the last time band (23-02), the opposite occurs. This pattern follows the hypothesis outlined in the initial conceptual framework, as morning users usually come from different residential zones and commute to (mostly) specific clustered workplaces. In the late hours, users do the opposite, coming from clustered after-work locations and returning to those dispersed residences. In some cases, these residential areas may match, meaning that late-night users are leaving mopeds at the same or near the same areas where morning users will take them, which will make the system self-balanced. However, in most cases, the ending spots do not match the starting ones, which requires vehicle redistribution by the operator to cover demand areas in mornings.

On the other hand, band 2 (13-16) and 3 (19-22) have more similar dynamics since origins and destinations are homogeneously distributed, with a slight difference in band 3 when destinations appear to be a bit more concentrated. In these two bands, trips are coming and arriving at similar areas, enabling a higher vehicle rotation. This time period of the day responds to midday-activities, like having lunch, running errands, and doing after-work activities, which usually take place at public facilities, restaurants, bars, gyms, and entertainment locations that are very spread throughout the city. This contributes to a less marked difference between origins and destinations. Hence, this is the period of time when the system's self-balance potential is most realized, in comparison with bands 1 and 4.

These results illustrate that the different spatio-temporal dynamics for shared mopeds in cities are closely related to their land-use distribution. For each city, we can identify the most important origins and destinations by time of the day, which informs operators where to allocate their resources at each time to cover a greater demand, and also for public authorities to know where to allocate infrastructure like parking facilities. The results obtained in the particular case of Cadiz, for this analysis and subsequent analyses, must be carefully interpreted, considering its particular location and shape: the city of Cadiz is located on a narrow slice of land surrounded by the sea. All results and maps are affected by this spatial singularity.

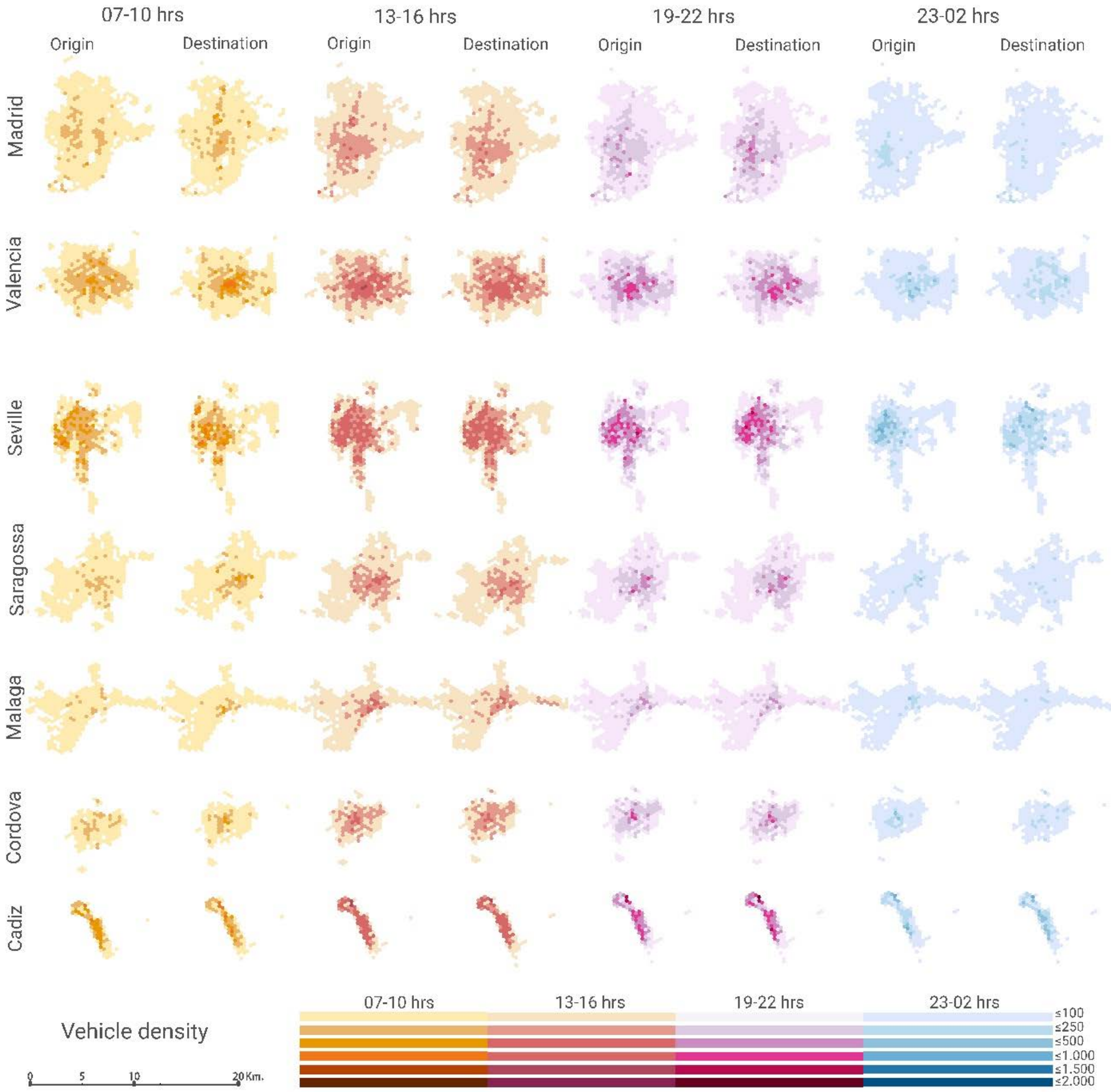

Fig 6- Spatio-temporal dynamics of mopeds during working days. Source: the authors.

4.4 Spatial autocorrelation analysis: local trends

As described in the methods section, in addition to map visualisations, we performed a series of spatial statistical analyses in order to further explore and quantify the trends previously identified. Firstly, Anselin Local Moran's I statistic was calculated in order to map the presence of origin and destination clusters at local level. The maps illustrated in Figure 7 show the marked differences between High-High clusters in bands 1 and 4, due to the location of residential zones and workplaces, especially in Valencia and Madrid, whereas HH clusters in bands 2 and 3 are located quite similarly. In all cases, there is a clear concentration of HH clusters in the city centre and LL on the periphery. Interestingly, the HH cluster maps of destinations in each time band are very similar to the HH cluster maps of origins in the following time band, which proves that the availability of vehicles near the users' location clearly influences increased usage.

Moreover, interesting results are obtained from observing spatial outliers, especially in the first band, which is mostly for commuting trips. In Madrid, for example, an HL spatial outlier for origins is located at Ciudad Universitaria, which is Madrid's main higher-education hub, meaning that from 07 to 10 AM, many trips begin on these university campuses.

Fig 7- Univariate LISA cluster maps for origins and destinations by time bands and working days. Source: the authors.

When considering Madrid as an example case to zoom closer, we differentiate certain dynamics throughout the day, especially during band 1 (see Figure 8). In the morning hours, demand mostly comes from districts that concentrate residential zones with a medium-high income population (Chamberi, Salamanca, and the east area of Tetuan) and mostly arrives at workplaces and offices located over the north-south axis of Paseo de la Castellana. The geolocation of demand is consistent with results obtained by Aguilera-García et al. (2020), which revealed that most moped users had relatively high incomes.

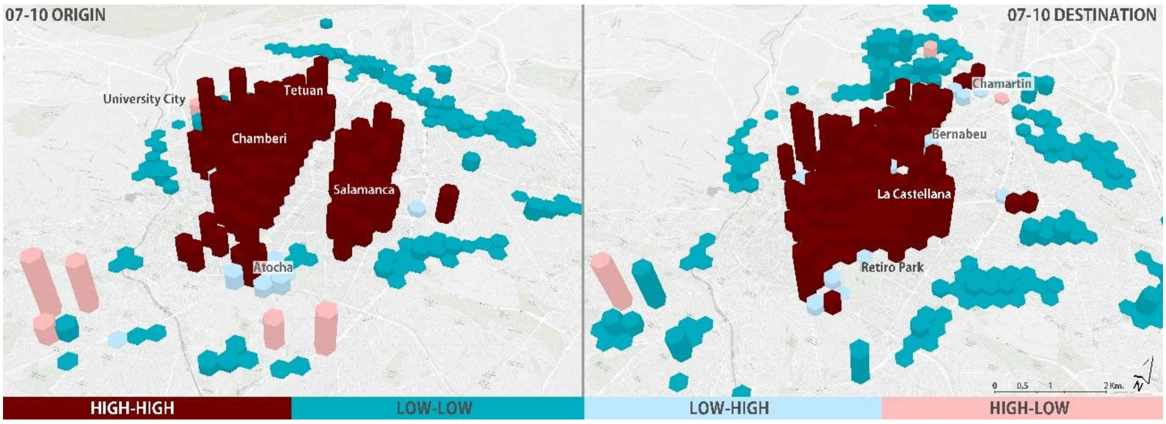

Fig 8-visualisation of Madrid's spatial clusters on band 1 during working days. Source: the authors.

Moreover, Bivariate Anselin Local Moran's I statistics for destinations around origins were calculated for every city and time band on working days. The results illustrated in Figure 9 show the same centre-periphery pattern for all case studies, with the exception of Cadiz, which seems to rather have a north-south pattern with HH clusters in the north area and LL clusters in the south. We observe that in time bands 2 and 3, HH clusters are more compacted around the city centres in comparison with bands 1 and 4.

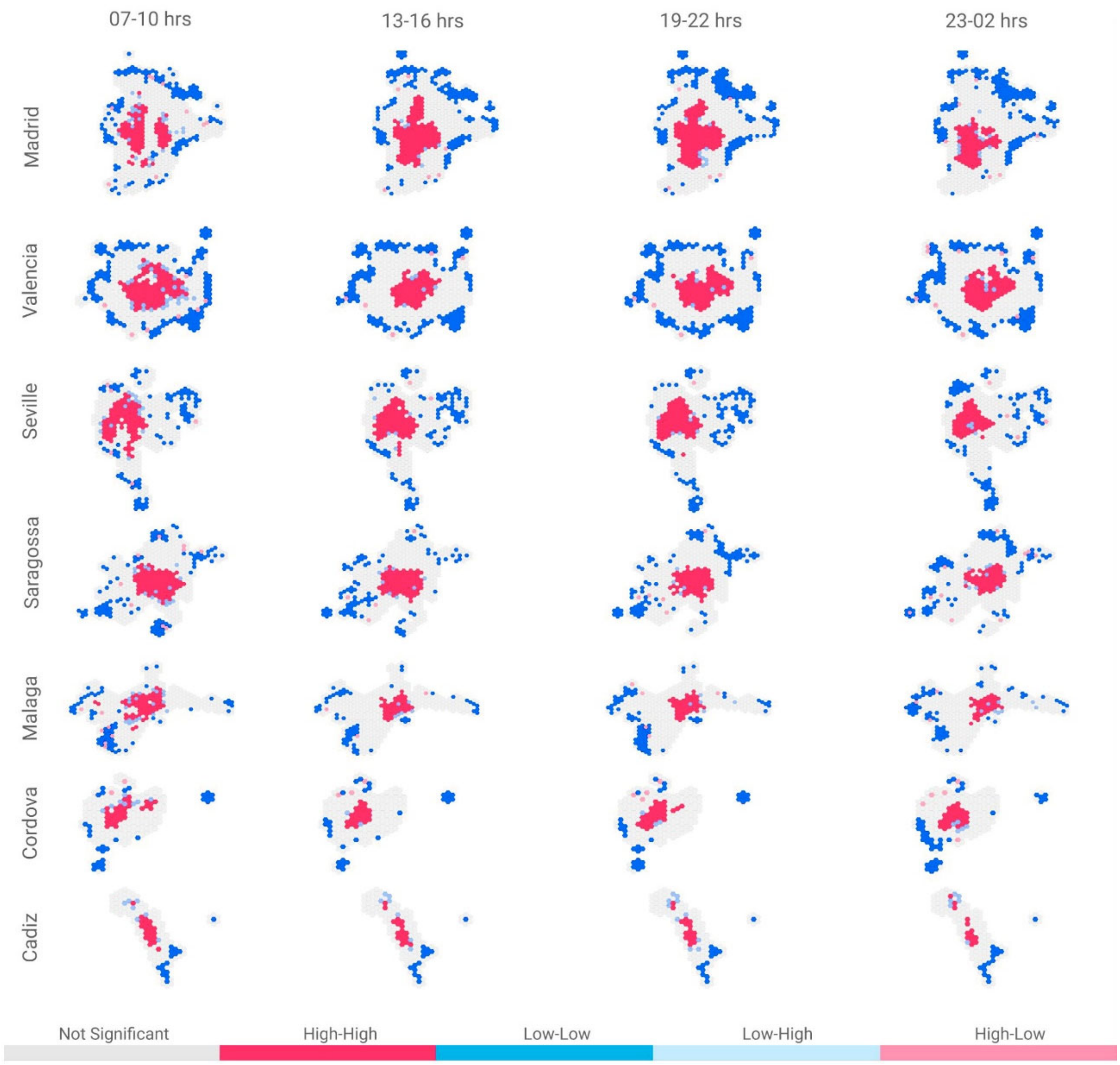

Fig 9- Bivariate LISA cluster maps for origins around destinations by time bands for working days. Source: the authors.

4.5 Spatial autocorrelation analysis: global trends

In order to better understand the system's spatio-temporal trends and assess its potential to be self-balanced, we graphed the calculated Global univariate and bivariate Moran's indices for each time band as seen in Figure 10. Most of the cities fall under the expected conceptual framework and their clustering degree is very similar in the central time bands (2 and 3), whereas origins are more clustered than destinations in late hours (band 4), and the opposite tends to occur in early hours (band 1). More interestingly, when observing the result from bivariate Global Moran's I statistics, the seven cities display the same dynamic: low values in early and late hours (07-10 and 23-02), since people are arriving at places where no trips are starting, and high values in midday and afternoon hours (13-16 and 19-22), since they are arriving at the same places where others are starting their trips. This dynamic makes the system less self-balanced during the first and last time bands, requiring moped redistribution, while band 2 and 3 are the hours when the system balances itself because mopeds are arriving where other users are starting their trips.

An exception, as we mentioned before, is Cadiz, which in general behaves as an outlier, most likely influenced by its particular urban structure, since its urban centre is located on a narrow peninsula, detached from peripheral residential areas.

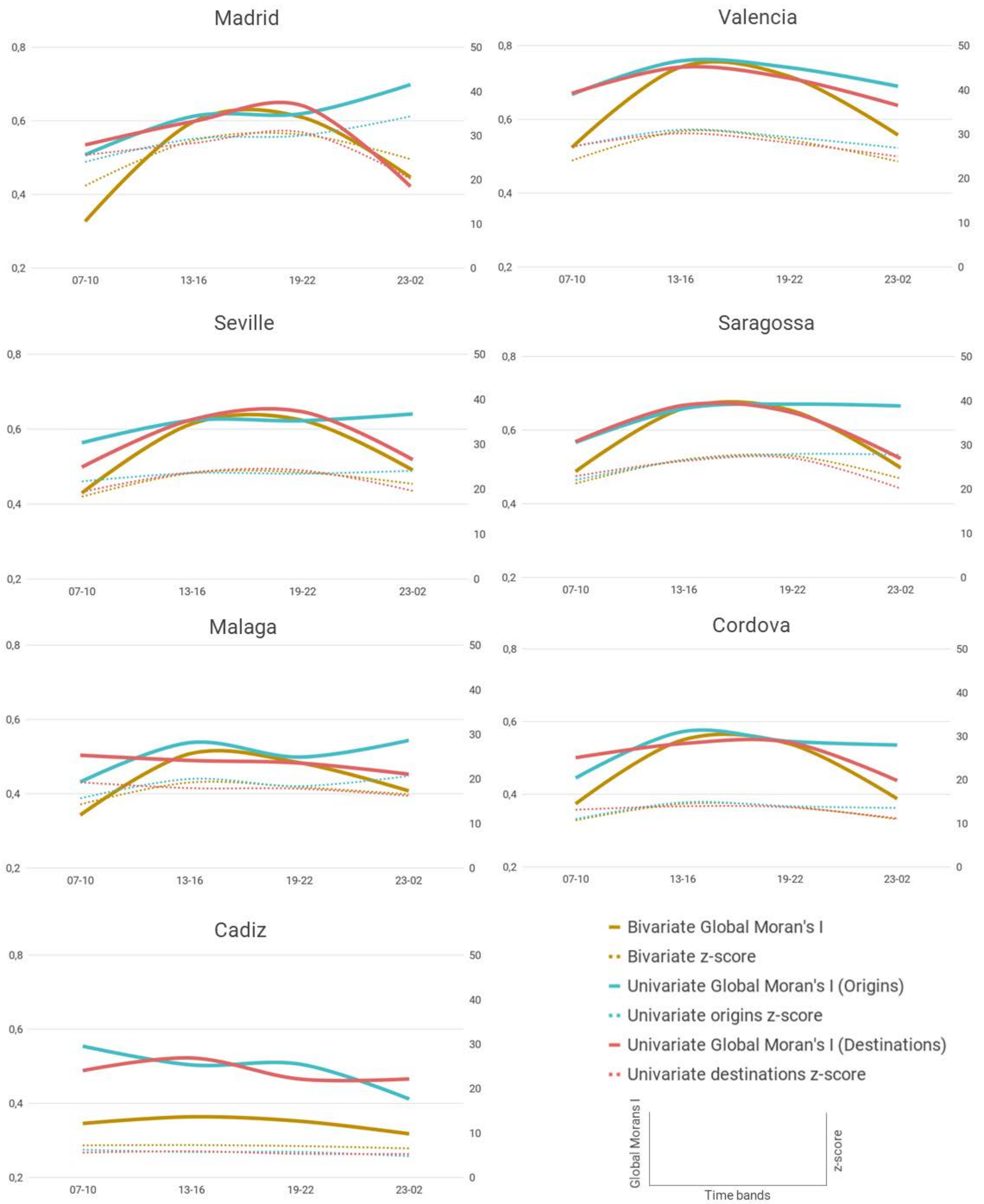

Fig 10- Global univariate and bivariate Moran Indices calculated for working days. Source: the authors.

The bivariate LISA results for working days also show how destinations in one time band are similar to origins in the following time band. When considering the results from the bivariate local Moran's I statistic between destinations and origins in all time bands, the highest numbers are found in the relationships of destinations with origins in the next time band (see Table 5).

	Origin (07-10 h)	Origin (13-16 h)	Origin (19-22 h)	Origin (23-02 h)
Madrid				
Destination (07-10 h)	0.327 (18.6)	0.529 (26.9)	0.486 (26.3)	0.393 (23.7)
Destination (13-16 h)	0.480 (24.5)	0.598 (28.9)	0.605 (29.6)	0.560 (30.1)
Destination (19-22 h)	0.516 (26.3)	0.574 (29.4)	0.610 (30.2)	0.626 (31.7)
Destination (23-02 h)	0.416 (21.4)	0.395 (21.8)	0.444 (23.6)	0.447 (24.7)
Valencia				
Destination (07-10 h)	0.524 (24.1)	0.705 (29.6)	0.655 (28.6)	0.584 (27.3)
Destination (13-16 h)	0.642 (28.0)	0.742 (30.7)	0.735 (30.0)	0.667 (28.4)
Destination (19-22 h)	0.652 (27.8)	0.681 (29.2)	0.717 (28.7)	0.680 (27.4)
Destination (23-02 h)	0.623 (26.3)	0.494 (23.6)	0.574 (25.2)	0.558 (23.9)
Seville				
Destination (07-10 h)	0.430 (18.3)	0.542 (21.5)	0.509 (21.0)	0.466 (20.5)
Destination (13-16 h)	0.561 (22.3)	0.615 (23.6)	0.620 (23.7)	0.589 (23.7)
Destination (19-22 h)	0.557 (22.8)	0.608 (23.9)	0.624 (23.7)	0.623 (24.0)
Destination (23-02 h)	0.524 (21.2)	0.504 (21.3)	0.525 (21.8)	0.491 (21.2)
Saragossa				
Destination (07-10 h)	0.488 (21.3)	0.595 (25.1)	0.593 (26.3)	0.571 (25.9)
Destination (13-16 h)	0.587 (24.2)	0.660 (26.7)	0.661 (27.5)	0.628 (27.1)
Destination (19-22 h)	0.562 (24.6)	0.639 (27.1)	0.653 (27.5)	0.641 (27.4)
Destination (23-02 h)	0.537 (22.3)	0.534 (23.2)	0.532 (23.5)	0.498 (22.4)
Malaga				
Destination (07-10 h)	0.343 (14.3)	0.505 (19.8)	0.465 (18.7)	0.445 (18.9)
Destination (13-16 h)	0.414 (16.2)	0.508 (19.2)	0.495 (18.6)	0.484 (19.1)
Destination (19-22 h)	0.412 (16.2)	0.486 (18.8)	0.484 (18.2)	0.494 (19.1)
Destination (23-02 h)	0.424 (16.7)	0.394 (16.3)	0.413 (16.7)	0.408 (16.6)
Cordova				
Destination (07-10 h)	0.374 (10.7)	0.526 (14.1)	0.493 (13.5)	0.471 (13.4)
Destination (13-16 h)	0.446 (11.9)	0.550 (14.5)	0.544 (14.2)	0.512 (13.8)
Destination (19-22 h)	0.432 (11.6)	0.546 (14.4)	0.539 (13.8)	0.520 (13.6)
Destination (23-02 h)	0.428 (11.3)	0.442 (12.4)	0.460 (12.4)	0.388 (11.0)
Cadiz				
Destination (07-10 h)	0.346 (7.2)	0.330 (6.8)	0.324 (6.8)	0.289 (6.3)
Destination (13-16 h)	0.398 (8.0)	0.364 (7.3)	0.363 (7.3)	0.318 (6.7)
Destination (19-22 h)	0.377 (7.7)	0.352 (7.1)	0.352 (7.1)	0.318 (6.5)
Destination (23-02 h)	0.401 (8.1)	0.365 (7.4)	0.366 (7.4)	0.318 (6.6)

Table 5 - Bivariate Moran's I (z-score) between destinations and origins for all time bands on working days. Source: the authors.

4.6 Relationship between spatial patterns and number of vehicles used

To explore the possible relationship between potential vehicle rotation and the number of vehicles used, we graphed the bivariate Global Moran's I results with the percentage of vehicles used by time band on working days (see Figure 11). A clear relationship was revealed, as the resulting curves tend to follow a similar pattern throughout the day for all the cities. Nevertheless, all the cities show a peak in the percentage of vehicles used around band 3 (19-22 hrs), while the peak for the bivariate results is in band 2 (13-16 hrs).

Consequently, potential vehicle rotation could support and stimulate a higher number of trips, but not determine it. The number of trips would be the result of a high demand and high moped availability and proximity, increased when origins and destinations are closed to each other. Therefore, operators should foster this dynamic, especially in band 2 and 3.

These differences between time bands are important when operators need to know how many vehicles to deploy according to the day of the week. Hence, operators could adjust their logistics to respond to the different dynamics, which could reduce and optimise their distribution tasks.

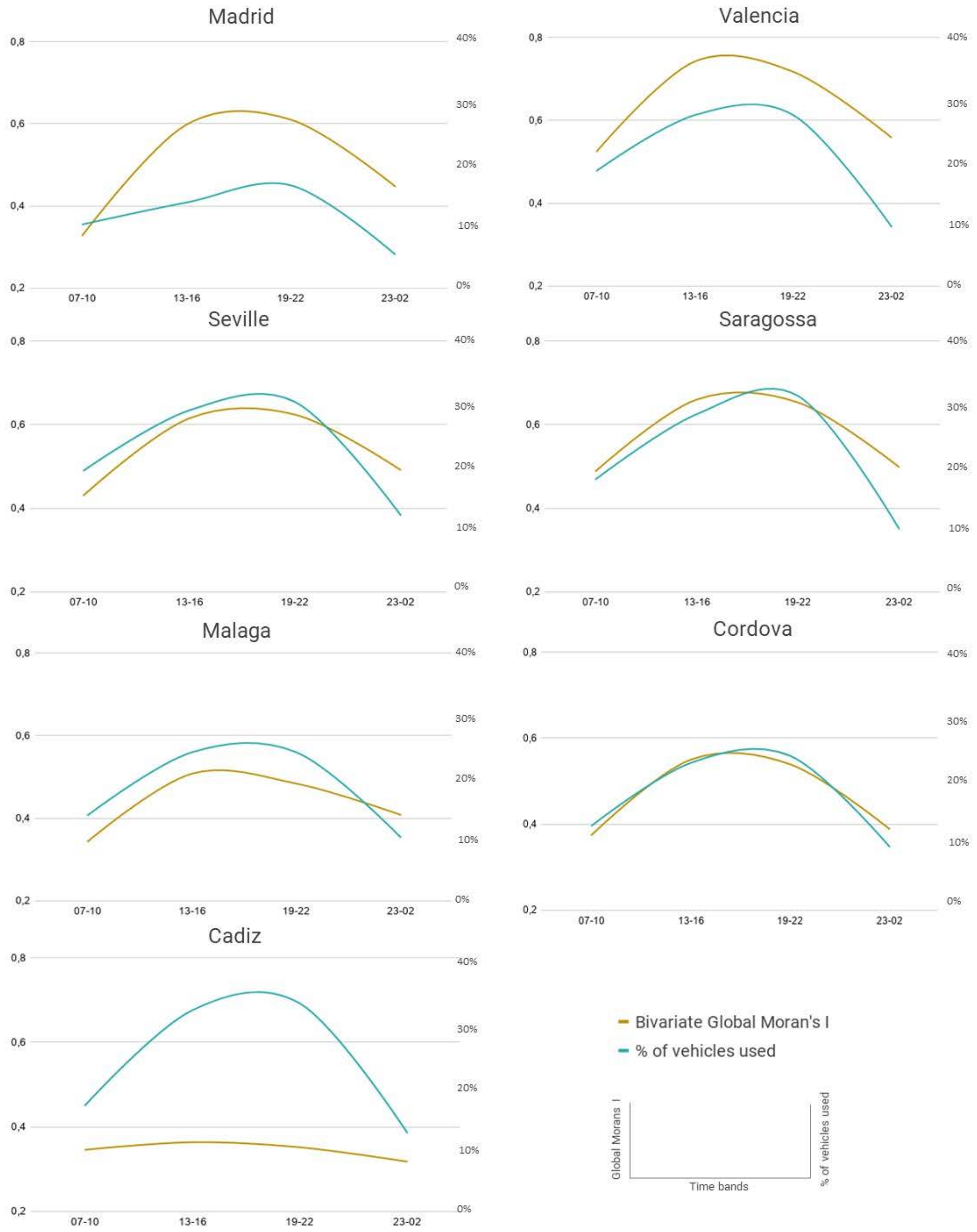

Fig 11- Bivariate Moran vs. percentage of vehicles used (working days). Source: the authors.

5. CONCLUSIONS

Based on GPS data collected, this paper explored the different dynamics of a moped-style scooter sharing service in urban areas over the course of a day. The research provides valuable information regarding the temporal and spatial patterns of this scarcely-studied micromobility service.

More importantly, it proposes a useful methodology based on the use of ESDA tools to understand travel patterns, increasing our knowledge of where demand comes from, when the service's peaks and valleys take place, popular destinations, the extent to which the system is potentially self-balanced, and how this is related to the percentage of vehicles being used. All these are insights that contribute to making better decisions in the shared mobility sector.

A considerable number of users have subscribed to moped services and use this shared mode even across different cities, which is an interesting fact related to the introduction of new concepts like mobility as a service beyond the city scale.

They ride mopeds mostly during warmer months in spring (May-June) and October when daily routines start. The dynamics revealed respond to certain patterns and variations that could be closely related to the existing land-use distribution in each city. In general, the spatio-temporal patterns identified correspond to what could be expected according to the conceptual framework initially outlined. We have learned that similarly to bicycles, mopeds are generally used for short urban trips (around 3.5 km). However, average speed is significantly higher for mopeds in comparison with cycling (14.3 kph in the case of bikeshare and 18.2 kph in the case of mopeds) (Romanillos & Gutiérrez, 2019). This fact makes this mode an attractive alternative, especially for cities like Madrid, which are not completely flat.

We have also demonstrated that time band 2 and 3 (13-16 and 19-22) are the most profitable hours for shared mopeds, as vehicle rotation (trip start and end locations are nearer) and the number of vehicles used are higher.

Our methodology also allowed us to identify when demand is more clustered (HH clusters in the univariate analysis) and more self-balanced (HH clusters in the bivariate analysis), pointing to the most profitable areas within the cities, and other areas where demand is particularly low (LL clusters) or not self-balanced (HL outliers). The assessment of both, the location of demand hubs, and the extent to which the system can balance itself, are important aspects to consider when planning and managing these micromobility services.

Our exploration results are useful for operators and authorities to make better decisions related to shared mobility services, especially in the post-pandemic era, when most of them are experiencing a worldwide boom (Ardila-Gomez, 2020; Harrabin, 2020).

As a clean alternative to cars, knowing where moped trips mostly start and end could have an impact on the infrastructure offered to improve the service and promote intermodality with mass transit.

Our study also demonstrated the importance of analysing and representing the dynamics of mopeds over time and illustrating activity during working days and weekends, which provides relevant knowledge when promoting policies or measures for specific periods of time. The fact that our methodology was tried in different cities allowed for comparisons and demonstrated that our methods are replicable.

Since our study was based on the dataset provided by one of the many moped-style scooter-sharing operators, it is important to consider that, while the sample is absolutely representative in small- and medium-sized cities where no other companies besides

Muving operate (we have all records), this is not the case for Madrid, Valencia, Seville, and Saragossa, which have more than one moped operator. In these cities, results must be carefully interpreted, as we are not covering the entire available moped fleet. When considering Madrid, Muving represented 14% of the available moped fleet during 2019, thus the presence of other companies would vary the vehicle density in some areas, which could have an impact that we are not yet able to identify. Nevertheless, the dataset allowed us to glean more meaningful insights into a sharing sector that has not been exhaustively studied.

Future studies could complement our study by analysing the all moped-sharing services in cities with more than one operator, and even by considering other shared services, in order to holistically comprehend what basically conforms the interconnected

Mobility as a Service network. Future research lines could also focus on monitoring travel behaviour in the coming months and even years, monitoring and visualising the impact of the COVID-19 pandemic on the use of this and other shared modes.

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THE URBAN FREIGHT DISTRIBUTION IN MEDIUM SIZE CITIES: DESCRIPTIVE DATA TAKEN FROM PAMPLONA (SPAIN) AND ANGERS (FRANCE)

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ABSTRACT

Medium-size cities around the world are experiencing rapid changes in their urban centers regarding sustainable mobility, pedestrianization of streets, and vehicle-access control to their city center. This situation is particularly important in the last-mile urban distribution in city centers due to the fact that private cars, public transportation, and freight transportation fiery compete for the same space. This article contextualizes this phenomenon in two European medium-size cities: Angers (France) and Pamplona (Spain).

The paper also draws the current situation regarding their mobility and freight-delivery systems in their city centers. Thus, an apposite survey has been deployed in both cities in order to collect social perceptions and mobility patterns data. Additionally, we have included a conjoint analysis study for examining the characteristic determinants for aerial (drone) distribution. Likewise, meaningful conclusions can be extracted from the analysis of the results generated by the current analysis.

Firstly, we have realized the immediate effects of a recent sustainable urban-mobility plan at Pamplona, which contrasts with the Angers case, where no similar plan has been deployed yet. Secondly, we have focused our attention on the socio-economic factors that determine the mobility in both cities. Thirdly, we have observed, in both cities, a clear preference for electric vehicles and cargo-bikes for driving inside the city center. Finally, there is a rejection to use drones for merchandise delivery.

1. INTRODUCTION

Urban distribution in medium-size cities is facing a major challenge. On the one hand, the growth in e-commerce and the development of commercial and leisure streets in the inner areas of cities are demanding for better freight and passenger transportation systems. On the other hand, medium cities do not have the required infrastructures for absorbing such a demand due to scarce public transportation and weak transportation network, among other factors. As a result, private cars, public transportation, and freight transportation fiery compete for the same space. Additionally, medium size cities are also encouraging sustainable transportation such as walking, biking, and a greater utilization of public transport (Boisjoly and Yengoh, 2017). That leads to pedestrianization of streets, creation of biking lanes, and higher frequency for bus lanes, respectively. Consequently, freight transportation companies have to comply with this new urban environment (Gedik and Yildis, 2016; Atakara and Akyay, 2017; Slovic and Ribeiro, 2018). Accordingly, this work draws the current urban freight distribution situation in two European medium size cities, i.e.: Pamplona, in Spain, and Angers, in France. Both cities have around 200,000 inhabitants in their metropolitan areas. In the study, we conduct a survey for collecting social perceptions and mobility patterns data to understand how urban freight distribution could be improved in medium size cities. Moreover, the survey pays a special focus on drone freight (Frachtenberg, 2019), medical distribution (Rabta et al., 2008), and the use of other environmental-friendly vehicles (Juan et al., 2016).

1.1 Angers and Pamplona: A tale of two cities

Angers is located in Western France, at the intersection of three major motorways: the A11 between Paris and Nantes, the A87 bound to La Roche-sur-Yon, and the A85 bound to Tours and Lyon. Due to its location, Angers is one of the most important logistic centers in the region. Furthermore, the city has several trains (including a high-speed connection to Paris) and central bus stations with direct connection to big cities. Hence, it is a transportation hub for travelers and freights from Western France to Paris. The transportation network is completed with a tramway system that runs through the Eastern part of the city. Moreover, there are more than 30 bus lines and a self-service cycling system.

Likewise, Pamplona is located in Northern Spain, about 45 km away from the French border. The city is crossed by one major motorway, the AP15 bound to Madrid, Zaragoza, and San Sebastian. It is also near another two motorways, the A12 and A21 to Logroño and Huesca, respectively. There are also train and bus central stations, but without high-speed connections. Finally, buses, including one electrified line, are the core of its public transportation. As a final point, Table 1 contains socioeconomic information regarding the two cities, remarking the homogeneity among them.

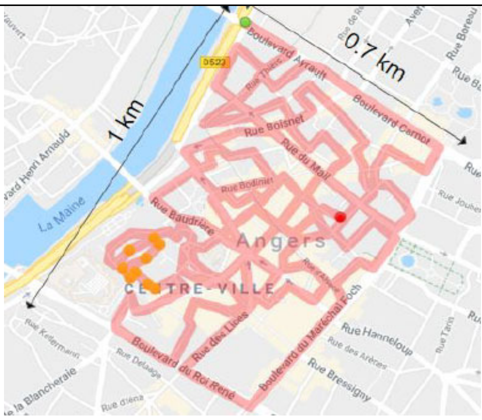
With respect to urban freight transportation, both city centers are characterized by the irregular morphology of their narrow streets, which makes it difficult for vehicles and pedestrians to share these spaces. Moreover, the areas are very dynamic, with shops, government offices, bars, and restaurants. Table 2 shows the characteristics of the city centers of Angers and Pamplona.

	Angers	Pamplona
Population (number of people)*	152,960	199,066
Area (km^2)	42.70	23.55
Density (people per km^2)	3,582	8,500
Per capita GDP (EUR €)**	28,619	28,520

* Data from 2018 ** Data from 2015 at regional level (Maine et Loire for Angers and Navarre for Pamplona).

Table 1 – Socioeconomic data from Angers and Pamplona.

Additionally, the sustainable urban mobility plan (SUMP) of Pamplona, which was recently adopted (Alvarez et al. 2018), led to many changes in the freight transportation in the city center. In particular, the SUMP establishes time windows for freight distribution, while deliveries are only allowed from 8am to 11am and between 2pm to 16:30pm. This policy is not running in Angers.

	Angers city center	Pamplona city center
		
Area	0,7 km^2	0.48 km^2
Road length	14 km	10 km
# bars*	40	20
# stores*	20	20
# hotels*	19	17

* Data from 2019

Table 2 – City center characteristics of Angers and Pamplona.

2. METHODOLOGY

Data collection consisted in the development of some online surveys carried out between April and June 2019 in the cities of Angers and Pamplona.

The questionnaire dissemination was based on mailing distribution lists at the Public University of Navarre and at the Polytechnic University of Angers, as well as its promotion from local authorities and retailers in the area. As a general approximation, we obtained 178 valid observations, 71 from Angers and 107 from Pamplona.

The questionnaire contained 38 closed questions and one open question organized in four different sections, as can be seen in Table 3. The average duration for completing one of the questionnaires was about 14 minutes.

Section	Time	Topic
I	2’	Introduction and classification data
II	4’	Mobility habits and city center weaknesses
III	3’	Freight transportation
IV	5’	Aerial distribution

Table 3 – Questionnaire structure.

Concerning the survey structure in general, and its inner description of its questionnaire, we can make the following description. Firstly, there is an introductory section in which the respondent is asked for sociodemographic information, including age, gender, and economic status, among others. Secondly, the respondent comes across a number of questions regarding the mobility habits in the city. These include how often he / she uses public transportation and the frequency in which he / she visits the city center. Moreover, this section also includes questions with the aim of identifying weaknesses in the city center, e.g.: too much traffic, lack of public transportation, lack of cycling lanes, etc.

Thirdly, there is a specific section for the freight transportation that includes different issues the respondent may suffer from. Thus, this group of questions is particularly important, since the social perception is clearly revealed in the areas of air and noise pollution, urban space invasion, or visual impact. Additionally, the restriction of entering / delivering in the city center is also investigated.

To this respect, we differentiate between traditional internal combustion engine vehicles, electric vehicles based on vans or small trucks, and cargo bikes / trikes deliveries. Finally, the survey contains a section devoted to aerial distribution. Similarly, we include in that section the following characteristics: firstly, general information related to drone-delivery concerns and, secondly, a conjoint analysis (Green et al., 2011) with the attributes and levels shown in Table 4.

In the conjoint analysis subsection, two options are made up by randomly blending their attributes levels. Then, the respondent is asked to choose one of those.

Finally, this is repeated 5 times per respondent with the different options randomly generated.

Attribute	Level
Height/ noise	20 meters off the ground
	120 meters off the ground
Frequency	Few times per day
	Many times per day
Product type	Medical deliveries
	Parcel deliveries
Proximity	Drones do not fly around my house
	Drones may fly around my house

Table 4 – Drone distribution attributes and levels for the conjoint analysis.

3. RESULTS

A comparative descriptive analysis is provided simultaneously in Table 5 and Figure 1. Gender and age distribution is generally balanced in both Angers and Pamplona samples.
Nevertheless, they are slightly biased with respect to their populations. In particular, our samples contain a higher proportion of young participants and a lower proportion of elderly population. This is mainly explained by the data sources as we used the mailing lists of the local universities in Angers and Pamplona. Gender proportion are consistent as 55% and 45% are male or female in the samples and populations, respectively. Regarding the educational level, both samples show similar proportions in elementary, secondary, and undergraduate levels whereas graduates show a higher proportion in the Angers sample and Master / PhD holders show a higher proportion in Pamplona sample.

		Angers	Pamplona	Total
Men	>64	1	0	1
	55-64	1	8	9
	45-54	8	10	18
	35-44	7	10	17
	25-34	4	5	9
	<24	18	22	40
	Total Men	39	55	94
Women	>64	0	2	2
	55-64	2	6	8
	45-54	5	13	18
	35-44	6	5	11
	25-34	4	10	14
	<24	15	16	31
	Total Women	32	52	84
Total		71	107	178

Table 5 – Gender/age sample distribution in Angers and Pamplona.

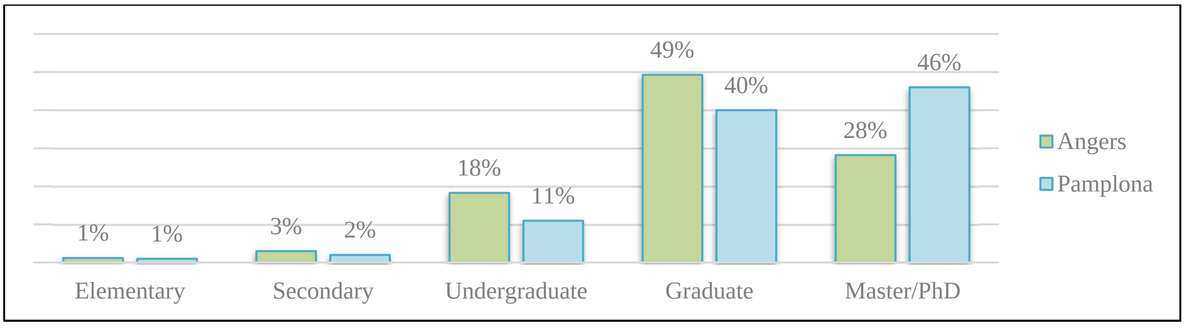


Figure 1 –Level of education in Angers and Pamplona.

The mobility habits are described in Figure 2. Most of the respondents walk regularly to move around the city. Nevertheless, a significantly higher proportion of Angers citizens habitually walk to reach their destinations. Similarly, biking and public transportation are more frequent in the city of Angers. The explanations of these figures are based on two characteristics. Firstly, the public cycling service that is currently running in Angers, which is not in Pamplona. Secondly, the stronger public transportation system in Angers which counts with more bus lines and the tramway system. Consequently, the use of private cars is significantly higher in the city of Pamplona than in Angers.

As the focus of our research is on the freight distribution in the city centers, we also asked for the patterns of going to the city center. These results are shown in Table 6. There are higher proportions of Angers citizens going to the city center more often than citizens from Pamplona. In particular, 69% of Angers respondents go frequently to the city center (at least once a week) whereas that number drops to 42% in the case of Pamplona.

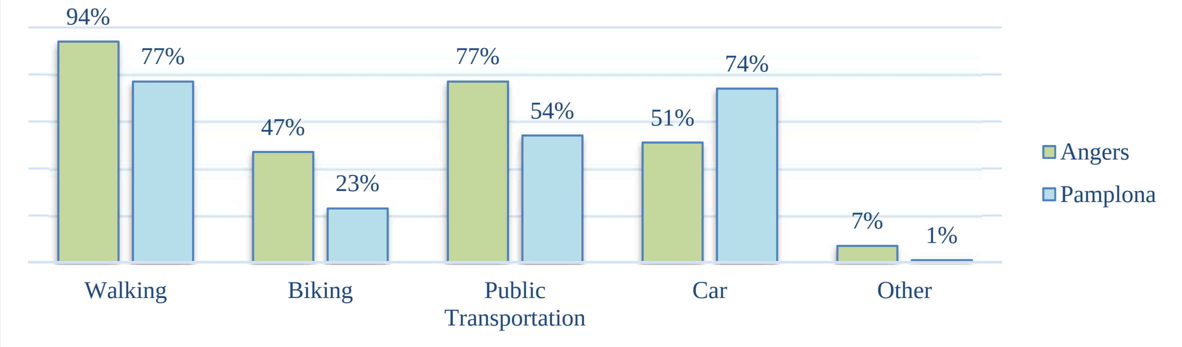


Figure 2 – Mobility habits in Angers and Pamplona.

	Angers	Pamplona
Everyday	28%	10%
At least once a week	41%	32%
Several times a month	4%	48%
Once a month	10%	6%
Almost never/ never	7%	4%

Table 6 – Frequency of going to the city center in Angers and Pamplona.

Table 7 refers to results associated with the restrictions of entering the city center depending on the type of the vehicle (combustion or electric characteristics), and the purpose (freight delivery, including parcels, taxi / bus / ambulance / police services, private nonresident, and private resident). It is particularly interesting how the percentage of participants significantly drops when denying the access to electric vehicles. For example, in Angers 62% would deny entry in the city center to combustion private nonresident vehicles, whereas that figure falls to 23% in the electric case. Similarly, respondents from Pamplona have a higher propensity to allow the entrance of combustion vehicles.

Finally, the respondents identified the city center weaknesses shown in Figure 3. To this respect, pollution, noise, and the lack of cycling lanes are the weakest points in Angers, whereas the noise, excessive freight traffic, and pollution are the ones in Pamplona.

Additionally, levels of importance are always greater in Pamplona than in Angers. That is particularly clear in the case of public transportation and the excessive freight traffic perceptions.

	Angers		Pamplona	
	Combustion	Electric	Combustion	Electric
Deliveries	23%	13%	22%	7%
Services	22%	18%	13%	4%
Private nonresident	62%	23%	50%	39%
Private resident	7%	5%	7%	4%

Table 7 – Denying vehicles entry in the city center of Angers and Pamplona.

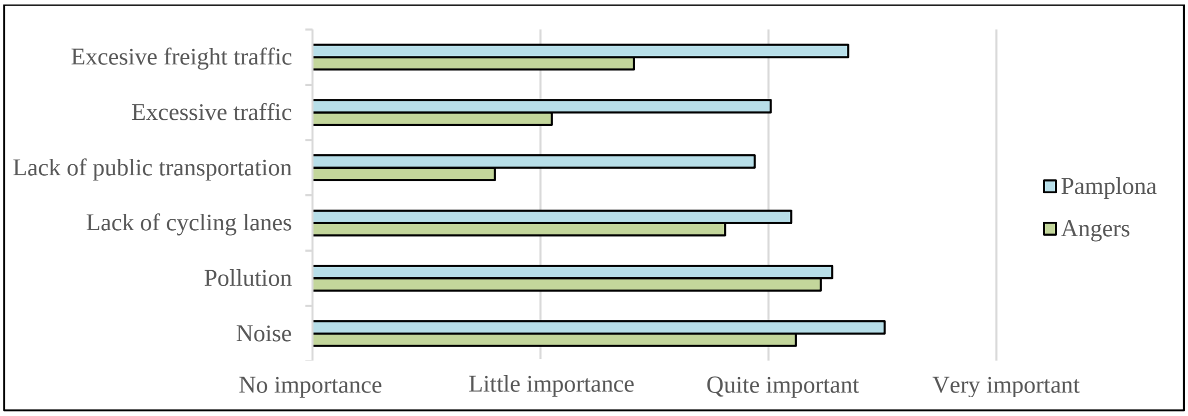


Figure 3 – Transportation issues importance in the city center.

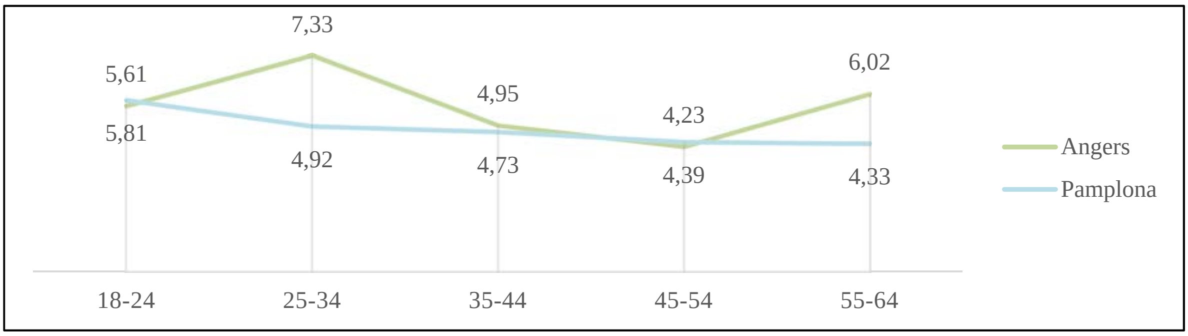


Figure 4 – Sustainability of freight delivery by age group (0: least sustainable; 10: most sustainable).

Concerning the freight transportation particularities, Figure 4 shows the results corresponding to the sustainability perception of the urban deliveries by age group, while Figure 5 shows the freight distribution issues identified. On the one hand, young participants found freight deliveries to be more sustainable than older responders. This is particularly strong in the case of Pamplona, in which there is a clear downward tendency.

On the other hand, Pamplona city center is clearly more annoyed by the freight distribution than Angers one as urban space invasion, excessive speed, and the visual impact are much more important for the former than for the later. However, there are still important issues in the city center of Angers, especially the case of accidents.

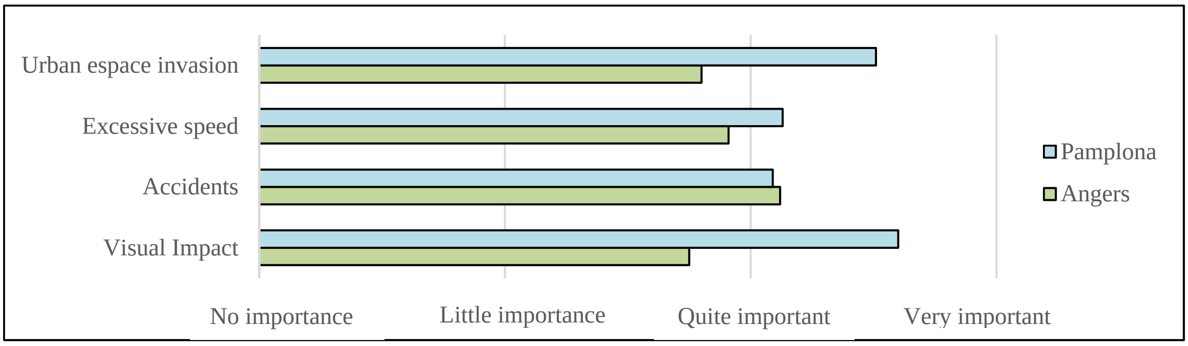


Figure 5– Freight transportation issues importance in the city center.

Finally, future perspectives of urban deliveries are investigated, with a special focus on aerial distribution (drones). To this respect, Table 8 shows the outcomes regarding using the same distribution policy (vans and small trucks), changing to electric vans, changing to a cargo bikes and trikes distribution, and changing to an aerial distribution. Most of the respondents declared that they would like to change the current approach (81.7% and 76.0% in Angers and Pamplona, respectively) to a more sustainable distribution mode. Thus, most of the population agrees on the use of electric vans or cargo bikes / trikes for urban deliveries. The aerial distribution is still scarcely preferred in Pamplona, as only 39.5% of the respondents approved it. This mode is supported in Angers by 69.0% of the respondents.

Following with the drone distribution, Figure 6 shows a preliminary exploration of the conjoint analysis we have developed in these two scenarios. It summarizes the attribute relative importance of choosing an option as a consequence of mixing the attribute levels described in Table 4. As can be seen in the charts from Angers and Pamplona (Figure 6), the 'product type' attribute (i.e., whether the drone is used for delivering parcels or medical deliveries) results in the most determinant with a 38% and 30%, respectively. It means that the use of aerial distribution for medical commodities or parcels significantly affects its approval. Secondly, the flying proximity also strongly determines the drone characteristics.

Here, it is interesting to observe the small distance between the 'product type' and 'proximity' attribute distance in Pamplona city (around 1%), whereas that distance grows up to 11% in Angers. Thirdly, the flying height, which is related to the noise a drone produces, weighs around 25% in both cities. Finally, the least important attribute is related to the flying frequency, as only accounts for about 15%. All in all, the most preferred product consisted in a drone carrying medical supplies that flies high, a few times, and far from home.

	Maintaining		Electric vans		Bikes and trikes		Drone	
	A	P	A	P	A	P	A	P
I'd very much	0.0%	1.9%	33.8%	40.4%	40.8%	30.8%	35.2%	13.5%
I'd like	18.3%	22.1%	52.1%	50.0%	52.1%	45.2%	33.8%	26.0%
Yes	18.3%	24.0%	85.9%	90.4%	92.9%	86.0%	69.0%	39.5%
I'd like a little	57.8%	52.9%	12.7%	8.7%	1.4%	14.4%	21.1%	25.0%
I'd not like	23.9%	23.1%	1.4%	0.9%	5.6%	9.6%	9.9%	35.6%
No	81.7%	76.0%	14.1%	9.6%	7.0%	24.0%	31.0%	60.6%

Table 8 –Opinion about changing (maintaining) to new distribution approaches.

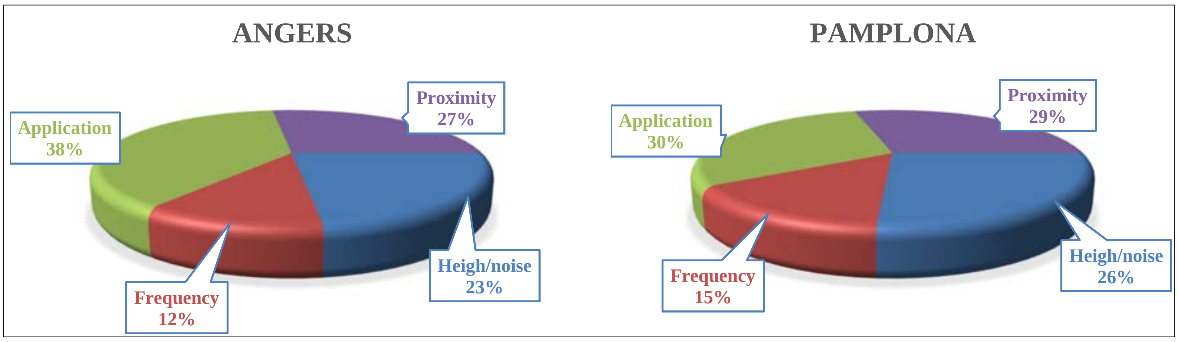


Figure 6– Attribute relative importance resulting from the conjoint analysis.

4. CONCLUSIONS

Medium-size cities are experiencing many changes related to sustainable mobility, which significantly affects the traditional last-mile urban distribution. In this paper, we have deployed a survey in the cities of Angers (France) and Pamplona (Spain) in order to investigate the current status of their mobility policies, with a special focus on the comparison of their mobility patterns and city center freight transportation. That is particularly interesting as the city of Pamplona has recently unfolded a sustainable urban mobility plan whilst Angers has not.

The analysis of the results allows us to describe a number of conclusions:

1) The current situation of transport and mobility in both cities are similar in terms of city-center dimension and services, i.e.: administrative-related paperwork, monuments, and bars or restaurants. However, Angers transport and mobility infrastructure seems to be stronger as the presence of public transportation is higher. While the mobility in each city includes buses routes, in Angers, cycling is an important transportation mode, with a self-service bike service. The tramway also brings variety to the French city.

2) As regards to freight delivery, both cities are at the same point, finding solutions like cargo bikes or tricycles and other electric vehicles to replace traditional combustion vans and small trucks. However, mobility patterns are significantly different, being Angers much more sustainable in the way of higher use of public transportation and lower use of private cars. However, the frequency and the affluence of people in the city center is greater in Angers than in Pamplona. Clearly, the transportation systems and mobility policies are ruling better in the French city, while the SUMP in Pamplona is not offering comparable results in terms of the public transportation share.
3) Both cities face similar weaknesses in their city centers. Nevertheless, in Pamplona these weaknesses are considerably more serious. In fact, noise and air pollution are major problems in both city centers, and some other problems have been identified affecting specially to Pamplona -e.g., the excessive freight traffic or the lack of biking lanes.
4) It is of high interest the propensity to allow electric vehicles to enter in the city centers. This policy involves the detriment of the traditional combustion vehicles, especially if they are private cars. Actually, there is a clear tendency to change the current freight distribution systems, which are generally supported by the population. This behavior is particularly evident when moving towards electric distribution. Furthermore, freight transportation is clearly worse organized in Pamplona, resulting in higher levels of urban space invasion, excessive speed, and visual impacts concerns.
5) Aerial distribution at city centers are somehow conflictive. On the one hand, around half of the sample are prone to allow drone distribution, a much lower ratio than the use of electric distribution using vans or bikes / trikes, which accounts for approximately 90% of respondents. On the other hand, there is a clear difference between the approval of the two cities. Just 39% of Pamplona participants support drone distribution, whilst this figure grows up to 69% in the city of Angers. Thus, we have observed clear culture-related issues to tune when dealing with a real and effective drone distribution deploy. Finally, we have identified what are the most important characteristics of this kind of distribution, being dominated by the product type transported (medical / parcel) and height the drone flies. Hence, a clear rejection for using drones for parcel distribution has been observed in our survey.

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OPTIMIZACIÓN DE DATOS GEOLOCALIZADOS DE TELEFONÍA MÓVIL EN ESTUDIOS DE DEMANDA DE VIAJEROS

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RESUMEN

Con la entrada de la telefonía móvil en el análisis de la movilidad se ha cambiado la forma tradicional de obtención de las matrices origen-destino de viajes. Las ventajas de utilizar estos datos georreferenciados se traducen especialmente en los grandes tamaños de muestra, lo que conlleva la detección de viajes en gran parte de los pares O-D, la reducción de plazos y costes y la posibilidad de analizar periodos de tiempo pasados. Sin embargo, la caracterización del viaje (modo, motivo) y del viajero (nivel socioeconómico, motivo de elección) quedan en cierta medida algo desdibujados en este nuevo escenario.

La experiencia acumulada en el desarrollo de estudios con este tipo de soluciones ha permitido detectar la importancia de llevar a cabo un proceso de enriquecimiento y alimentación de las matrices de telefonía móvil para aunar las ventajas del método tradicional y de las nuevas tecnologías e incrementar la calidad de los resultados a obtener. Para ello se describen las fuentes de datos disponibles y los trabajos de campo complementarios que se pueden llevar a cabo en función del tipo de resultados que se deseen obtener.

Las matrices enriquecidas con este proceso deben ser convenientemente validadas, para lo cual es necesario analizar posibles inconsistencias en los resultados y, en ocasiones, realizar una tarea de ajuste final con ayuda del modelo de transportes.

1. INTRODUCCIÓN

La irrupción de la información espacio-temporal de los teléfonos móviles en los análisis de movilidad cuenta ya con varios años de utilización para este tipo de estudios. Para el Censo de población de 2021 el INE ha confiado en esta solución para la obtención de la información sobre movilidad, sustituyendo al cuestionario tradicional.

En Ineco se comenzó a trabajar con esta fuente de datos en el año 2017 y se ha utilizado hasta el momento en una veintena de proyectos de diversas características, aunque todos ellos con un denominador común: la necesidad de obtener matrices de viajes con más detalle que la matriz de movilidad general.

Dentro del contexto de la Movilidad Segura, Sostenible y Conectada 2030 y su predecesora nuestros proyectos se orientan a nuevas infraestructuras, servicios o eficiencia del transporte público. Por ello, resulta de especial importancia la segmentación de las matrices de demanda por modo y motivo de viaje, pudiendo caracterizar los usuarios susceptibles de ser captados por las actuaciones analizadas.

Con base en nuestra experiencia y en las lecciones aprendidas, se ha elaborado una relación de fuentes de datos y trabajos complementarios como herramientas para mejorar la precisión de las matrices obtenidas de la telefonía móvil (matrices primarias) en las matrices modales más idóneas para cada tipo de estudio (matrices segregadas).

2. MATRICES PRIMARIAS, FORTALEZAS Y ÁREAS DE MEJORA

A continuación, se exponen fortalezas y áreas de mejora detectadas en el trabajo realizado con matrices primarias obtenidas a partir de registros de telefonía móvil.

2.1 Fortalezas de las matrices primarias

Actualmente la telefonía móvil es empleada frecuentemente para la detección de desplazamientos en forma de matrices primarias, dadas las numerosas ventajas que presenta esta solución. Entre las principales fortalezas se encuentran:

Datos de movilidad de usuarios recogidos de forma pasiva: los usuarios, objeto de investigación, no forman parte activa del proceso de recolección de datos, al no tener que realizar ninguna tarea específica para que estos datos queden registrados.

Monitorización o seguimiento continuo de datos: en caso de ser necesario, los datos de movilidad pueden recogerse de forma continua durante un periodo de tiempo determinado, que puede prolongarse en el tiempo. Esto facilita el análisis de la evolución continua de la movilidad en algunos ámbitos.

Análisis de eventos históricos: pueden recogerse y analizarse datos históricos de eventos para examinar patrones o situaciones que, de otra forma, no podrían analizarse, de no planificarse antes de suceder.

Muestras de gran tamaño: en general, esto depende de la cuota del operador de telefonía móvil en el ámbito de estudio, aunque habitualmente es factible contar con un alto porcentaje de muestra entre la población investigada, ante la generalización que existe actualmente en el uso del teléfono móvil. Esta alta cantidad de muestra puede además estar repartida en diferentes momentos temporales a lo largo de un periodo, permitiendo aumentar la representatividad de esta.

Grado de penetración: el uso de datos de telefonía móvil permite investigar generalmente la movilidad en todo tipo de zonas y a todo tipo de usuarios, aunque ello depende también de la composición de usuarios que forma la cuota del operador. Además, al ser un proceso de registro pasivo, pueden evitarse sesgos asociados con la selección de individuos que realiza el investigador o entrevistador, en el caso de encuestas.

Plazo y coste de ejecución: el proceso de registro y tratamiento de estos datos de telefonía para la obtención de matrices de viajes suele llevar un menor tiempo de ejecución de tareas y con ello, además, un menor coste en la producción de estos resultados.

2.2 Áreas de mejora de las matrices primarias

Sin embargo, en la obtención de matrices de viajes a partir de datos de telefonía móvil existen también áreas de mejora, entre las que se encuentran:

Caracterización del viaje y del usuario: la información disponible para caracterizar en detalle a los viajeros y sus desplazamientos mediante telefonía móvil es reducida, en comparación con la metodología de encuestas. Actualmente, las variables de análisis que pueden determinarse mediante la telefonía móvil no son muy numerosas, quedando con escaso detalle características como el motivo o la frecuencia del desplazamiento.

Identificación de viajes en determinados modos de transporte: frecuentemente se presentan dificultades en el momento de segmentar los viajes de la matriz según modos de transporte, especialmente en el caso de desplazamientos entre distintos medios asociados a la carretera (autobús, vehículo particular, camiones, furgonetas, etc.) o en el caso de distintos modos terrestres (ferrocarril y carretera), si estos discurren por una infraestructura paralela, con escasa separación y velocidades medias similares.

Desplazamientos asociados al transporte de mercancías: como se menciona en el punto anterior, la dificultad para segmentar a los distintos tipos de usuarios de la carretera entre tipos de vehículos hace que no puedan detectarse con claridad todos los desplazamientos asociados al transporte de mercancías, que son realizados por conductores profesionales utilizando camiones o furgonetas.

Esto resulta un inconveniente en el caso de estudios de movilidad donde únicamente se desee identificar viajeros potenciales de modos de transporte públicos y se acentúa especialmente si este análisis desea efectuarse sobre el ámbito de un polígono industrial con gran volumen de transporte de mercancías.

Muestras insuficientes en ámbitos espaciales muy pequeños: cuando el análisis de la movilidad desea efectuarse sobre espacios reducidos como, por ejemplo, un polígono industrial o zona residencial pequeña y poco urbanizada, la muestra de usuarios a investigar puede ser muy limitada, en función de la cuota y penetración del operador de telefonía móvil.

Investigación de movilidad internacional: habitualmente la posibilidad de obtener registros de telefonía móvil en territorio extranjero es limitada y depende de los convenios existentes con las distintas operadoras de telefonía móvil en cada país.

3. ELEMENTOS PARA EL ENRIQUECIMIENTO DE LA MATRIZ PRIMARIA

Las matrices primarias pueden enriquecerse integrando datos procedentes de otras fuentes o de trabajos de campo específicos para realizar segmentaciones más precisas.

3.1 Fuentes de datos complementarias

Las fuentes de datos complementarias aportan información adicional en el proceso de obtención de las matrices de viajes por modo, ayudando a paliar determinados aspectos del proceso sobre los que hay una mayor incertidumbre. Estas fuentes de datos externas pueden englobarse en:

Datos de usuarios de modos de transporte público: esta información, generalmente aportada por operadores o administradores de transporte, puede contener detalles sobre los viajeros que utilizan el servicio indicando sus paradas de subida y bajada, o bien, sobre el conjunto de viajeros que se suben y se bajan en las distintas paradas, sin indicar la relación entre las paradas de subida y bajada.

Estos datos suelen tener su origen en el registro del uso o compra de los billetes o títulos de transporte de los usuarios del modo de transporte público o, en algunos casos, en aforos realizados específicamente por los operadores dentro de su labor de gestión, control y regulación de la explotación del servicio.

Estos datos facilitan la identificación, en la matriz global de viajes, de usuarios que utilizan modos de transporte público. Por otro lado, cuando la infraestructura de estos discurre de forma paralela y con escasa separación a lo largo de un corredor, también puede ayudar a desagregar la demanda entre modos de transporte terrestre.

Entre las limitaciones que presentan este tipo de datos se encuentra, frecuentemente, la ausencia del registro del resto de etapas del viaje entre origen y destino, la relación entre parada de subida y bajada si existe transbordo o si solo se cuenta con datos agregados de subidos o bajados por parada, sin relación entre paradas.

Aforos de vehículos en carretera: los mapas de tráfico que se generan habitualmente a nivel regional o estatal proporcionan la intensidad de vehículos ligeros y pesados en numerosos puntos de la red de carreteras del Estado.

Estos datos facilitan la detección de vehículos pesados, que en su mayor parte están asociados al transporte de mercancías, aportando además información sobre los vehículos ligeros, en su mayoría vehículos particulares. Esta información resulta de interés cuando no es posible segmentar los viajes realizados en carretera, entre el autobús y el vehículo privado.

No obstante, estos datos de intensidades ofrecen información puntual de vehículos, sin detallar relación entre origen y destino y sin identificar el número de ocupantes de dichos vehículos, de forma que pudieran transformarse los datos de vehículos en viajes.

Adicionalmente, este tipo de datos no presentan una identificación desagregada en detalle entre vehículos asociados al transporte de mercancías y vehículos asociados al transporte de viajeros o vehículos particulares. Este hecho sucede dado que, generalmente, dentro de la categoría de vehículos ligeros se incluyen, no solo turismos y motocicletas o ciclomotores, sino también furgonetas o furgones dedicados al reparto y distribución de mercancías.

Igualmente, dentro de la categoría de vehículos pesados, en ocasiones se encuentran agrupados camiones o vehículos dedicados al transporte de mercancías y autobuses o vehículos dedicados al transporte de viajeros, dificultando así la identificación directa de vehículos asociados al transporte de mercancías y de viajeros.

Estadísticas públicas de movilidad general: son varias las estadísticas generales públicas disponibles que pueden encontrarse y utilizarse para enriquecer las matrices de viajes, aunque una parte de ellas no ofrecen detalles de viajes completos, sino de etapas. Entre estas estadísticas se encuentran las de distintos organismos públicos en España, como:

- El Instituto Nacional de Estadística (INE): proporciona información mensual sobre el número de viajeros transportados en su Estadística de transporte de viajeros. Esta información se encuentra además segmentada según medio de transporte, distancia o ámbito. El INE publica también la Estadística de movimientos turísticos en frontera, que proporciona estimaciones mensuales y anuales del número de visitantes no residentes en España que llegan al país.
- El Observatorio del Transporte y la Logística en España (OTLE): proporciona datos, gráficos, mapas e indicadores generales de movilidad agregada y en los distintos modos de transporte (carretera, ferrocarril, aéreo y marítimo).

- AENA: en la página web de Aena pueden consultarse datos de pasajeros en los aeropuertos españoles, indicando la relación entre aeropuerto de salida y aeropuerto de llegada de los pasajeros.
- El Observatorio del Ferrocarril en España (OFE): facilita anualmente un registro de estadísticas de viajeros en ferrocarril, indicando los viajeros en las principales estaciones ferroviarias y una segmentación de estos según los distintos tipos de servicios ferroviarios, entre otros indicadores generales de movilidad.
- La Encuesta Permanente de Transporte de Mercancías por Carretera (EPTMC): registra anualmente el tráfico de mercancías por carretera en España, indicando además del tipo de vehículo, el origen y destino de los vehículos entre las distintas Comunidades Autónomas, entre otras variables.
- Memorias anuales de operadores de transporte: las empresas públicas operadoras de transporte de viajeros publican habitualmente de forma anual las estadísticas y cifras generales de viajeros transportados en su ámbito de operación, encontrándose desagregada esta información en ocasiones, según líneas o paradas, entre otras características.
- Anuario estadístico del Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA): proporciona información estadística anual sobre los viajeros transportados en ferrocarril, avión, barco y autobús urbano o internacional, además de estadísticas de tráfico por carretera.
- Anuario estadístico de Puertos del Estado: en este anuario se encuentra información sobre los pasajeros que utilizan los servicios de transporte marítimo en las distintas Autoridades Portuarias de España.

Estas son solo algunas de las estadísticas públicas que pueden ayudar a enriquecer la obtención de las matrices de viajes de un estudio de movilidad, aportando información por modos de transporte, datos sobre viajeros internacionales no residentes en España, viajes encaminados a determinados nodos de transporte como puertos y aeropuertos o detectando movilidad asociada a transportistas de mercancías.

Al igual que otras fuentes de datos, las principales limitaciones que presentan estas estadísticas están asociadas a la ausencia de la relación entre origen y destino o, en caso de que esta información exista, no se encontrará recogida la información de todas las etapas del viaje, entre otros aspectos.

Otros estudios específicos: además de las fuentes de datos anteriormente mencionadas, es recomendable la recopilación y consulta de antecedentes de estudios en el ámbito de análisis que puedan contener datos de movilidad. Entre estas fuentes de datos, pueden existir Encuestas Domiciliarias de Movilidad (EDM) recientes o Planes de Movilidad Urbana o Regional en las zonas de estudio.

Como ejemplo, entre las EDM que han sido publicadas recientemente se encuentra la de la Comunidad de Madrid (2018), donde se ofrecen los resultados de viajes en un día laborable en la Comunidad, según origen y destino, modos de transporte, títulos de viaje, etc. La zonificación recogida en esta EDM cuenta con una extensa división de más de mil zonas.

Como puede observarse, existen diferentes fuentes de datos que pueden utilizarse como herramientas que ayuden a enriquecer la obtención de matrices de viajes en un estudio de movilidad. Sin embargo, al realizar este proceso es necesario tener presente las limitaciones o carencias de cada una de estas fuentes de datos complementarias.

3.2 Trabajos de campo *ad hoc*

Los trabajos de campo pueden planificarse específicamente para aportar un mayor grado de detalle al proceso de segmentación por modos de las matrices de viajes, tras conocer en detalle el ámbito de estudio, la zonificación empleada y los medios de transporte que serán analizados entre otros aspectos.

De esta forma, la realización de encuestas de preferencias reveladas (PR) y/o de aforos pueden enriquecer el proceso de obtención de resultados aportando de la siguiente forma:

Mayor detalle de las características del viaje y del viajero: La encuesta de preferencias reveladas permite obtener un mayor detalle acerca del motivo y frecuencia del viaje, la utilización de modos de acceso y dispersión, la situación laboral del usuario o su ocupación profesional, etc.

Desagregación de los viajes realizados en carretera: La realización de encuestas PR a usuarios de autobús ayuda a conocer un subconjunto de los viajes que se realizan por carretera y que son difícilmente detectables mediante telefonía móvil. Puede plantearse también la realización de estas encuestas a los usuarios del vehículo privado, sin embargo, es posible que exista un mayor sesgo en la selección de usuarios, además de las dificultades para interceptar a estos durante la realización de su viaje. En función de la disponibilidad de datos de viajeros, puede ser necesario contar también con la realización de un aforo de viajeros de este medio público.

Desagregación de viajes terrestres (ferrocarril y carretera): En el caso de que la situación geográfica dificulte la segregación de demanda entre ferrocarril y carretera, puede plantearse la realización de encuestas de preferencias reveladas a usuarios del ferrocarril para caracterizar los desplazamientos de este subconjunto de viajes y permitir diferenciar entre ambos modos terrestres. La necesidad de realizar conjuntamente aforos de viajeros en ferrocarril, para la expansión de esta muestra de viajes, será variable en función de la disponibilidad de otros datos, por ejemplo, registros de demanda proporcionados por el operador.

Identificación de viajes realizados por transporte de mercancías: En determinados ámbitos de estudio, el volumen de este tipo de desplazamientos puede adquirir un peso significativo en la movilidad global, lo que puede requerir un conocimiento detallado de estos viajes para poder caracterizarlos adecuadamente. La realización de aforos para identificar este tipo de vehículos puede ser de gran ayuda para cuantificar estos flujos en las principales relaciones de análisis.

Cabe recordar que este tipo de tareas específicas también conllevan determinadas limitaciones, dado que pueden ser trabajos que involucren un mayor coste o introducir algunos sesgos.

Como ejemplo de aplicación simultánea de tareas de investigación de campo y utilización de datos de telefonía móvil, cabe destacar la realización de la última encuesta de movilidad de la Comunidad de Madrid (EdM2018), donde se utilizaron, en este caso, la encuesta domiciliaria para investigar la movilidad de los residentes en la Comunidad, empleando los datos de telefonía móvil para estudiar la movilidad de los no residentes.

4. AJUSTES FINALES Y VALIDACIÓN

Tras obtener las matrices de viajes segregadas es relevante validar los resultados obtenidos mediante la generación de estadísticas e indicadores de movilidad vinculados a la demografía y al territorio o comparando nuevamente con fuentes de datos complementarias.

Algunos de los indicadores que pueden extraerse a partir de los datos de desplazamientos de la matriz son:

Generación de viajes por habitante (viajes/habitante): Esta relación puede obtenerse para la matriz global de viajes, según relaciones origen-destino, y analizar la dispersión de estos valores conjuntamente con las características del territorio, o comparar las tendencias observadas con otros estudios.

Índice de etapas (etapas/viaje): Este índice revela la composición de etapas de los distintos viajes, permitiendo analizar en determinadas relaciones origen-destino y modos de transporte, la coherencia de los viajes y sus cadenas de etapas.

Atracción de viajes laborales (viajes/empleado): Si se disponen de datos estadísticos sobre el número de empleados en las zonas de concentración empresarial, analizando esta ratio puede observarse el comportamiento de los viajes en estas zonas, en función de las características de dichas empresas. Esta relación dependerá del tipo de empresa y del número de visitantes asociados a la misma.

Comparativa con datos de usuarios de operadores de transporte: Estos datos, además de tenerse en consideración en el proceso de obtención de la matriz de viajes como fuente externa, puede utilizarse igualmente como fuente de datos de validación del proceso seguido. En este caso es posible, por ejemplo, comparar las etapas entre zonas, ya que los datos de viajeros de operadores de transporte contienen habitualmente etapas en el modo entre paradas, en vez de viajes completos entre origen y destino.

Analizando los valores de estas ratios a nivel global y en las distintas relaciones origen-destino, pueden observarse tendencias sobre valores medios y su dispersión, que pueden conducir a detectar anomalías en la caracterización de viajes de la matriz.

Adicionalmente, en la mayoría de los estudios de demanda se construye un modelo de transportes como herramienta para la simulación de escenarios y estimación de previsiones a futuro. El modelo está formado por tres componentes principales: zonificación, modelo de oferta y modelo de demanda.

Este modelo ha de estar debidamente calibrado y validado en el año base con la información de referencia previamente recopilada, a fin de que sea capaz de reproducir adecuadamente la realidad observada, respondiendo además de forma adecuada frente a cambios tanto a nivel socioeconómico como de la oferta de transporte.

Es habitual que, durante el proceso iterativo de calibración del modelo en el año base, este sirva además como herramienta de apoyo en el análisis de los datos geolocalizados de telefonía móvil y la validación de las matrices origen destino segregadas, las cuales constituyen uno de los pilares de la modelización.

En este análisis que se lleva a cabo con el objetivo de validar los resultados, se detectan en ocasiones inconsistencias en los datos, que pueden ser resueltas mediante ajustes concretos con ayuda del modelo de transportes. A continuación, se describen algunos ejemplos de ajustes realizados mediante la utilización del modelo de transportes construido de forma específica para el estudio de demanda en cada caso.

Hay que tener presente que la fiabilidad en las matrices de movilidad obtenidas mediante estos métodos alternativos de ajuste es siempre inferior a la que se puede alcanzar si directamente la información es obtenida con el detalle necesario desde un primer momento.

Zonificación: En general, resulta más indicado que las zonas origen destino que se definan como referencia espacial en la obtención de los datos para elaborar la matriz de viajes sean consistentes con la zonificación empleada en el modelo de transportes, con una desagregación igual o de mayor detalle. No obstante, en el caso de que el nivel de desagregación en que se obtengan las matrices origen destino no sea suficiente, es posible utilizar submodelos de generación y distribución para estimar los viajes con el grado de detalle requerido de forma sintética. Para ello, se procede según los pasos que se indican a continuación.

En primer lugar, es preciso definir el submodelo de generación de viajes, el cual permite reproducir la mecánica de producción y atracción de viajes en cada una de las zonas del modelo. Así, para cada uno de los segmentos de demanda y motivos de viaje se estiman ratios de producción de viajes, que representan el número de viajes de un motivo realizados a nivel individual. Para el cálculo de las atracciones zonales se emplea la información relativa a los usos del suelo y a variables relacionadas con la actividad económica.

Una vez se tienen las ratios de producción por grupo de demanda y motivo de viaje, estas se aplican sobre las variables socioeconómicas con el nivel de desagregación inferior, obteniendo así los vectores de generación (producciones y atracciones) relativos a la zonificación del modelo de transporte.

A continuación, se define el submodelo de distribución espacial de viajes cuyo objetivo es estimar el número de viajes que se realizan entre dos zonas origen destino a partir del total de viajes producidos por la zona origen y el total de viajes atraídos por la zona destino. Si se trata de un modelo de tipo gravitatorio, la distribución se hace depender también de la impedancia al transporte existente entre ambas zonas.

Para la calibración del submodelo de distribución espacial de viajes por cada segmento de demanda y motivo de viaje, se ajustan los parámetros de la función de impedancia de manera que se minimicen las diferencias entre la matriz origen destino de partida para la segregación y la ajustada por el modelo. Para poder realizar la comparación entre ambas matrices, éstas deben tener la misma zonificación, para lo cual es necesario agregar los viajes estimados por el modelo hasta que su referencia espacial coincida con la de la matriz de partida.

Finalmente, una vez concluido el proceso de calibración del submodelo de distribución, la nueva matriz origen destino segregada será la estimada por aquél.

Detección de inconsistencias: En ocasiones, en el proceso de cálculo de los modelos de generación se observan ratios de producción inferiores o superiores a lo esperado según experiencias previas en estudios similares. Este hecho puede hacer detectar inconsistencias en el registro de datos.

Entre las distintas experiencias analizadas en los últimos años, cabe destacar la detección de ratios de generación más elevadas en determinadas zonas fronterizas de España.

Además, en la calibración del submodelo de reparto modal, se detectó que las cuotas de vehículo privado eran muy superiores al resto de los modos.

Tras analizar este caso concreto, fue necesario optar por ajustar las matrices de partida, tomando como referencia ratios de generación (para la matriz de movilidad general) y cuotas de reparto modal (para la segregación por modos) procedentes del propio estudio en otras zonas no afectadas.

5. NUESTRA EXPERIENCIA

Desde el año 2017 se han desarrollado en Ineco los siguientes proyectos con base en matrices de telefonía móvil.

- Estudios de demanda para la implantación de cinco nuevos apeaderos en polígonos industriales sobre la red de Cercanías existente de Madrid.
- Estudios de demanda para la implantación de cinco nuevas estaciones sobre la red de Cercanías existente. Varios núcleos.
- Estudio de demanda de cinco núcleos de Cercanías.
- Estudio de demanda de viajeros para la rehabilitación de la línea ferroviaria transfronteriza Zaragoza-Pau.
- Estudio de demanda de viajeros en el Corredor Sur de la isla de Gran Canaria para la implantación de un ferrocarril.
- Estudio de demanda de viajeros del Corredor Mediterráneo.
- Modelo Nacional de transporte de viajeros.

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TWITTER Y MOVILIDAD ESPACIO-TEMPORAL: VISUALIZACIÓN 3D DE FLUJOS DE MOVILIDAD

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RESUMEN

La movilidad individual de un individuo está estructurada en la necesidad de conducir diferentes actividades que requieren estar en unas determinadas coordenadas espaciales y temporales. La Geografía del Tiempo es una aproximación que reconoce que la localización en el espacio no puede estar separada del momento en el tiempo. Los progresos recientes en los SIG y computación y la riqueza de los datos espacio-temporales obtenidos a partir de nuevas fuentes basadas en las Tecnologías de la Información y Comunicación han contribuido a la evolución de la Geografía del Tiempo. Actualmente es posible visualizar y representar los movimientos de la gente en su doble dimensión espacio-temporal. En este trabajo, usamos datos geolocalizados de la red social Twitter para mostrar el valor de las nuevas fuentes de datos para la Geografía del Tiempo. La metodología consiste en visualizar prismas espacio-temporales tanto en 3D como en 2D en cuatro zonas de estudio de la ciudad de Madrid, cada una con diferentes perfiles de uso del suelo (residencial, trabajo, estudios, y ocio). Para ello se han empleado como datos tweets recopilados durante un periodo de dos años que se han combinado con información de usos del suelo del Catastro. Aprovechando las ventajas de la visualización 3D y 2D es posible analizar la movilidad individual tanto en el tiempo como en el espacio. Los resultados muestran los diferentes comportamientos de movilidad de los individuos en cada zona de estudio durante el día, con datos complementarios para mostrar la actividad principal de la población en diferentes horarios.

1. INTRODUCCIÓN

La movilidad diaria de un individuo se estructura por la necesidad de realizar diferentes actividades que requieren estar en determinadas localizaciones durante tiempos concretos (Miller, 2005). El espacio no está completamente separado del tiempo, sino que ambos se combinan, por lo que la localización en el espacio no puede ser separada del momento temporal (Hägerstraand, 1970). La Geografía del Tiempo es una aproximación orientada a entender las actividades en esa doble componente espaciotemporal, reconociendo que la gente puede estar físicamente solo en un lugar y un tiempo en concreto (Miller, 2017).

Los datos diarios de las actividades realizadas por muestras de individuos en un determinado periodo de tiempo han servido como fuente de datos en muchos estudios de actividades humanas espaciotemporales. La ciencia de la información geográfica y las

Tecnologías de la Información y la Comunicación (TIC) están convergiendo para recrear una revolución temporal en la que las ciencias urbanas y del transporte pasan de ser ciencias basadas en el lugar a ciencias basadas en las personas (Miller, 2005). Con los avances en la computación y los Sistemas de Información Geográfica (SIG), es actualmente posible cartografiar los procesos que ocurren en el espacio en diferentes momentos temporales. Juntos, la geografía del tiempo y los SIG pueden dar un ambiente analítico útil para visualizar y explorar datos de actividad a nivel individual en un contexto espacio-temporal (J. Chen et al., 2011; Q. Huang & Wong, 2015).

Desde la perspectiva de la visualización en los SIG, es posible representar los datos espaciales tanto en vistas 2D cómo 3D dependiendo de la información suministrada. Las representaciones 2D son mejores para ilustrar relaciones espaciales precisas. Sin embargo, con esta visualización no se puede observar información basada en el tiempo (Keskin et al., 2014). Mientras, los métodos 3D en los cuales el tiempo es integrado ortogonalmente a un plano geográfico llevan de forma cualitativa a un pensamiento visual claro sobre los comportamientos humanos, la accesibilidad, y los patrones geoespaciales (Neutens, Van de Weghe, Witlox, & De Maeyer, 2008). Sin embargo, hay varias dificultades técnicas y de usabilidad: la orientación del usuario en una escena visualizada (la gente puede encontrar difícil percibir la información en 3D con ángulos cambiantes), la complejidad de los datos visualizados, y la falta de diseño cartográfico (Keskin, Dogru, Çelik, Doğru, & Pakdil, 2014). Por ello, en esta comunicación se propone diseñar una visualización 3D de cada área de estudio, apoyada en una visualización 2D, para poder complementar las ventajas de cada visualización.

Para la visualización en 3D, la herramienta propuesta es el camino espaciotemporal. Esta herramienta de representación mide el movimiento de un individuo en el espacio tridimensional, situándose el espacio en una llanura horizontal y el tiempo en una dirección perpendicular, a partir de una lista de puntos de control estrictamente ordenados en el tiempo (Miller, 1991, 2005). En el espacio-tiempo el individuo describe un camino en el que el lugar donde está ahora está críticamente atado al “lugar de ahora” de un tiempo anterior. Un camino puede ser enseñado gráficamente fácilmente si se colapsa el espacio tridimensional en una llanura bidimensional y se usa una dirección perpendicular para representar el tiempo. El individuo no puede pasar un punto en el espacio-tiempo más de una vez, pero tiene que estar siempre en un punto (Hägerstraand, 1970). La región espacio-temporal de un camino está representada con una triada ortogonal de ejes, dos ejes x e y definiendo el espacio bidimensional plano, y un eje z representando el tiempo. Un objeto localizado en (x, y, z) muestra las coordenadas de localización del objeto en un espacio bidimensional en el tiempo z (Miller, 1991).

Dentro de las TIC, los datos de Twitter contienen información espacial y temporal precisa en forma de coordenadas donde ocurre un evento específico, permitiendo el análisis a diferentes escalas (García-Palomares et al., 2018). Los datos de fuentes como Twitter no generan caminos espaciotemporales directamente, sino que generan una secuencia temporal de localizaciones espaciales que son usadas para construir el camino. Con estos puntos, los investigadores pueden representar caminos espacio-temporales para individuos, y usar estas trayectorias para desarrollar la localización y el tiempo de actividades (L. Yin, Shaw Shih-Lung, & Yu, 2011). Los datos georreferenciados suelen ser generados por usuarios de forma voluntaria y hay que tener en cuenta que no tienen como objetivo analizar patrones de actividades.

Sin embargo, aunque hay que tratar de forma cuidadosa la calidad de los datos, estos capturan algunos aspectos de las trayectorias espaciotemporales de los usuarios. Aunque los datos de Twitter pueden no reflejar la trayectoria detallada de un usuario en el día, ofrecen localizaciones seleccionadas del individuo sobre periodos más largos de tiempos.

Además, estos datos normalmente incluyen un gran número de usuarios para periodos relativamente largos, a coste mínimo (Q. Huang & Wong, 2015). El análisis espaciotemporal de esos datos puede revelar numerosa información oculta sobre comportamientos humanos en el espacio y tiempo, e interrelaciones con otras variables que afectan la movilidad (Keskin et al., 2014). Agrupando la información de la localización por múltiples días, los marcos de muestra temporales más largos pueden compensar la escasez espacial de la muestra en cada día, permitiendo el diseño de caminos espacio-temporales precisos (Q. Huang & Wong, 2015).

En esta comunicación, se busca indagar en el comportamiento temporal de la movilidad metropolitana y la naturaleza de las diferentes actividades desarrolladas a lo largo del día. Para este fin se propone como metodología la visualización de caminos espacio-temporales construidos a partir de datos de Twitter, el uso de datos de usos del suelo para predecir la actividad realizada por los usuarios en unas coordenadas espaciotemporales específicas, y la combinación de visualización en 2D y 3D para obtener la máxima información posible.

Mientras ha habido trabajos previos que han creado caminos espaciotemporales o han usado Twitter como fuente de datos para analizar la movilidad, solo se ha encontrado un estudio que ha empleado Twitter para la construcción de caminos espaciotemporales (Q. Huang & Wong, 2015). Este trabajo ha querido combinar estas dos vertientes. Sin embargo, los datos de Twitter capturan tiempo y localización, pero no recogen información más detallada como la naturaleza de los eventos o actividades realizadas. Por ello, una mejora metodológica que realiza este trabajo para paliar esta desventaja es la combinación del mapeado de caminos espacio-temporales creados a partir de datos de Twitter con datos estadísticos de usos del suelo. Unir los datos de usos del suelo con la actividad recopilada por los usuarios de Twitter tiene el potencial de informar de forma profunda el modo en el que los usuarios de Twitter interactúan con el espacio.

2. ÁREA DE ESTUDIO

Esta comunicación usa como área de estudio el Área Metropolitana de Madrid durante días laborables. Dentro de la ciudad de Madrid se han escogido cuatro zonas con actividades y usos del suelo dominantes o específicos. El objetivo a la hora de escoger dichas zonas es recoger la actividad y usos del suelo de los usuarios de Twitter en días laborables a cada hora, y usar estos resultados como proxy para estudiar los usos del suelo del Área Metropolitana de Madrid a lo largo del día (Figura 1).

1. Distrito de Puente de Vallecas. – Este distrito es un espacio netamente residencial y una de las zonas más densamente pobladas de la ciudad de Madrid. Para recoger usuarios de Twitter asociados a este espacio residencial, se han seleccionado los usuarios que han tuiteado habitualmente en este distrito en horario de noche (8 PM a 9 AM), de manera que podemos pensar son usuarios residentes en dicho espacio.

2. Complejo Nuevos Ministerios-AZCA. – Situado en el eje de la Castellana (una de las arterias principales de la ciudad que conecta el centro con el sector norte), es una de las principales zonas empresariales y financieras de Madrid, con un importante número de empleos. En este caso, se han seleccionado usuarios de Twitter que han tuiteado habitualmente en esta zona en horario de mañana (8 AM a 3 PM), considerando por tanto que se trata de usuarios cuyo empleo está en esta zona.

3. Ciudad Universitaria. - Es el principal campus universitario de la ciudad, donde se concentran las principales facultades de la Universidad Complutense de Madrid, pero también de la Universidad Autónoma de Madrid y otras universidades de ámbito privado. Nuevamente la selección de usuarios de Twitter se ha realizado a partir de aquellos usuarios que han tuiteado en este espacio en horario de mañana (8 AM a 3 PM).

4. Parque del Retiro. – Uno de los principales atractivos turísticos del centro de la ciudad, además de ser una de las zonas de ocio más utilizadas y uno de los pulmones más importantes de Madrid. En este caso, los usuarios de Twitter asociados al parque son aquellos que han tuiteado habitualmente en horario de tarde y tarde-noche (4 PM a 9 PM).

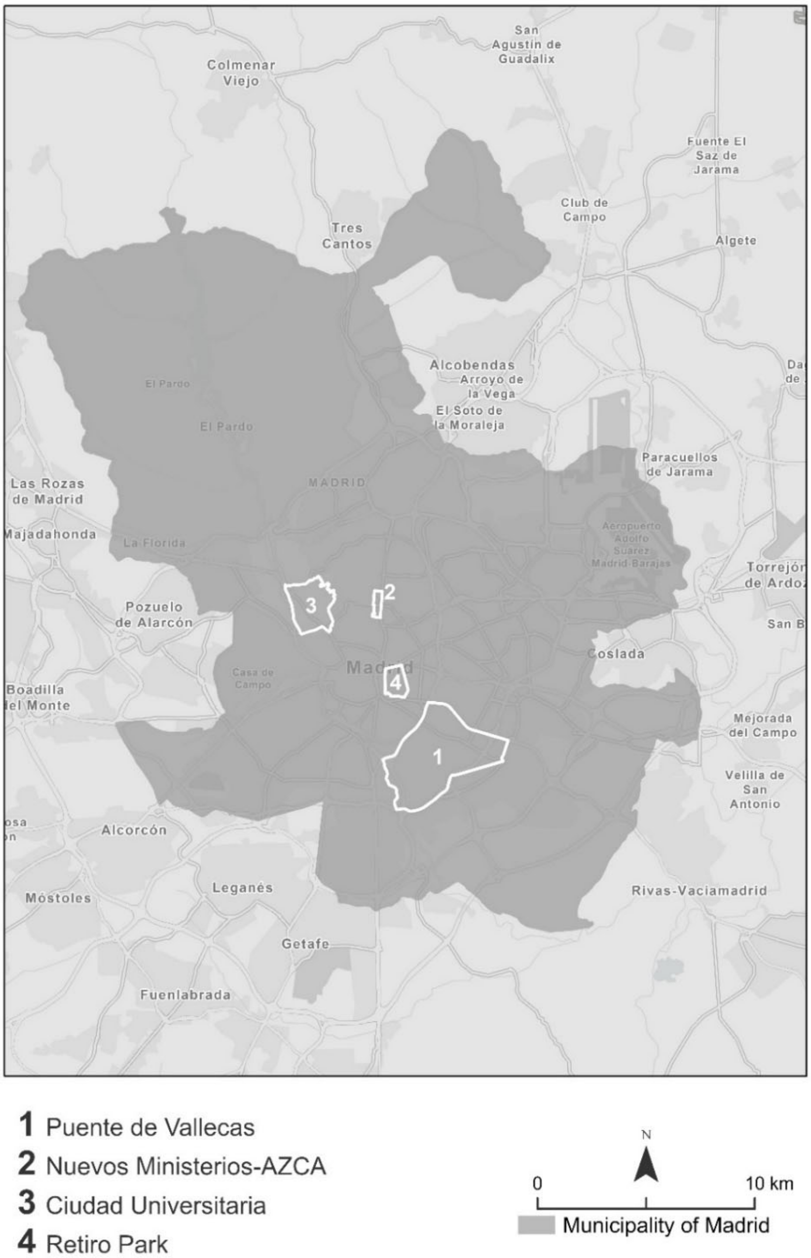

Fig. 1 – Zonas de estudio a analizar dentro del municipio de Madrid.

3. DATOS Y METODOLOGÍA

La base de datos de Twitter empleada para para esta comunicación tiene un total de 2.229.253 tweets, todos ellos georreferenciados y producidos por 171.631 usuarios localizados dentro del área metropolitana de Madrid. Estos tweets fueron recogidos en un periodo de dos años (desde el 1 de junio de 2016 hasta el 31 de mayo de 2018). Cada tweet cuenta con información relativa al identificador de usuario, el nombre de usuario, coordenadas espaciales de latitud y longitud, estampa temporal de fecha y hora, idioma y los hashtags que incluye el tweet.

Una vez incorporados los datos en un SIG, se procedió a una selección general de filtros para seleccionar usuarios útiles para la investigación y eliminar lo máximo posible el sesgo y ruido de los datos: Primero se eliminaron de la base de datos tweets cuyo identificador de usuario perteneciese a cuentas bot (cuentas con más de 1000 tweets publicados y con las mismas coordenadas en todos sus tweets, o cuentas con más de 10 tweets publicados con el mismo contenido semántico en el campo de texto de los tweets). Después, se eliminaron usuarios con muy baja actividad en Twitter, borrando los tweets de usuarios que hayan publicado menos de 20 tweets en total. A continuación, se eliminaron los mensajes de aquellos usuarios con poca movilidad espacial (una distancia media menor a 50 metros en la localización de todos sus tweets), y poca movilidad temporal (usuarios que tienen todos sus mensajes concentrados en un periodo temporal de dos semanas seguidas). De esta forma, se filtran posibles visitantes o turistas, y se asegura trabajar con población residente.

Además, se añadió un filtro consistente en eliminar usuarios con un rango horario igual o menor a ocho horas, con el fin de obtener solamente usuarios que hayan estado activos en la mayor parte del día.

A continuación, se amplió la muestra de datos a partir de la descarga de los últimos mensajes publicados por cada usuario con el objetivo de aumentar la precisión espacial y temporal de los movimientos individuales. Esta ampliación permite conseguir los últimos 3.200 tweets de cada usuario. Tras este segundo proceso de descarga, se filtraron los tweets no geolocalizados y que no se hallasen en el área de estudio o durante el periodo temporal de la muestra original. De esta forma se obtuvo una base de datos final con 18923 tweets de 2706 usuarios. Para mejorar la resolución temporal de los datos de Twitter, se trabajó agregando los tweets de múltiples días laborables, con el fin de obtener localizaciones concretas suficientes en una secuencia de 24 horas y diseñar así los caminos espacio-temporales diarios de cada usuario (Q. Huang & Wong, 2015). Estos tweets ya están previamente enriquecidos con datos del uso del suelo del Catastro. Al trabajar con tweets en días laborables se pueden hallar comportamientos regulares de movilidad, mientras que la movilidad urbana en los fines de semana es más errática. A partir de las fechas de cada tweet, y trabajando con un total de 516 días laborables, se calculó el número de días que cada usuario ha twitteado en un lugar y hora determinada.

Por cada usuario, se agregó el número de hora y el identificador de la zona de transporte de cada uno de sus tweets, con el objetivo de extraer en que zonas ha publicado cada usuario un mayor número de tweets en un número determinado de hora. Sin embargo, un individuo puede tener más de una localización visitada regularmente o múltiples trayectorias de viaje. Los puntos que están relativamente lejos de otros puntos tanto espacialmente como temporalmente pueden ser resultados de actividades aleatorias. En cambio, puntos cercanos espaciotemporalmente reflejan actividades regulares (Q. Huang & Wong, 2015). En casos en los que un usuario ha tuiteado desde más de una zona en una misma franja horaria, se seleccionó la zona de transporte donde se tuiteo un mayor número de días en dicha hora.

Si la frecuencia máxima de días en una hora dada coincide en más de una zona de transporte, se seleccionó la zona teniendo como referencia las zonas en las que se había escrito con mayor frecuencia en la hora anterior y posterior a la tratada.

Esta metodología de trabajar con los datos agrupados para el conjunto de días permite conocer patrones de actividad regular de los usuarios, pero pueden incluir actividades irregulares, introduciendo ruido o incertidumbre (Q. Huang & Wong, 2015). Para calcular caminos espaciotemporales de recorrido recurrente, se han definido estancias en cada una de las franjas horarias para las localizaciones de zonas de transporte donde el usuario ha tuiteado durante un mínimo de 3 días laborables. De esta forma se descartan puntos con potencial actividad aleatoria. Entonces, se simplificó la base de datos para que solo hubiese un punto registrado por usuario, lugar, y zona de transporte. Como resultado, se han obtenido 18923 puntos con los que se puede simular el camino espacio-temporal de 2706 usuarios en el Área Metropolitana de Madrid.

A continuación, se seleccionaron las cuatro áreas de estudio con una orientación fuerte a un uso de suelo concreto en las horas más propicias para el desarrollo de determinadas actividades. El siguiente paso fue seleccionar de la base de datos los usuarios que tengan un punto dentro de cada franja temporal definida en cada zona de estudio. La Tabla 1 presenta el número de usuarios válidos para los que se han obtenido caminos espaciotemporales en las distintas zonas de estudio. Finalmente, para la representación de los recorridos espaciotemporales en 3D, se ha otorgado a cada punto un valor de altura igual al número de hora, multiplicado por un factor de exageración de 200. Con estos valores, se han construido capas de líneas para representar los caminos espaciotemporales.

Zona	Horario	Tipo	Número usuarios validos
Puente de Vallecas	Noche (8 PM a 9 AM)	Residencial	27
Nuevos Ministerios-AZCA	Mañana (8 AM a 3 PM)	Trabajo	19
Ciudad Universitaria	Mañana (8 AM a 3 PM)	Estudios	30
Parque del Retiro	Tarde (4 PM a 9 PM)	Ocio	39

Tabla 1 – Número de usuarios en cada zona de estudio.

3. RESULTADOS

Los resultados obtenidos muestran el comportamiento de los usuarios en distintos momentos del día acorde con las actividades principales en cada una de las zonas de estudio seleccionadas para la elaboración de este capítulo (a partir de las muestras de usuarios detalladas en la Tabla 1). La zona residencial de Puente de Vallecas muestra una disminución gradual del porcentaje de usuarios durante la mañana, y un aumento del porcentaje a lo largo de la tarde, hasta llegar al horario de noche donde se concentran los mayores porcentajes de usuarios. Esta es una pauta característica del carácter residencial de la zona. En el área de oficinas de Nuevos Ministerios-AZCA se aprecia una mayor concentración de usuarios a lo largo de la mañana (con un pico determinado en las 2PM, fin del horario laboral por la mañana) y un fuerte descenso de usuarios por la tarde. El caso de Ciudad Universitaria es relativamente similar, aunque el porcentaje de usuarios aumenta de forma más brusca a primeras horas de la mañana y desciende más lentamente por la tarde. En el Parque del Retiro, el porcentaje de usuarios va en aumento a lo largo del día, con predominancia de usuarios en el horario de tarde. Cuando llega la noche, este porcentaje de usuarios empieza a disminuir prolongadamente (Figura 2).

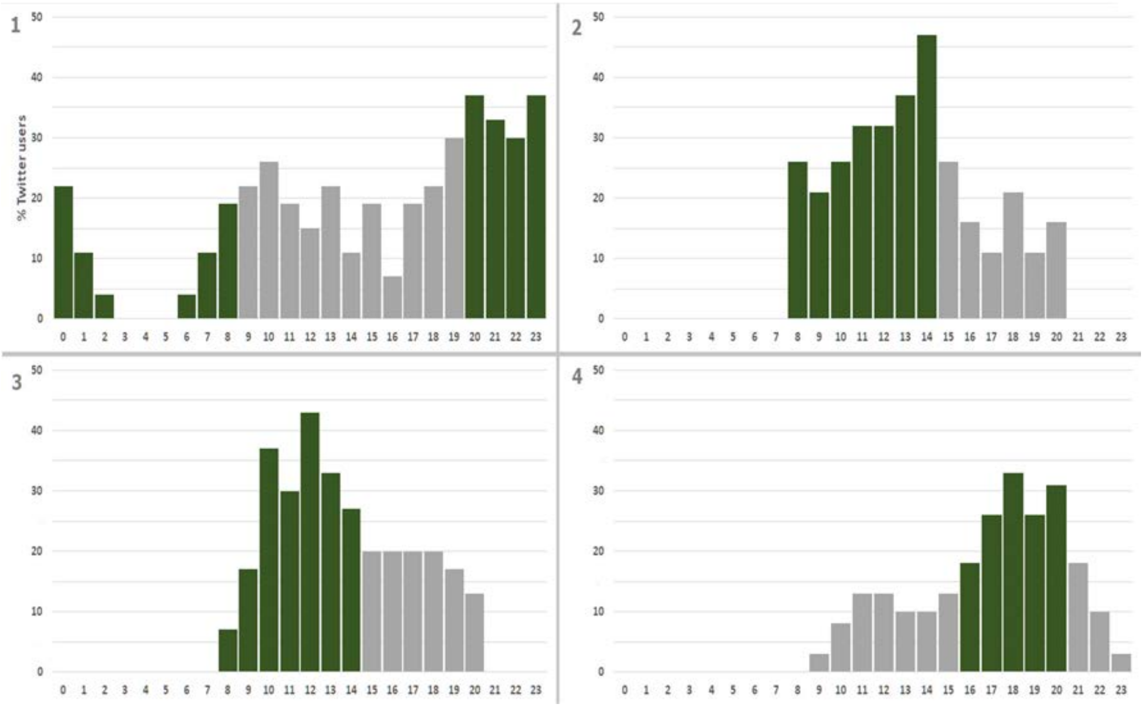

Fig. 2 – Distribución de usuarios por hora en Puente de Vallecas (1), Nuevos Ministerios-AZCA (2), Ciudad Universitaria (3), y Parque del Retiro (4).

La distribución temporal de usuarios basada en los usos del suelo, corrobora la situación observada en las zonas de estudio. En la zona de Puente de Vallecas, el principal uso del suelo, el residencial, consta de un continuo aumento a lo largo del día a partir de primera hora de la tarde hasta llegar a su máximo por la noche. Se puede observar en menor grado un constante uso comercial a lo largo del día, y un uso de hostelería en las horas de almuerzo y cena. Nuevos Ministerios-AZCA presenta un uso del suelo principal de oficinas en horario de mañana y que va descendiendo por la tarde, cuando a su vez, el uso comercial pasa a ser la principal actividad de los usuarios de la zona. También se pueden apreciar dos picos de hostelería a la hora del desayuno y almuerzo. El uso cultural es predominante en Ciudad Universitaria durante todo el día, especialmente durante la mañana y las primeras horas de la tarde. Se puede apreciar usos del suelo de oficinas e industrial por la mañana, y uso de los espacios deportivos a últimas horas de la mañana y durante la tarde. Finalmente, el Parque del Retiro presenta sus mayores porcentajes de usos del suelo en horario de tarde, a la vez que paralelamente se da uso del suelo de hostelería (Figura 3).

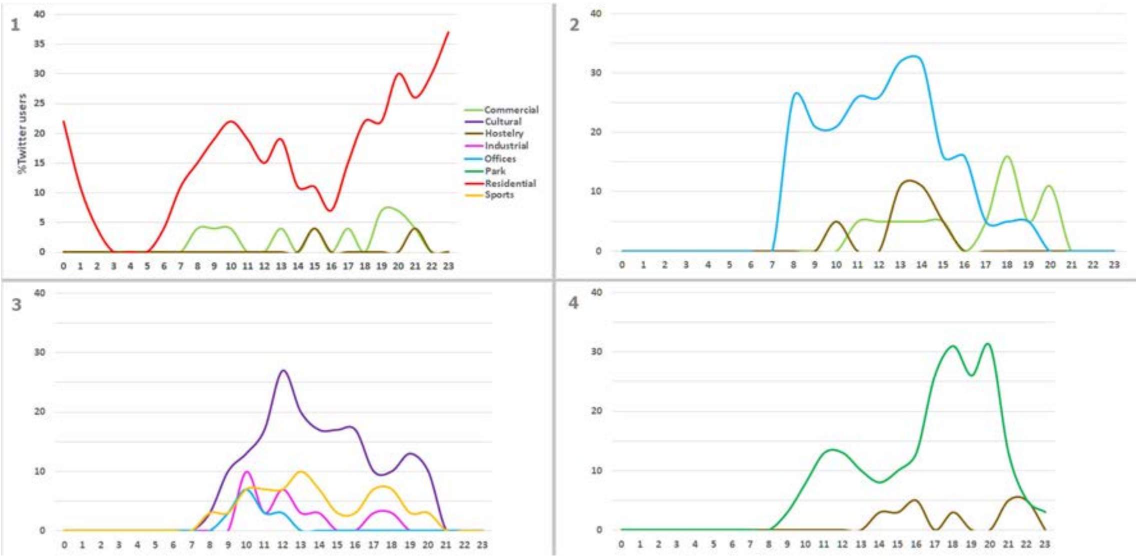

Fig. 3 – Distribución de usuarios por usos de suelo y hora en Puente de Vallecas (1), Nuevos Ministerios-AZCA (2), Ciudad Universitaria (3), y Parque del Retiro (4).

La visualización de los caminos espaciotemporales en 2D muestra los destinos de los desplazamientos para los residentes en el espacio residencial de Puente de Vallecas y los orígenes de los trabajadores en la zona de oficinas de AZCA, los estudiantes de Ciudad Universitaria o los usuarios del parque del Retiro (Figura 4). Mientras, la visualización en 3D permite contemplar los movimientos de estos usuarios a lo largo del día y su distribución temporal en las zonas de estudio (Figura 5).

En la visualización 3D se puede apreciar que los residentes detectados en Puente de Vallecas salen del barrio preferentemente a primera hora de la mañana y se desplazan principalmente a la cercana estación de trenes de Atocha, desde donde se mueven a otros puntos de la ciudad (principalmente el centro o zonas del norte de la ciudad que concentran la oferta de trabajo). También se aprecia algunos movimientos de regreso y salida entre las 2PM y las 4PM, usuarios que vuelven a la residencia a almorzar y vuelven al trabajo, y un regreso al barrio a partir de las 8PM. Paralelamente se puede apreciar un movimiento interno de usuarios que se desplazan a lo largo del día por la zona, mostrando el carácter dinámico de un distrito de población obrera que también cuenta con actividad de trabajo y ocio internos.

Mientras, la zona de oficinas de Nuevos Ministerios-AZCA recibe usuarios en horario de mañana, que provienen principalmente de las estaciones de tren de la ciudad (usuarios del área metropolitana que viajan a la zona en tren) y también del este de la ciudad o de los municipios colindantes del norte o del oeste (caracterizados por una población empresarial con niveles altos de renta). Igualmente, se aprecia una amplia diversificación de los caminos al resto de la ciudad a lo largo del día, principalmente por la tarde (usuarios que retornan a su residencia).

Una situación similar aparece en la Ciudad Universitaria, donde destaca un número importante de caminos a partir de las estaciones de tren, que van a la universidad en horario de mañana y salen de la universidad constantemente durante la tarde. En este caso se aprecia un flujo de caminos importante que proviene principalmente de las zonas residenciales del oeste y del sur del área metropolitana, pero que cuenta con un área de influencia mayor que la zona de oficinas. Además, las horas del día en la que los estudiantes llegan a Ciudad Universitaria están más concentradas, principalmente por la mañana y a primera hora de la tarde.

En el Parque del Retiro se pueden apreciar movimientos en la zona durante todo el día provenientes principalmente de espacios próximos en norte y el este de la ciudad y con mayor frecuencia en horario de tarde. La visualización en 2D muestra un área de influencia de sus visitantes mucho más pequeña en comparación con las dos zonas anteriores de trabajo y estudios, e indica un desplazamiento de ciudadanos principalmente del propio municipio de Madrid debido a su carácter temático y recreacional.

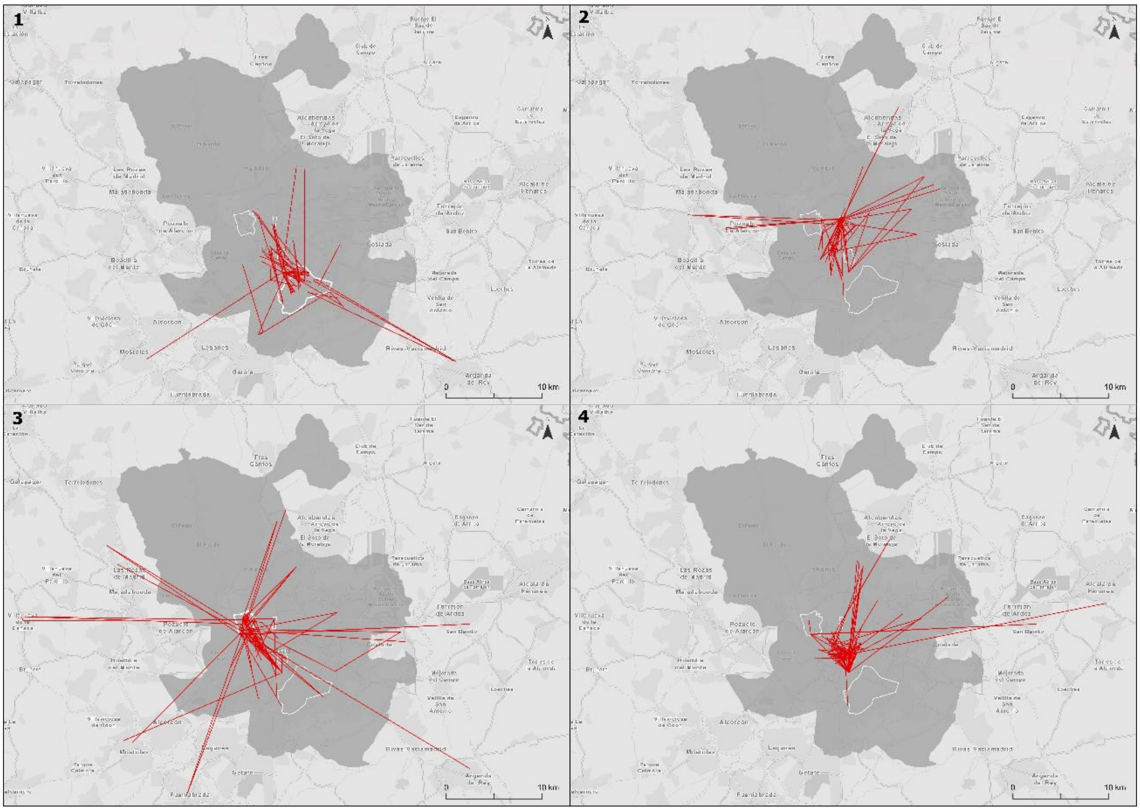

Fig. 4 – Caminos espaciotemporales a lo largo del día (2D) en Puente de Vallecas (1), Nuevos Ministerios-AZCA (2), Ciudad Universitaria (3), y Parque del Retiro (4).

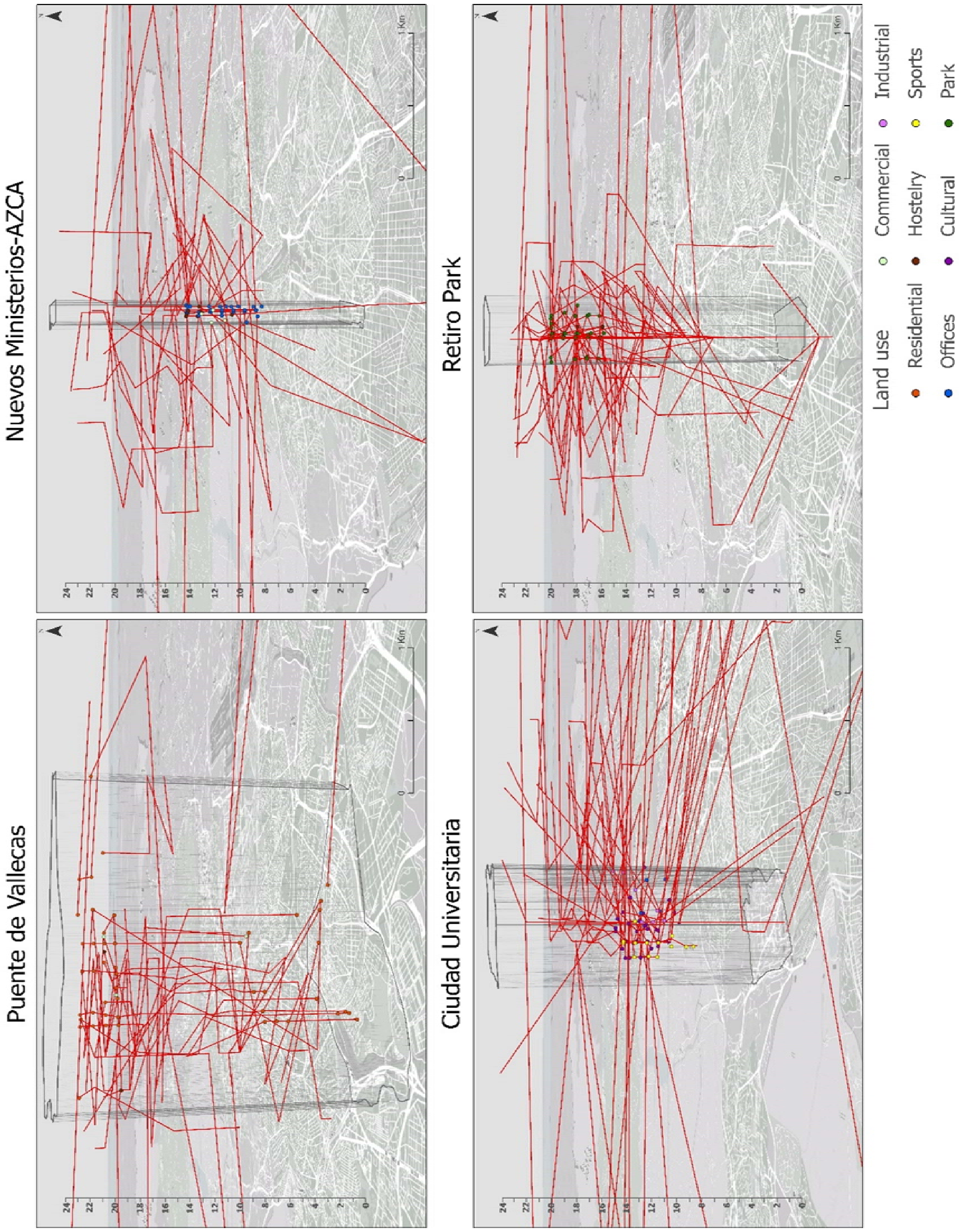

Fig. 5 – Caminos espaciotemporales a lo largo del día (3D).

4. CONCLUSIONES

La evolución en los últimos años de los SIG para el análisis y computación de datos, aunada con la aparición de nuevas fuentes de datos basadas en las TIC, han propiciado una nueva etapa en la Geografía del Tiempo. Una de las herramientas más empleadas en este campo es el camino espacio-temporal diseñado por Hägerstraand. Este tipo de análisis estaba limitado tradicionalmente por la disponibilidad de datos. Sin embargo, los datos procedentes de telefonía móvil o de redes sociales geolocalizadas, permiten hoy el procesado de caminos espaciotemporales con una alta resolución espacial y temporal.

En esta tesis se ha buscado indagar en las oportunidades de los datos de Twitter y las herramientas y visualizaciones necesarias para conocer la movilidad temporal de usuarios de distintos tipos de espacios urbanos.

De forma general se ha podido apreciar que los ciudadanos se desplazan a las áreas especializadas en trabajo por la mañana y regresan a sus residencias a lo largo de la tarde.

La distribución de los usos del suelo por hora concuerda con la visualización de la distribución de los usuarios de Twitter en el área de estudio, pudiéndose apreciar usuarios principalmente en usos de suelo relacionados con oficinas y estaciones de transporte por la mañana, y un número en aumento en parcelas residenciales a lo largo de la tarde.

Algunas limitaciones tradicionales de la geografía del tiempo consisten en que habitualmente, las vidas diarias presentan varias rutas o actividades, que, aunque ocurren en ciertas localizaciones primarias, pueden ocasionalmente ser conducidas en localizaciones alternativas. Igualmente, un individuo puede no realizar las mismas actividades en los mismos tiempos todos los días, o puede ir a un mismo sitio siguiendo una ruta alternativa (Q. Huang & Wong, 2015). El uso de filtros en datos de Twitter en función al número de días en los que un usuario ha estado en unas coordenadas espaciales y temporales puede ayudar a paliar estas limitaciones eliminando puntos aleatorios, y mostrando los puntos adecuados para realizar un camino espacio-temporal preciso y concurrente.

La cartografía tanto en 2D como en 3D realizada permite mostrar la utilidad del uso de Twitter como alternativa para la construcción de caminos espaciotemporales. Los datos de Twitter tienen la ventaja de una alta resolución espacial, en forma de coordenadas (x, y) a diferencia de los datos de telefonía, y la posibilidad de obtener datos a un coste bajo. Además, estos datos pueden enriquecerse con datos complementarios, como los usos de suelo del Catastro para poder estudiar la actividad principal de los usuarios en las distintas zonas de estudio a determinadas horas.

Sin embargo, este trabajo ha tenido algunos retos y limitaciones a tener en cuenta. El principal problema encontrado ha sido la baja muestra de usuarios en cada zona de estudio.

Este problema se debe principalmente al sesgo de la red social y a la poca cantidad de usuarios de Twitter que activan la opción de geolocalizar sus tweets. Otro desafío consiste en que habitualmente, las actividades diarias de la población se realizan en unas pocas localizaciones habituales (casa, trabajo, etc.), pero ocasionalmente pueden realizarse en localizaciones alternativas. Igualmente, un individuo puede no realizar una misma actividad en distintos tiempos según los días, o puede ir a un mismo sitio siguiendo una ruta alternativa (Q. Huang & Wong, 2015).

El uso de filtros en datos en función del número de días en los que un usuario ha estado en unas coordenadas espaciales y temporales puede ayudar a paliar estas limitaciones eliminando puntos aleatorios.

Un aumento del periodo temporal de la muestra permitiría recopilar más usuarios o caminos espaciotemporales más precisos, al disponer de mayor cantidad de localizaciones. Sin embargo, el aumento de la muestra también conlleva un mayor riesgo de obtener puntos aleatorios. Precisamente, otra mejora puede ser aumentar el número de días máximos en los que un usuario haya twitteado en un lugar a una hora para disminuir la probabilidad de tener puntos aleatorios, permitiendo el aumento de la muestra incrementar el filtro.

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EVOLUTION OF MOBILITY DURING THE COVID-19 CRISIS IN THE REGION OF MADRID

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ABSTRACT

The World Health Organization (WHO) declared COVID-19 a pandemic on March 11, 2020. Three days later, the Spanish Government declared a state of alarm, which lasted until June 20. This state consisted of a two-month lockdown with mobility restrictions and a two-month phased easing of lockdown.

This paper analyses the evolution of mobility patterns in the Region of Madrid through statistical information to study the impact of the COVID-19 crisis based on data from the Spanish National Statistics Institute (INE).

The results obtained in this paper show that, during the lockdown, trips made in the Region of Madrid fell by 70% compared to the usual scenario. However, the variations in mobility were very different in each area of the territory. For example, trips to San Sebastián de los Reyes were reduced by more than 90%, while trips from San Fernando de Henares decreased by only 30%.

Once the easing of lockdown phases began, there was an increase in trips in the Region of Madrid of more than 60% compared to trips made during the lockdown. This growth was also very irregular. For example, travels from Arganda del Rey increased by more than 260%, while trips to the same municipality only increased by 13%.

The mobility study is complemented with the analysis of socioeconomic variables, land use, and transport network to clarify the evolution of the different areas in the Region of Madrid during the COVID-19 crisis

1. INTRODUCTION

This document analyzes the evolution of mobility in the Region of Madrid during the state of alarm declared by Royal Decree 463/2020, of March 14, to manage the health crisis caused by the COVID-19, extended until June 21, 2020.

As a data source, the information provided by the Spanish National Statistics Institute (INE) is used, whose collection and preparation methodology is analyzed and discussed in the first section of this document.

With these data, the intra-areal and inter-areal movements in the Region of Madrid during the different phases of the state of alarm will be studied. Finally, a study of socioeconomic variables, land use, and transport network will be carried out to characterize how the state of alarm has affected the mobility of each territory of the region.

2. METHODOLOGY

2.1 Geographical and temporal scope

INE divides the national territory into 3,200 mobility areas. This unit comprises between 5,000 and 50,000 inhabitants, being much more homogeneous than the municipalities. Thus, in sparsely populated areas, an area of mobility will be the union of several municipalities, and in large cities, these areas will be districts or neighborhoods. The data are added from mobility areas, obtaining results at provincial, regional, and national levels.

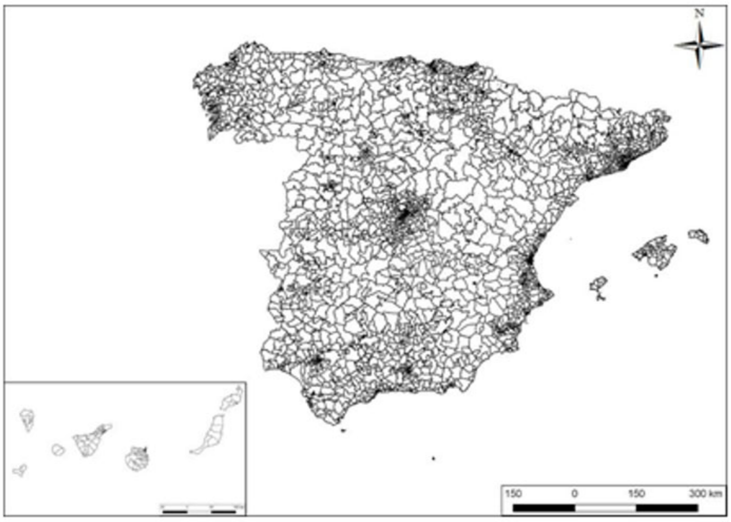

Fig. 1 – Mobility areas. Source: Own elaboration from INE

Because the data is based on the positioning of mobile devices, it is worth mentioning the precision of this method to analyze the data. According to sources, the accuracy will be tens or hundreds of meters in urban areas and kilometers in rural areas.

The temporal scope dealt with exclusively comprises the state of alarm, offering data from March 16 to June 20, 2020. On the other hand, the reference week to contrast the mobility data used is the week from Monday 18 to Thursday 21, November 2019, taking the average of this week's data as the mobility of a “normal” day.

2.2 Data sources, preparation, and supply of information

The primary data source for this study is anonymized mobile phone records, working with more than 80% of mobile phones throughout Spain in collaboration with the three leading mobile phone operators (Orange, Telefónica, and Vodafone). Regarding demographic data, these are obtained from the Municipal Register of Inhabitants on January 1, 2019.

In the technical project of the study, it is specified that the areas of residence are identified as the areas in which the telephone spends most of the time between 12 a.m. and 6 a.m. Destination areas are calculated as the most frequent area where the phone is between 10 a.m. and 4 p.m. as long as the device has been in that area for more than two hours.

Operators offer movements between areas as long as there are more than 10 or 15 movements, depending on the operator, to protect their users' privacy. For its part, the INE aggregates this information and offers the flows as long as it exceeds 100 movements.

This information allows knowing which part of the population remains in their area of residence most of the time, taking into account that movements within the area of residence are not counted.

The INE offers the population and its movement by mobility areas, provinces, regions, and the national total and data and origin-destination flows between mobility areas.

3. MOBILITY STUDY

3.1 Geographical and temporal scope

INE divides the Region of Madrid into 293 mobility areas. In this way, the most populated municipalities, such as Madrid or Móstoles, are divided into smaller areas. Similarly, the less populated municipalities are united in the same larger mobility area.

This study will work with the most significant territorial unit in each case. In the case of Madrid, for example, the 141 areas proposed by INE will be joined. In contrast, in the less populated areas, the INE mobility area will be used. In this way, the Region of Madrid will be divided into 102 study areas.

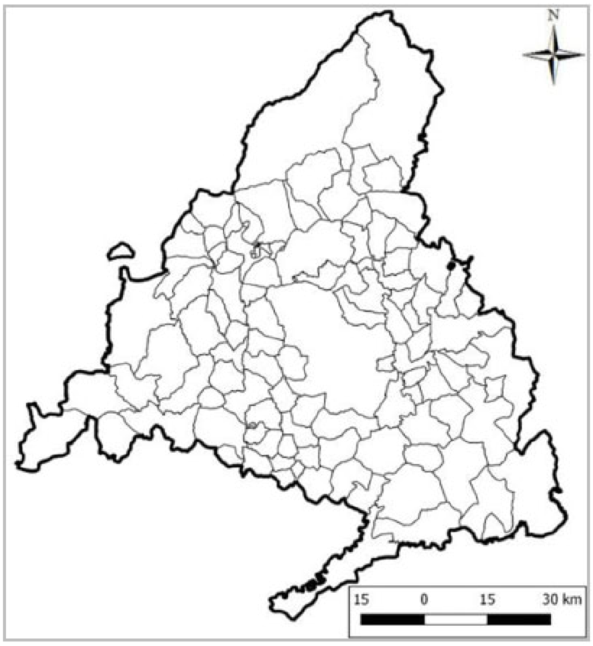

Fig. 2 – Study areas. Source: Own elaboration from INE

Before starting with the mobility data analysis, the different phases that the Region of Madrid went through during the state of alarm should be clarified:

- Lockdown: from March 15 to May 10, 2020.
- Phase 0: from May 11 to 24, 2020.
- Phase I: from May 25 to June 7, 2020.
- Phase II: from June 8 to 21, 2020.

To carry out an analysis throughout the different phases of the state of alarm, six dates have been selected for which an analysis of the origin-destination flows is made:

- Normality: average of data from November 18 to 21, 2019.
- Lockdown: average of data from March 26 and April 30, 2020.
- Phase 0: data from May 21, 2020.
- Phase I: data from May 28, 2020.
- Phase II: data from June 18, 2020.

3.2 General mobility

First, the number of total trips made with origin in the Region of Madrid will be analyzed.

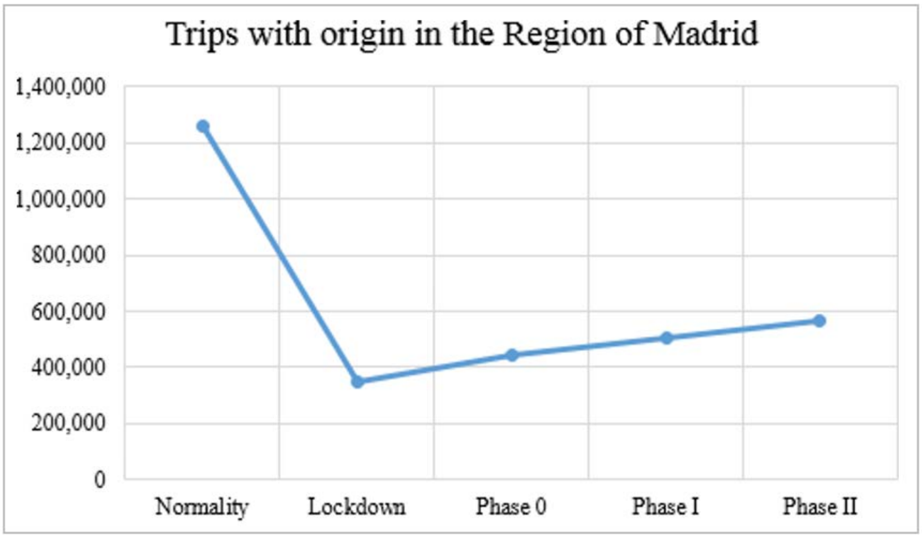

Fig. 3 – Evolution of trips with origin in the Region of Madrid during the state of alarm. Source: Own elaboration from INE

As shown in the previous figure, the data analysis allows us to see that the number of trips made in the Region of Madrid during a normal period is more significant than 1,250,000 trips. During the lockdown, this amount fell by more than 70%, with just over 350,000 trips. With the easing of lockdown, trips increased progressively but did not reach 50% of the trips made during a normal period

3.3 Intra-areal mobility

The analysis of intra-areal mobility consists of the study of movements within the same study area. For this reason, this analysis is only carried out in areas that are divided into several mobility areas, these being the most populated areas of the Region of Madrid.

Before entering into the data analysis, the particular case of Alcalá de Henares and Los Santos de la Humosa should be discussed. The municipality of Alcalá de Henares is divided into five mobility areas, the last of which is linked to Los Santos de la Humosa, so these two municipalities will be analyzed together as Alcalá de Henares.

STUDY AREA	MOBILITY AREAS	POPULATION (2019)
Alcalá de Henares	5	198,239
Alcobendas	3	117,040
Alcorcón	4	170,514
Aranjuez	4	59,607
Coslada	3	81,661
Fuenlabrada	9	193,700
Getafe	4	183,861
Leganés	7	189,861
Madrid	141	3,266,126
Majadahonda	2	71,826
Móstoles	6	209,184
Parla	3	130,124
Pinto	2	52,526
Pozuelo de Alarcón	2	86,422
Rivas-Vaciamadrid	3	88,150
Las Rozas de Madrid	3	95,814
San Sebastián de los Reyes	3	89,276
Torrejón de Ardoz	4	131,376
Valdemoro	2	75,983

Table 1 – Study areas in the intra-areal mobility analysis. Source: Own elaboration from INE

Intra-areal movements of the study areas correspond to approximately 70% of the trips made in the Region of Madrid. That is, 70% of the people do not leave their area of residence.

These intra-areal movements decreased by 68% during the lockdown, and during the easing of lockdown, they gradually increased until reaching 47% of the mobility of the normal period.

Analyzing the evolution of mobility in the different areas, the effect of mobility restrictions has not been uniform in all areas. Thus, the most affected areas have been Alcalá de Henares, Aranjuez and Madrid and the least affected Leganés, Móstoles and Torrejón de Ardoz.

LEVEL	DECREASES INTRA-AREAL	STUDY AREAS
Very high	> 70%	3
High	60-70%	5
Moderate	50-60%	8
Low	< 50%	3

Table 2 – Decreases in intra-areal mobility during the lockdown. Source: Own elaboration from INE

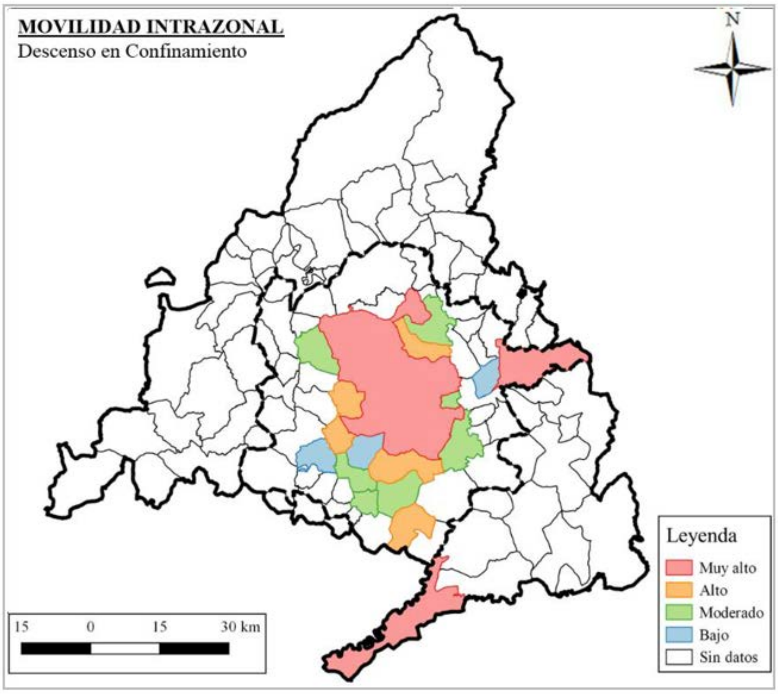

Fig. 4 – Decreases in intra-areal mobility during the lockdown.
Source: Own elaboration from INE

In the same way, the increase in mobility that occurred in the different phases of the easing of lockdown was not the same in the areas, with recoveries of between 4% and 30%, being the most pronounced in Alcalá de Henares and San Sebastián de los Reyes.

LEVEL	INCREASES INTRA-AREAL	STUDY AREAS
Very high	> 25%	2
High	20-25%	6
Moderate	15-20%	5
Low	< 15%	6

Table 3 – Increases in intra-areal mobility during the easing of lockdown. Source: Own elaboration from INE

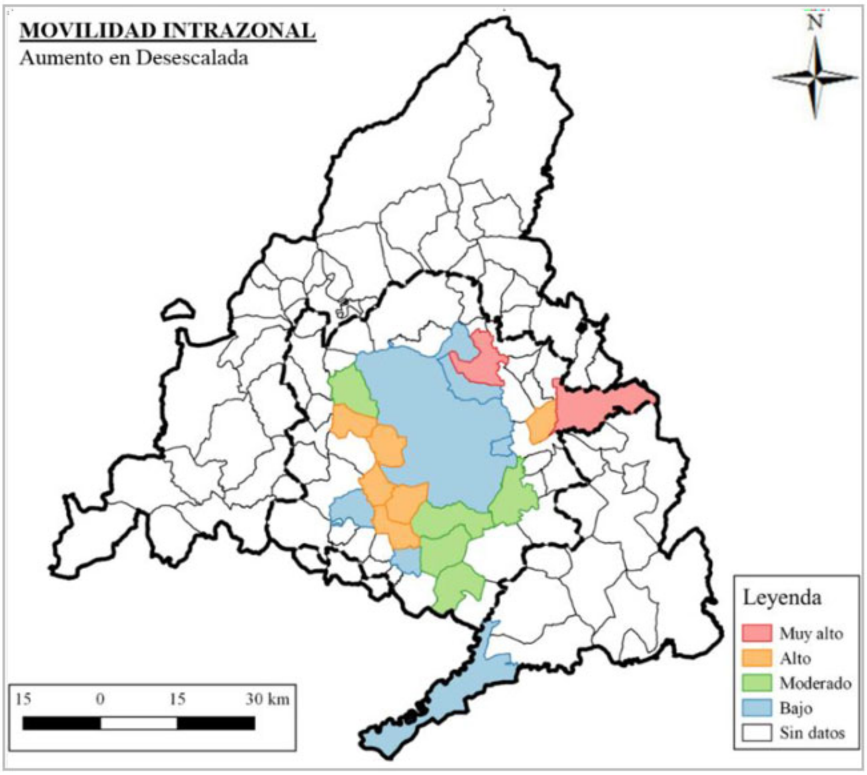

Fig. 5 – Increases in intra-areal mobility during the easing of lockdown.
Source: Own elaboration from INE

3.4 Inter-areal mobility

The analysis of inter-areal mobility consists of the study of the incoming and outgoing movements of each area. In this case, all study areas of the Region of Madrid are taken into account, and different areas of the Region of Castilla-La Mancha, which receive trips from Madrid.

The inter-areal movements of the study areas correspond to approximately 30% of the trips made in the Region of Madrid. That is, 30% of the people leave their area of residence.

These inter-areal movements decreased by 80% during the lockdown, and during the easing of lockdown, they gradually increased until reaching 42% of the mobility of the normal period.

3.4.1 Flows

To understand the evolution of the relationships of the study areas during the state of alarm, six flow maps have been made.

The first of them corresponds to the period of normality, in which it can be seen that the trips are concentrated in the capital and the north, west, and south sectors and, to a lesser extent, in the Henares Corridor. Most of the trips are located within the metropolitan area, with more superficial relationships in the provincial area, from which trips are made to the municipalities of Guadalajara and Toledo, adjacent to the Region of Madrid.

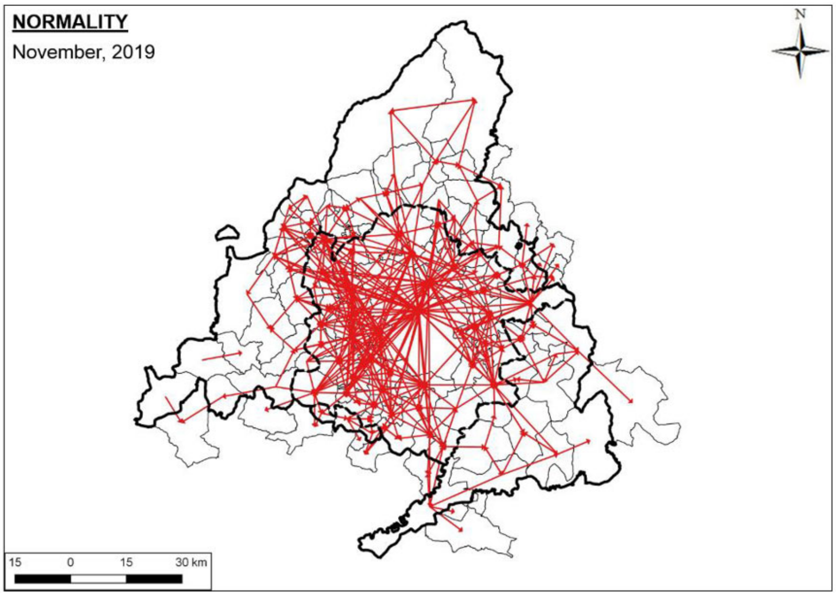

Fig. 6 – Origin-destination flows during the normality period (November 2019). Source: Own elaboration from INE

The flow maps of the trips made during lockdown are shown below. In these, it can be seen that the volume of flows is considerably reduced; practically disappearing trips in the provincial area, as well as in the foreign area.

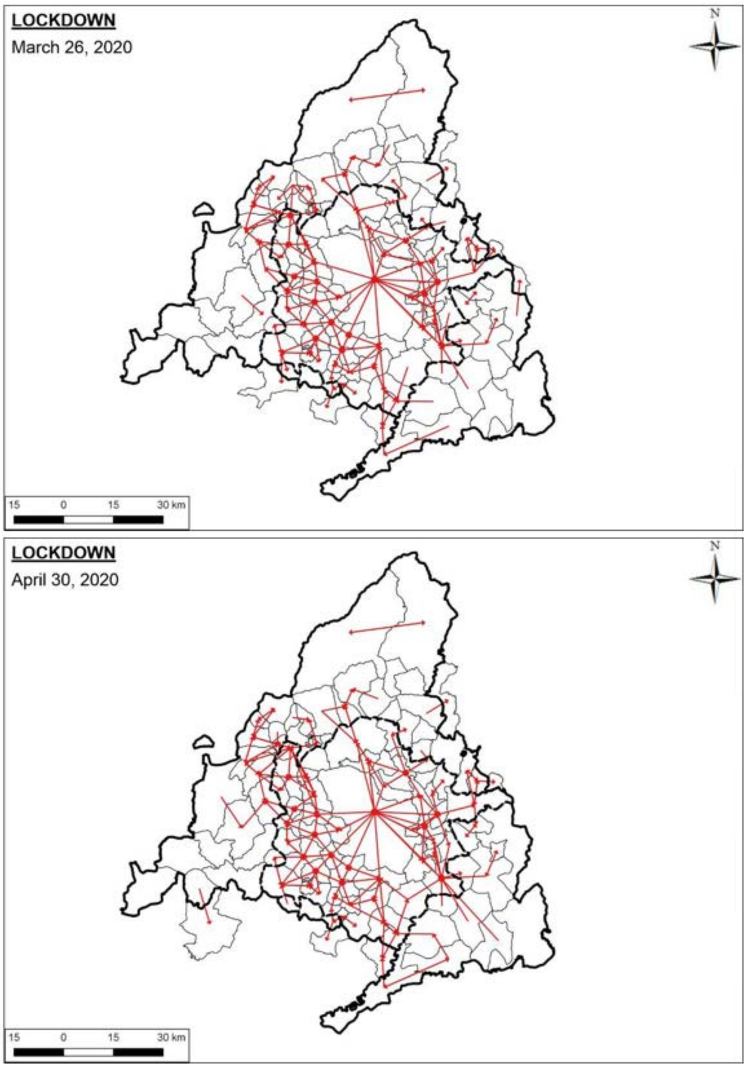

Fig. 7 – Origin-destination flows during the lockdown (March and April 2020). Source: Own elaboration from INE

Finally, flow maps have been made for each phase of the easing of lockdown. It should be noted that, despite the increase in mobility, the provincial and foreign areas do not increase their relationships.

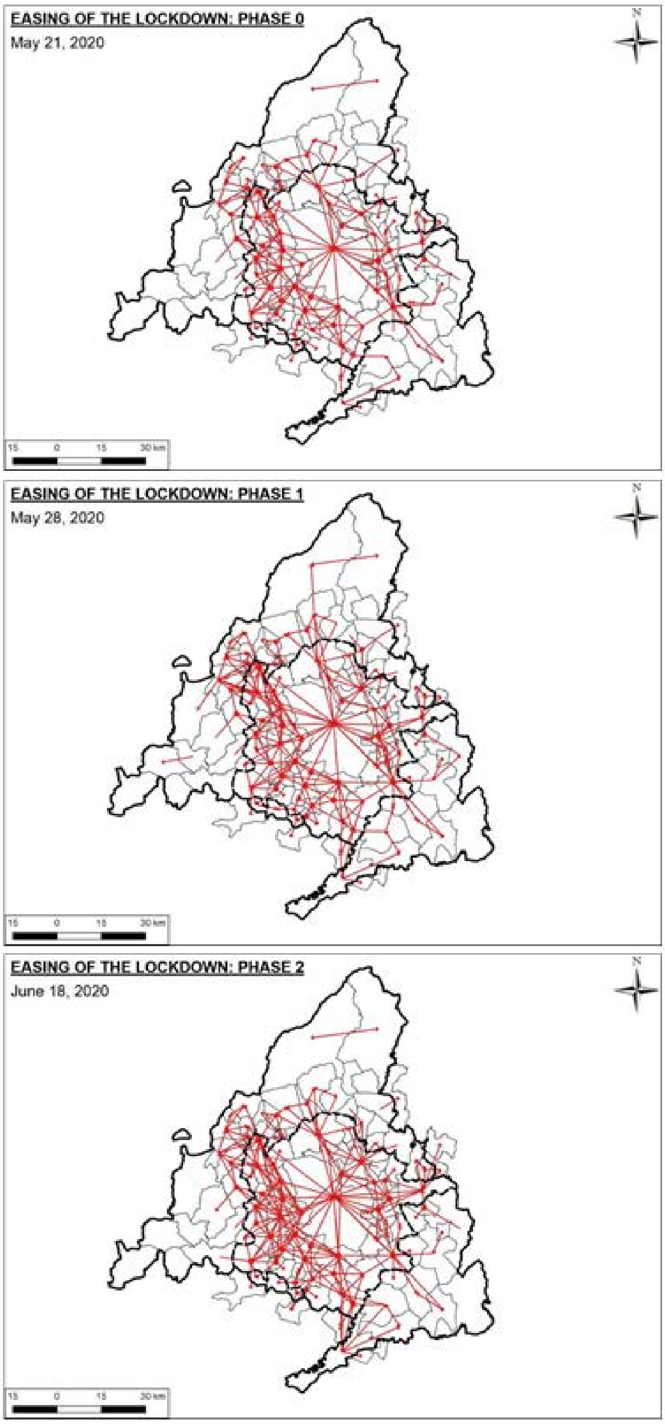

Fig. 8 – Origin-destination flows during the easing of lockdown (May and June 2020). Source: Own elaboration from INE

3.4.2 Outgoing movements

The evolution of the outgoing inter-areal movements has not been uniform in each study area of the Region of Madrid. To see how the effect has been in each area, the same methodology used in the intra-areal movements is followed.

According to the data structure, only flows in which more than 100 trips are made are shown. Due to this restriction, the study areas of Fuentidueña de Tajo and other municipalities, Navalagamella and other municipalities, and Navas del Rey and Chapinería do not have data on outbound trips, so they will not be taken into account in this analysis.

In the analysis of the outgoing inter-areal movements, it can be seen that the most affected areas during the lockdown, for the most part, are within the metropolitan area, in addition to some areas of the northeast of the region and the most rural areas of the southwest.

LEVEL	DECREASES OUTGOING INTER-AREAL	STUDY AREAS
Very high	> 90%	15
High	80-90%	28
Moderate	60-80%	38
Low	< 60%	18

Table 4 – Decreases in outgoing inter-areal mobility during the lockdown. Source: Own elaboration from INE

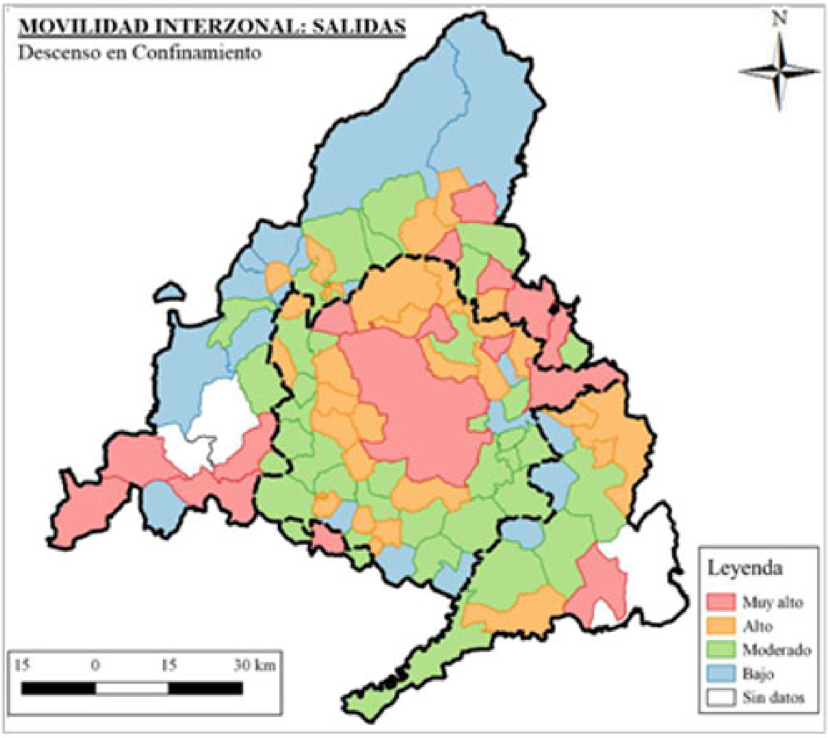

Fig. 9 – Decreases in outgoing inter-areal mobility during the lockdown.
Source: Own elaboration from INE

Outgoing movements increased in a high-moderate way in the metropolitan area during the easing of lockdown, with very high data in Arganda del Rey and San Martín de la Vega.

There were significant increases in the north of the provincial area, contrasting with the low increases in the east and west.

LEVEL	INCREASES OUTGOING INTER-AREAL	STUDY AREAS
Very high	> 50%	9
High	25-50%	30
Moderate	10-25%	32
Low	< 10%	28

Table 5 – Increases in outgoing inter-areal mobility during the lockdown. Source: Own elaboration from INE

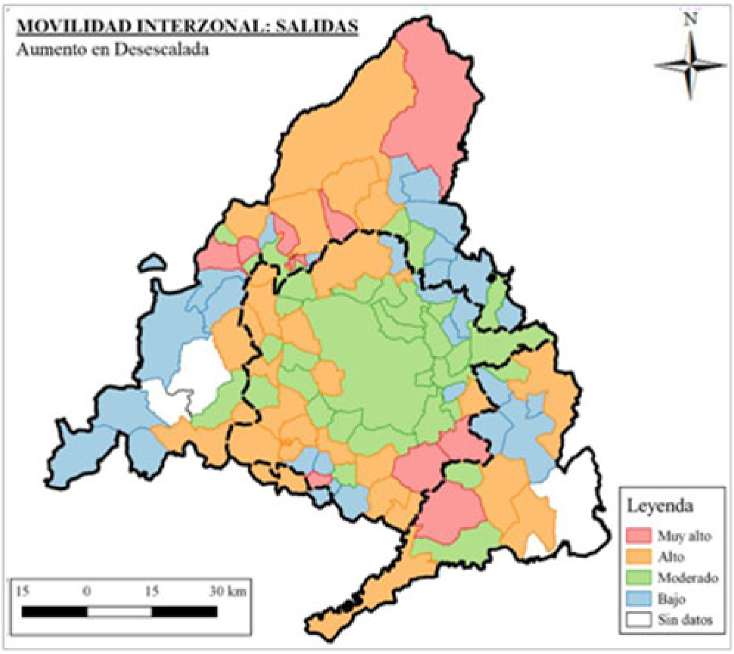

Fig. 10 – Increases in outgoing inter-areal mobility during the easing of lockdown. Source: Own elaboration from INE

3.4.3 Incoming movements

The evolution of the incoming inter-areal movements has not been uniform in each study area of the Region of Madrid. To see how the effect has been in each area, the same methodology used in the intra-areal movements is followed.

According to the data structure, only flows in which more than 100 trips are made are shown. Due to this restriction, the study areas of Aldea del Fresno and Villamanta, Cadalso de los Vidrios and other municipalities, Pedrezuela, San Martín de Valdeiglesias and Pelayos de la Presa, Sevilla la Nueva and Valdetorres de Jarama do not have travel data for input, so they will not be taken into account in this analysis.

The lockdown brought a high decrease in incoming trips in the central and south-eastern areas of the region. It should be noted that the southern regions of the metropolitan area did not undergo significant changes, remaining at low-moderate levels of decrease.

LEVEL	DECREASE INCOMING INTER-AREAL	STUDY AREAS
Very high	> 90%	23
High	80-90%	13
Moderate	60-80%	33
Low	< 60%	27

Table 6 – Decreases in income inter-areal mobility during the lockdown. Source: Own elaboration from INE

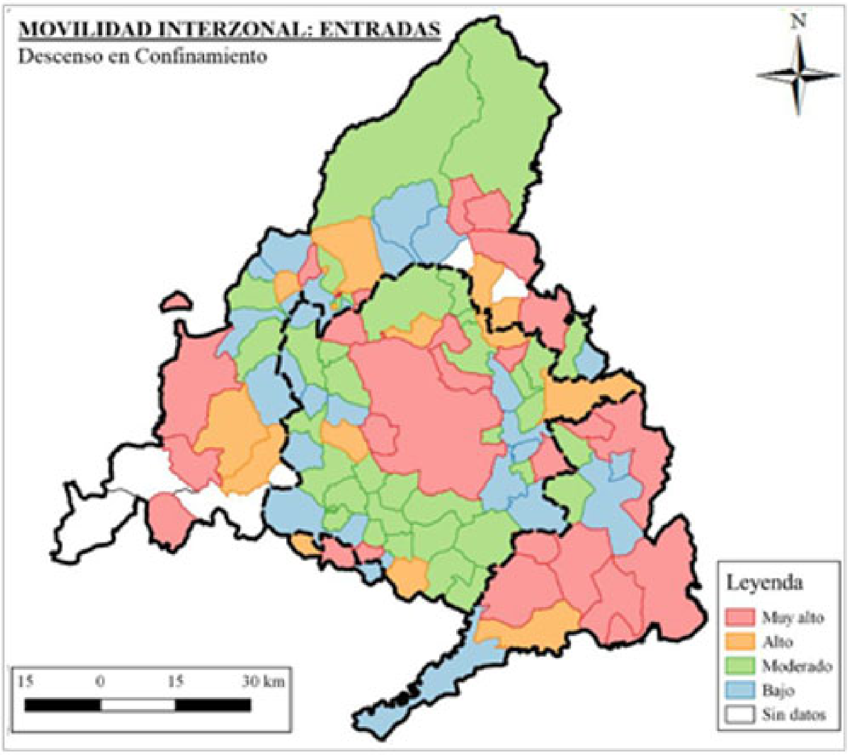

Fig. 11 – Decreases in income inter-areal mobility during the lockdown. Source: Own elaboration from INE

The increase in incoming trips during the easing of lockdown was generally moderate- high. In contrast to the trend of low changes in the south of the region, these areas suffered high increases during the easing of lockdown.

LEVEL	INCREASES INCOME INTER-AREAL	STUDY AREAS
Very high	> 50%	16
High	25-50%	29
Moderate	10-25%	29
Low	< 10%	22

Table 7 – Increases in incoming inter-areal mobility during the easing of lockdown. Source: Own elaboration from INE

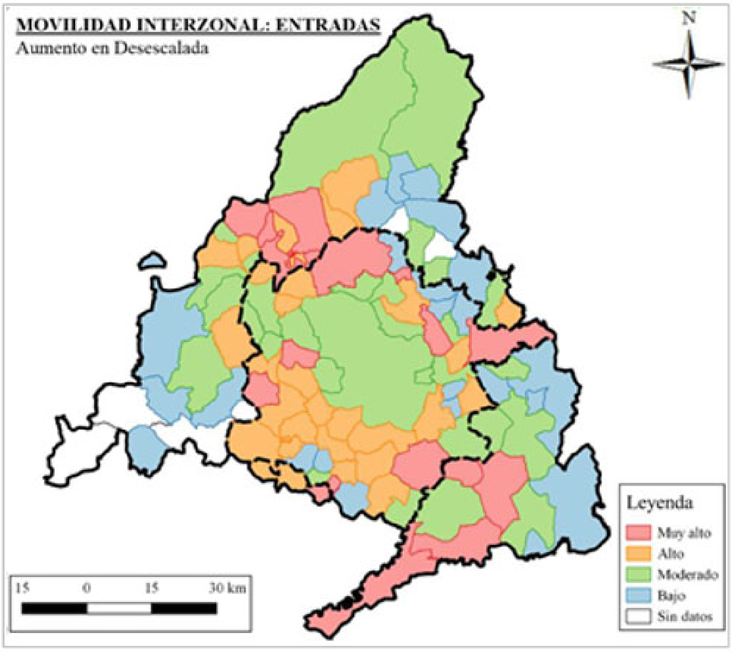

Fig. 12 – Increases in incoming inter-areal mobility during the easing of lockdown. Source: Own elaboration from INE

4. SOCIOECONOMIC, LAND USE AND TRANSPORT STUDY

4.1 Introduction and methodology

The socioeconomic analysis of the different study areas of the Region of Madrid is carried out to contextualize the condition of the lockdown and the easing of lockdown in mobility.

Different socioeconomic variables that will characterize each study area have been analyzed. In the same way that the mobility analysis has been carried out, these variables will be discretized into four categories.

The data that have been used in the analysis have been extracted from ALMUDENA Municipal and Zonal Data Bank of the Region of Madrid and National Geographic Institute (IGN), and it has been added to calculate the data of the study areas used by INE in the collection of mobility data.

4.2 Population density

The Region of Madrid is the most densely populated region with a density of 829.72 people per km2 in 2019. Focusing on the study areas, these densities range between 10 and 7,000 people per km2, concentrating the most densely populated within the metropolitan area.

LEVEL	POPULATION DENSITY	STUDY AREAS
Very high	> 900 people per km^2	27
High	300-900 people per km^2	22
Moderate	100-300 people per km^2	30
Low	< 100 people per km^2	23

Table 8 – Population density. Source: Own elaboration from ALMUDENA

4.3 Per capita income

The Region of Madrid has the highest per capita income data at the national level, with more than 35,000 € per inhabitant. The per capita income data for the region oscillate between 11,000 and 70,000 € per inhabitant, also concentrating the areas with the highest income in the metropolitan area.

LEVEL	PER CAPITA INCOME	STUDY AREAS
Very high	> 25,000 € per inhabitant	27
High	20,000-25,000 € per inhabitant	18
Moderate	15,000-20,000 € per inhabitant	29
Low	< 15,000 € per inhabitant	28

Table 9 – Per capita income. Source: Own elaboration from ALMUDENA

4.4 Employment data

Employment data is a crucial variable to consider since 20% of trips made in the Region of Madrid are associated with work, according to the Home Mobility Survey of the Region of Madrid (EDM2018).

The percentage of the population of each study area affiliated with Social Security has been calculated to see the level of employment of the same. These percentages range from 30% to 50%.

LEVEL	POP. AFFILIATED SOCIAL SECURITY BY RESIDENCE	STUDY AREAS
Very high	> 45%	6
High	40-45%	40
Moderate	35-40%	45
Low	< 35%	11

Table 10 – Population Affiliated to Social Security by Residence. Source: Own elaboration from ALMUDENA

On the other hand, the total number of workers attracted by each study area has been obtained, calculating their percentage concerning the area's population, which varies between 13% and 100%.

LEVEL	POP. AFFILIATED SOCIAL SECURITY BY WORK C.	STUDY AREAS
Very high	> 40%	19
High	25-40%	31
Moderate	20-25%	21
Low	< 20%	31

Table 11 – Population Affiliated to Social Security by Work Centre. Source: Own elaboration from ALMUDENA

From the data of the affiliations, the balance of each study area has also been obtained. This balance is defined as the difference between the workers received by the area and the workers residing in it. In this way, if the balance is positive, the analysis says that the study area needs to attract trips.

BALANCE	STUDY AREAS
Positive	19
Negative	83

Table 12 – Balance of Affiliates to Social Security. Source: Own elaboration from ALMUDENA

The unemployment rate is another variable taken into account as it directly influences the number of trips made in each study area. These rates range from 2.5% to 10%.

LEVEL	UNEMPLOYMENT RATE	STUDY AREAS
Very high	> 6.5%	25
High	5.5-6.5%	27
Moderate	4.5-5.5%	25
Low	< 4.5%	25

Table 13 – Unemployment rate. Source: Own elaboration from ALMUDENA

Finally, the data on the economic activities of each study area have been analyzed, obtaining the majority branches of activity in each of them. The Other Services branch includes Administration, health, education, recreational, personal and associative activities, and households.

BRANCH	RESIDENCE AREAS	WORK AREAS
Construction	1	0
Mining, Industry, and Energy	0	7
Other Services	36	37
Distribution and Hospitality Services	53	50
Business and Financial Services	12	8

Table 14 – Branches of activity. Source: Own elaboration from ALMUDENA

4.5 Land use

Land use in the Region of Madrid has been analyzed, as it is an excellent indicator of job creation and, therefore, of attracting trips.

This analysis has focused on the economic lands in the Region of Madrid: Agriculture, Industry and Mining and Construction.

LAND USE	STUDY AREAS
Agriculture	102
Industry	75
Mining y Construction	51

Table 15 – Land uses. Source: Own elaboration from IGN

Although Agriculture is present in all the study areas, most of it is concentrated in the southern and eastern parts of the region. Industrial land is concentrated in the metropolitan area and, lastly, Mining and Construction in the southeast.

It should be noted that Agriculture is not such an essential sector in the region, the Industrial and Mining and Construction areas attract more trips, on which this analysis will focus

4.6 Transport

The analysis of transport is based on two fundamental axes: motorization and the evolution of the use of Public Transport.

The first one is calculated using the Motorization Index. This index relates the vehicles in a specific area and the population that resides in it. The region is very heterogeneous when it comes to the Motorization Index, with values between 400 and more than 20,000 vehicles per 1,000 inhabitants.

Although it should be mentioned that there is a bias in this variable since the existence of differences in the tax regime between the areas means that in some of them, a large number of vehicles are registered, most of them belonging, for example, to fleets of car-sharing companies. Once this has been clarified, the discretization of the data is presented.

LEVEL	**MOTORIZATION INDEZ**	**STUDY AREAS**
Very high	> 750 vehicles per 1,000 inhabitants	18
High	650-750 vehicles per 1,000 inhabitants	24
Moderate	600-650 vehicles per 1,000 inhabitants	28
Low	< 600 vehicles per 1,000 inhabitants	32

Table 16 – Motorization Index. Source: Own elaboration from ALMUDENA

The second axis of this analysis is, as mentioned previously, the use of Public Transport. INE publishes data on passengers transported monthly by city bus and Metro System. It should be noted that around 85% of the trips made by bus are made within the municipality of Madrid.

The following graph shows the evolution of the use of these two modes of transport. This evolution shows a significant drop with minimum values in April. Mention that the March values are so high since no restrictions were applied to mobility in the first half of this month.

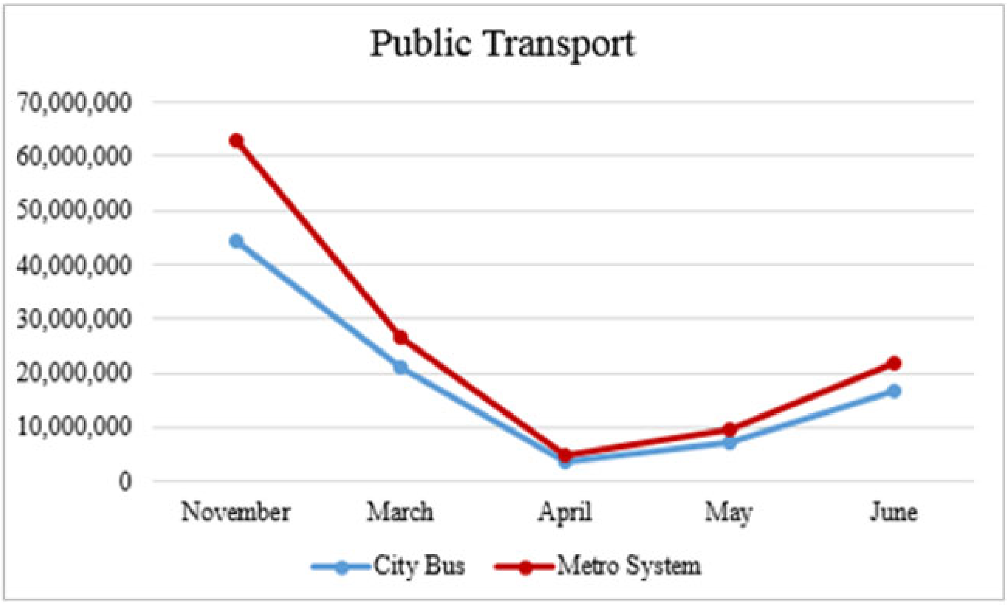

Fig. 13 – Evolution of the use of Public Transport during the state of alarm. Source: Own elaboration from INE

5. DISCUSSION OF RESULTS

This analysis will start from the employment data for mobility analysis, as the main reason for the trips.

The branch to which the population living in each study area is dedicated allows us to analyze the outgoing inter-areal mobility, so the generation of trips in each area.

Thus, it is observed that the areas in which the majority of the population is dedicated to Business and Financial Services, the most economically powerful (Madrid, Alcobendas, Majadahonda, Pozuelo de Alarcón, etc.), suffered a significant decrease during the lockdown and moderate increases after it. This is explained by the fact that the presence of these services was reduced and, after lockdown, a teleworking regime has continued.

On the other hand, the areas in which the population is dedicated to distribution were less affected in lockdown and, therefore, suffered more minor increases in the easing of lockdown. This happened since these services have a high degree of presence and are associated with negative balances, generating many trips.

Incoming inter-areal mobility is given by the branches in each destination area and is highly conditioned by their land uses.

In the same way, the areas that base their activity on business and financial services (Alcobendas, Pozuelo de Alarcón, Tres Cantos, etc.) lost a large percentage of trips and did not recover mobility primarily during the easing of lockdown.

These areas have in common that they present positive balances, that is, they attract many trips, and that they have large areas of industrial land.

Again, areas with heavy distribution services were not significantly affected by the lockdown, receiving practically the same trips as in a normal period.

The per capita income analysis shows that fewer resource areas suffered fewer decreases than those with higher incomes. This may reflect the high unemployment rates in areas with fewer resources, so people who did not work did not make as many trips during normality.

Finally, it should be mentioned that the Motorization Index does not have much impact on this analysis, as it is not an accurate reflection of people's mobility since the Region's Public Transport system is widely used and carries a large number of travelers. However, it has been seen that areas with high Motorization Index are associated with very high decreases and low increases, which leads to the conclusion that the abundance of vehicles in the areas does not ensure low conditions

6. CONCLUSIONS

With this analysis, it has been concluded that the state of alarm brought with it a change in the habits and mobility of the population of Spain and the Region of Madrid. Mobility was drastically reduced during March and April due to lockdown. With the easing of lockdown, mobility grew but, even so, at the end of the state of alarm, the mobility that occurred in normal periods, before the arrival of the pandemic and state of alarm, has not recovered.

Once the condition has been characterized, it has been seen that it is closely related to employment data. The sector most affected by the lockdown was the business and financial industry, which suffered significant declines and did not recover in the easing of lockdown due to the adoption of teleworking.

On the other hand, the distribution sector, the majority in the region, was not significantly impacted due to its degree of presence, so it suffered low decreases and increases, remaining very stable during the state of alarm.

Mention that the municipalities with fewer resources in the region had suffered fewer decreases, related to the high unemployment rates, which meant that the trips before the state of alarm were not very high.

Finally, it has been seen that highly motorized areas have been most affected by mobility restrictions, which can conclude that the abundance of vehicles does not lead to mobility stability.

These conclusions can lead to different strategies, adapted to each branch of activity and study area, to act in the face of new waves of the pandemic in the future

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MOBILITY TO THE UNIVERSITY CAMPUSES OF THE COMMUNITY OF MADRID: DIAGNOSIS AND BASES FOR A SUSTAINABILITY STRATEGY

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ABSTRACT

The movements to the university campuses bring a challenge to the sustainability and public transportation. Taking into account the EDM2018 (home mobility survey of the Community of Madrid) an analysis of university mobility has been made in order to define global and specific strategies for this segment of recurring trips.

The study perform, divides the survey data according to different type of users: students, workers (PAS) and teachers/researchers (PDI). Each of these groups have different socio-economic profiles, work patterns and availability of their own vehicle, which conditions their daily mobility. Second, the different mobility patterns of the 14 Campuses of the 6 public universities in the region are compared. The results are clearly influenced by location variables (urban, metropolitan, isolated) and their accessibility by public transport.

Therefore, a multiple causal relationship can be established between the above factors, which determine the modal distribution for each campus and each group. The variations are important, going from 78% of trips by public transportation made by students in urban campuses to 14% of trips by public transportation made by workers in isolated fields.

The analysis methodology contrasts the previous results, based on the data obtained from the EDM2018 with the level of infrastructure and transport offer: car parks, entrances, railway stations and bus stops, and their accessibility to the campus.

These analyzes make it possible to propose a series of recommendations to reduce car use and promote the use of collective transport.

All of this will be part of the diagnosis for the development of Sustainable University Mobility Plans, which will be the second phase of this work.

1. INTRODUCTION AND OBJECTIVES

1.1 Issue

There is a big problem with pollution in the city of Madrid. We need to promote sustainable mobility to give a solution to this issue. Nowadays there is talk of using active modes of transport such as bicycles, electric vehicles, walking… but first it is necessary to facilitate their use and make people aware so that they choose to use them.

1.2 Objectives

The main objective of this research is to reduce the CO_2 emissions produced by motor vehicles and improve the mobility of the city, in this case of the university community.

1.3 Structure of paper

The structure of the paper is the following:

First, it will show an analysis of the existing studies that have been carried out on sustainable university mobility will be shown, highlighting proposed solutions and problems that remain to be solved. For this, the mobility of the public universities of Madrid will be taken as a case study.

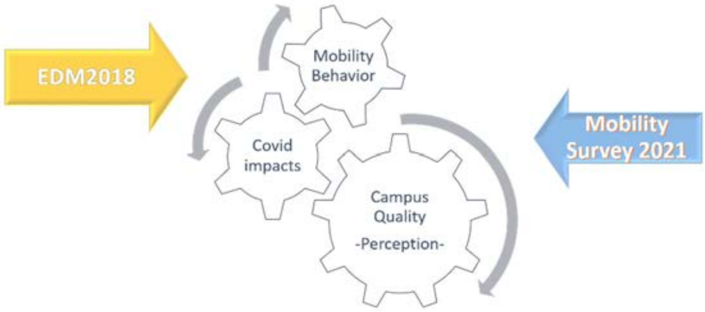
After it will do a recompilation of mobility data with a mobility survey ad hoc EDM2018, where it will obtain the mobility patterns of university users and it will do a comparative analysis with the mobility survey 2021 that was created for this research aimed at students, teachers, administrators, and providers. With the data obtained from the survey 2021, it will do a statistic analysis to identify mobility patterns and to define key factors improving sustainable mobility, in addition to being able to appreciate the incidence of COVID-19.

2. BACKGROUND

2.1 State of the art (key papers <12)

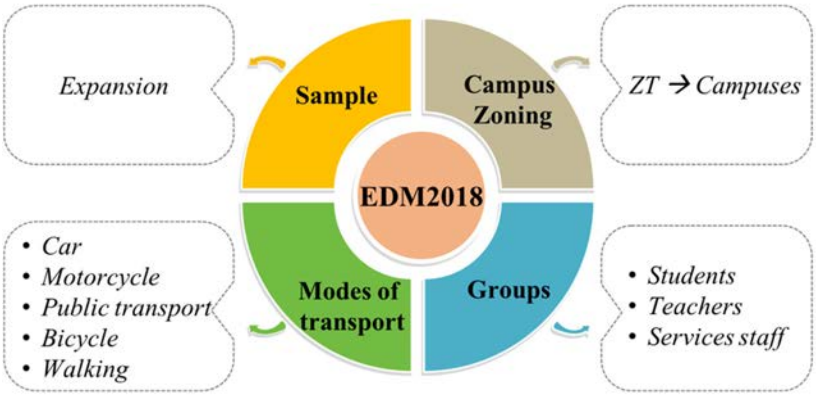
The published literature on sustainable transport is extensive, although it focuses mainly on car use, its impacts, and infrastructure (Balsas, 2003).

3. METHODOLOGY



3.1. Mobility survey ad hoc EDM2018

The mobility survey ad hoc EDM2018 was done by Regional transport consortium of the Community of Madrid to study the mobility general of population of Madrid. This survey was done in person, between February 13 and June 12, 2018 in the Community of Madrid, grouping the areas where the surveys were conducted as transportation areas. For use this data, it has been filtered by age, degree, transportation areas that coincide with our study areas, in this case university campuses and reason for the trip.



The population of the university is made up of students, teachers and service staff that have been identified with the following characteristics:

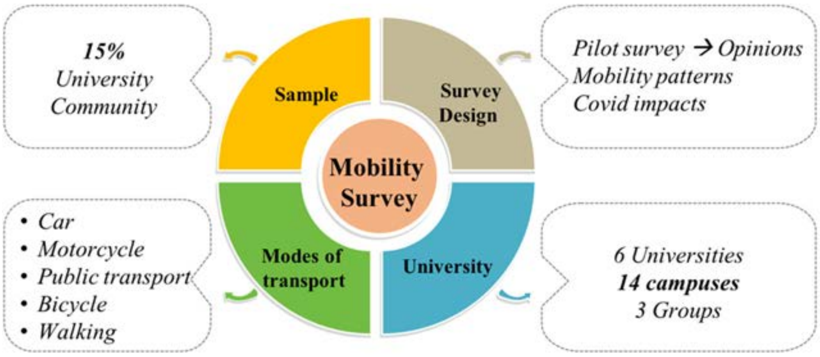
- Students: over 18 years old, with professional or university training, studying or studying and working, study trips.
- Teachers: over 30 years old, with high school studies and/or professional training, public sector employees, work trips.
- Service staff: over 20 years old, public or private sector employees, work trips.

Once the groups have been made with the filters described, the number of trips made by each group is obtained and with this the modes of transport used are classified with the information that EDM2018 provides per trip.

Based on these data, an analysis of trips to university campuses has been made.

3.2. Mobility survey for the university community 2021 (App: survey monkey)

The mobility survey for the sustainable university community 2021 was designed based on the detailed study of the mobility of the university campuses of the 6 public universities of the Community of Madrid in an application called Survey Monkey.



This survey is aimed at students (over 18 years old, studying or studying and working), teachers (over 30 years old, public sector employees) and service staff (over 20 years old, public or private sector employees).

3.2.1 Pilot for students, research teaching staff, and administration and services staff

To prepare it, first of all, a series of pilot surveys were launched, a total of three per group at each campus, with a total of 135 responses throughout the university community. This pilot survey was distributed as follows: three student surveys, two being undergraduate and one master's degree; another three to professors (one to a non-permanent professor and two to permanent professors); and three more to service personnel, two under 30 years old, another over 30 years old.

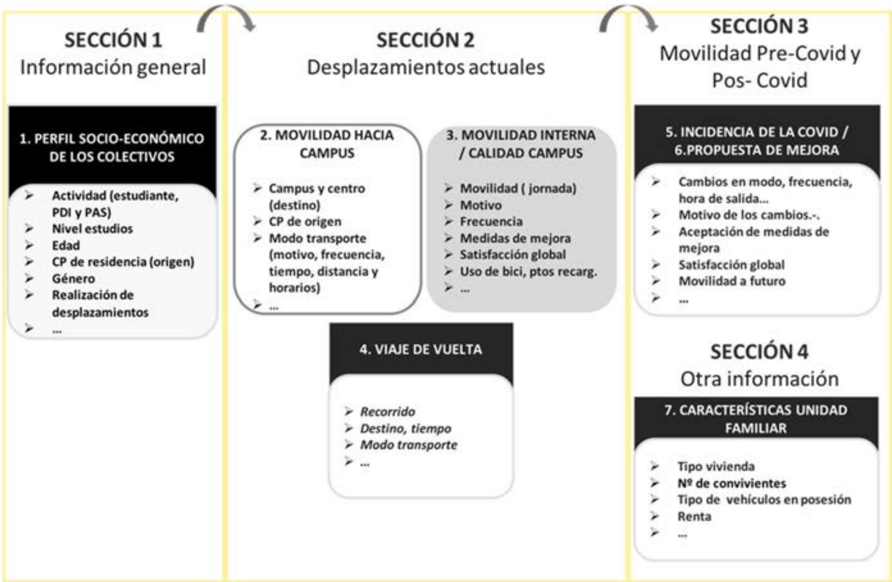
They were able to draw conclusions about the perception of those surveyed with the survey and the aspects to improve.

3.2.2 General survey students, research teaching staff, and administration and services staff (launch communication campaign with posters, screens, complaints management, and recruitment of non-institutional staff with cards)

The general survey consisted of 4 sections, section 1 of general information, section 2 of current trips (including the mode of transport, frequency, origin of the trip, the distance traveled, the trips within the campus and the trip of return), section 3 on pre-Covid and post-Covid mobility (it asks about the perception of quality in their mobility to the campus) and section 4 of other information (where data on the family unit were asked).

For the launch of this survey, a communication campaign was carried out through physical posters and on screens in the buildings of the study universities until March 26, 2021.

During those weeks, an exhaustive control of incidents with the survey was maintained through social networks and email



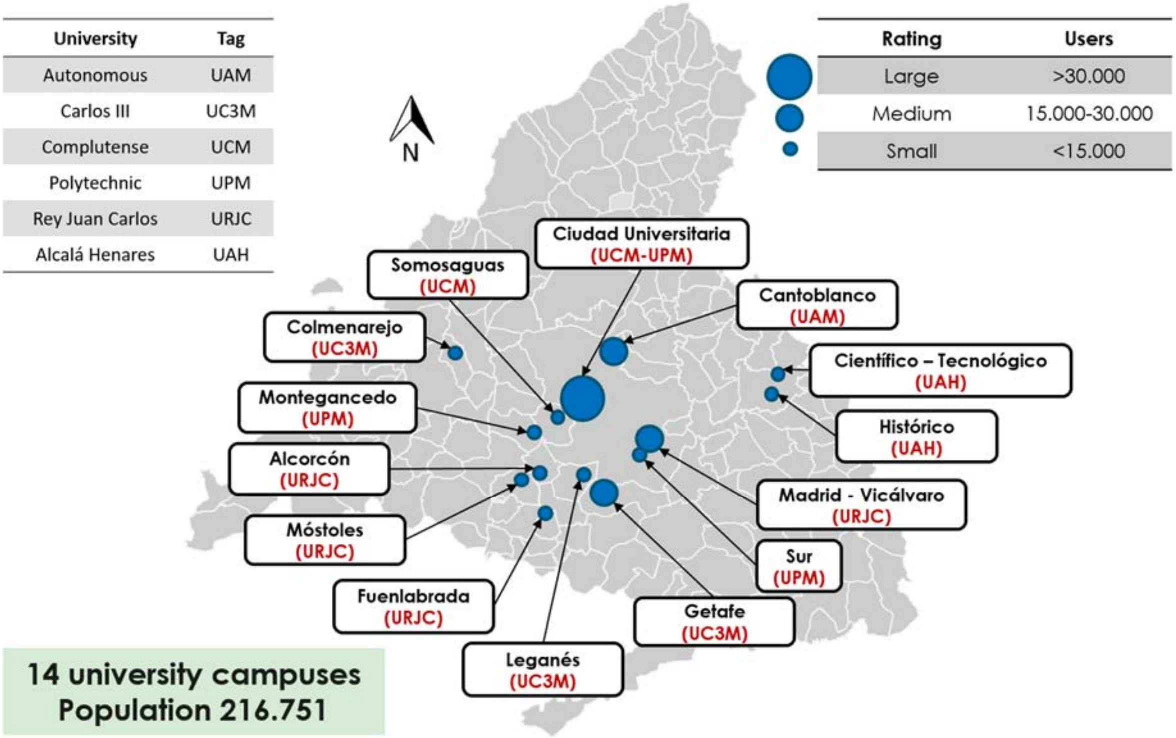
The external contracted service personnel also had access to this survey through cards containing the QR and the survey link, which were sent to them through the management of each university.

4. CASE STUDY

4.1 CAM (public universities of the Community of Madrid)

The objective of the community of Madrid is to acquire a more sustainable mobility in the city and for this purpose a pilot scenario has been created which is the university community, where the main problems in mobility will be collected on a small scale, the main problems in mobility will be determined. majority mobility patterns and a series of recommendations will be provided that will be carried out through the drafting of sustainable university mobility plans that, once completed, can be extrapolated to larger scales, such as the city of Madrid and other cities with similar characteristics.

the universities that have participated in the study are the 6 public universities of the Community of Madrid and the campuses universities study are the following:



There are a total of 14 university campuses, the university campus being shared by the UPM and the UCM.

5. RESULTS

When analyzing the results, this information has been divided into four criteria:

- Socioenomical
- Mobility patterns
- Impacts by Covid
- Perception of mobility and future

5.1 Descriptive analysis (statistic analysis)

The statistical analysis includes the following variables:

Variable	*UPM*	*UCM*	*UAM*	*UAH*	*UC3M*	*URJC*
1. *Activity*						
Students	72%	70%	67%	81%	85%	88%
Teachers	16%	19%	20%	13%	8%	10%
Service Staff	12%	11%	13%	6%	7%	3%
2. Studies						
School	56%	53%	48%	66%	66%	65%
College	6%	7%	4%	8%	10%	11%
Degree	15%	15%	17%	10%	13%	11%
Master	10%	9%	13%	4%	6%	5%
Doctorate	14%	16%	18%	12%	5%	8%
3. Gender						
Man	53%	33%	34%	31%	43%	31%
Woman	45%	65%	64%	67%	56%	68%
I prefer not to specify	2%	2%	2%	1%	1%	1%
4. Monthly income						
1000 – 2500€	44%	48%	44%	51%	40%	55%
2500-5000€	38%	34%	37%	34%	37%	27%
> 5000€	9%	7%	8%	4%	13%	5%
< 1000€	9%	12%	10%	11%	11%	13%
5. Age						
Minimum	18	18	18	18	18	18
Half	35	35	35	29	27	28

Table 1. Socioeconomic characteristics variables

5.2 Mobility patterns

The following variables are used to determine mobility patterns:

Variable	*UPM*	*UCM*	*UAM*	*UAH*	*UC3M*	*URJC*
1. *Current displacements*						
Yes, some day a week	37%	26%	41%	47%	63%	32%
Yes, most of the days	36%	47%	39%	36%	29%	20%
Yes, but less than 1 days a week	27%	19%	19%	17%	8%	48%
2. Transport mode						
Driver car	26%	26%	30%	27%	28%	31%
Accompanying car	3%	2%	3%	3%	3%	3%
Motorcycle	2%	0%	1%	1%	0%	1%
Public transport	59%	65%	63%	58%	52%	61%
Bicycle	2%	1%	1%	1%	0%	0%
Walking	7%	5%	2%	10%	15%	3%
Others	1%	1%	0%	1%	1%	0%
3. Time travel						
0-15min	11%	9%	15%	15%	19%	14%
15-30min	34%	29%	25%	25%	30%	30%
30-60min	37%	41%	38%	29%	33%	34%
>60min	18%	21%	23%	32%	18%	22%
4. Satisfaction	1--6					
Half	4,108	4,058	4,145	3,614	4,082	3,995
5. Campus stay						
Tomorrow	35%	36%	36%	29%	24%	36%
Afternnon	15%	20%	17%	23%	25%	29%
All day	12%	12%	15%	11%	9%	5%
Night	0%	0%	0%	0%	1%	0%
It varies according to the days	38%	32%	32%	38%	41%	29%
6. Moving frequency on campus						
Daily	23%	30%	26%	20%	18%	16%
2 times a week	30%	27%	34%	46%	64%	26%
Occasionally	35%	36%	33%	29%	14%	54%
Never	11%	7%	6%	5%	4%	4%

Table 2. Mobility characteristics variables

5.2.1. Qualitative variables by group

Chart 1. Group mobility – UCM -

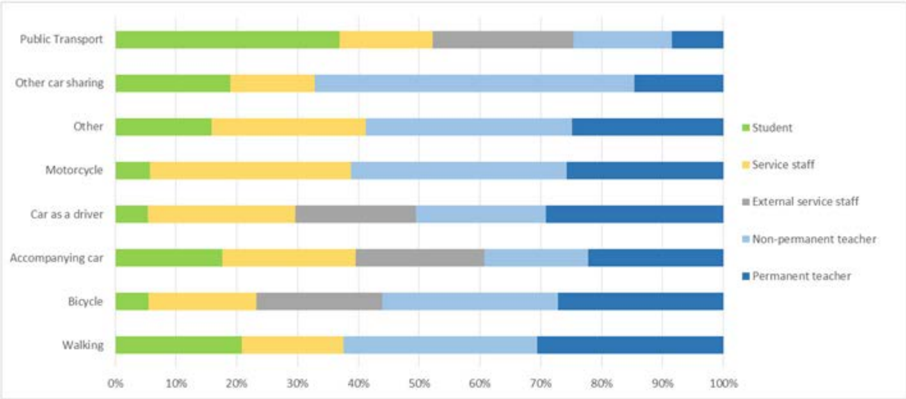


Chart 2. Group mobility – UC3M -

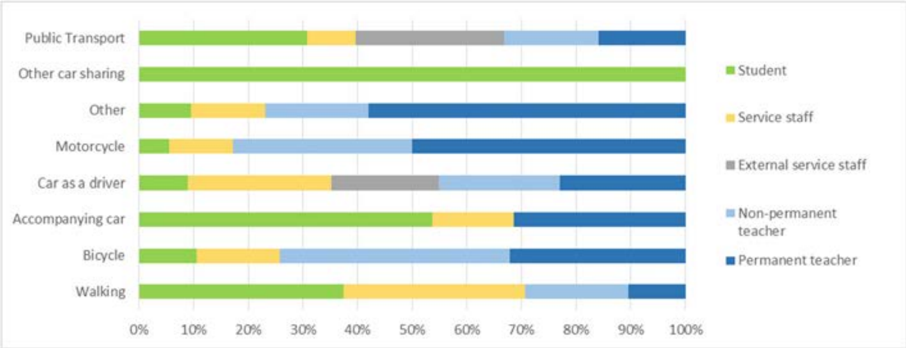


Chart 3. Group mobility – URJC -

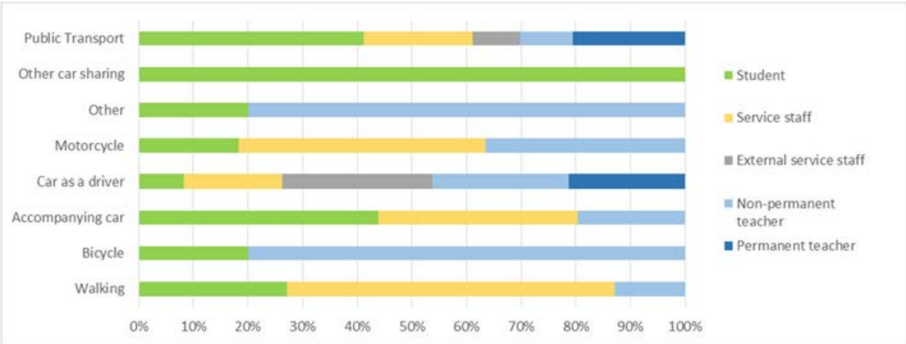


Chart 4. Group mobility – UPM -

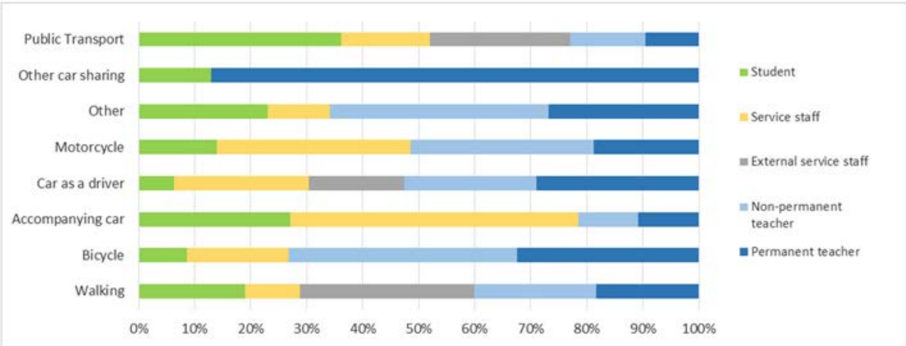


Chart 5. Group mobility – UAM -

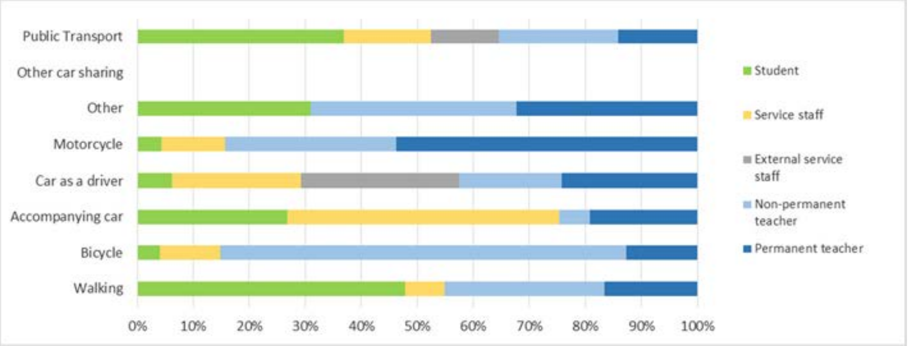
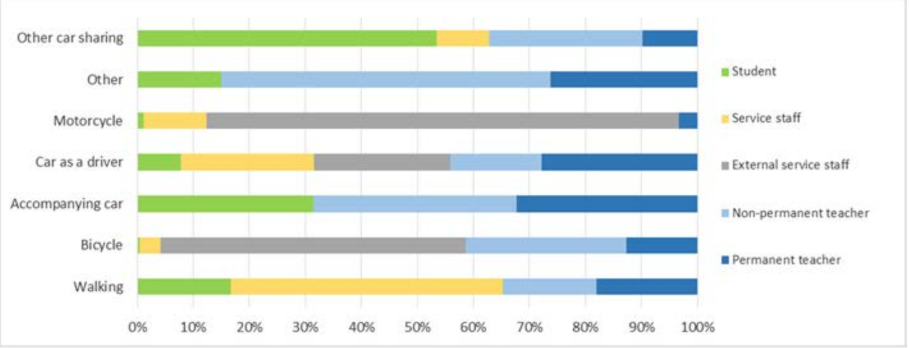


Chart 6. Group mobility – UAH -



5.2.2. Age mobility variables

Chart 7. Mobility & Year - UPM -

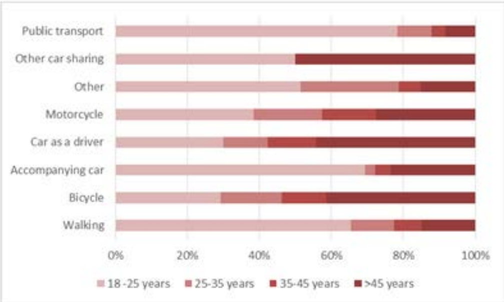


Chart 8. Mobility & Year - UCM -

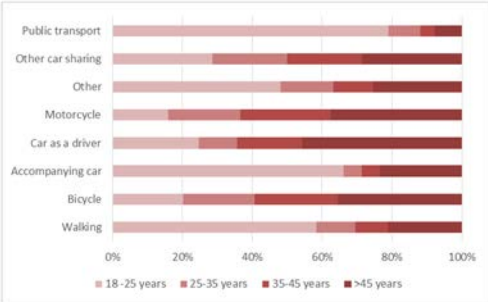


Chart 9. Mobility & Year - UAH -

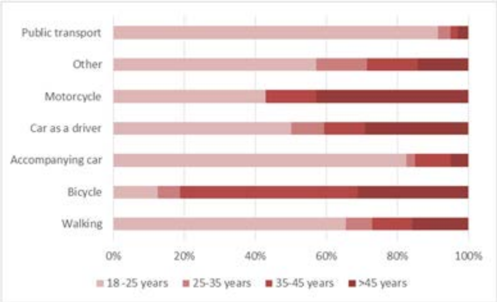


Chart 10. Mobility & Year - UAM -

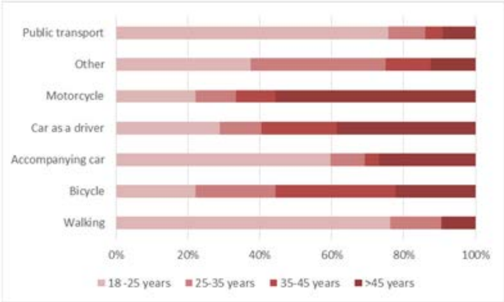


Chart 11. Mobility & Year - UC3M -

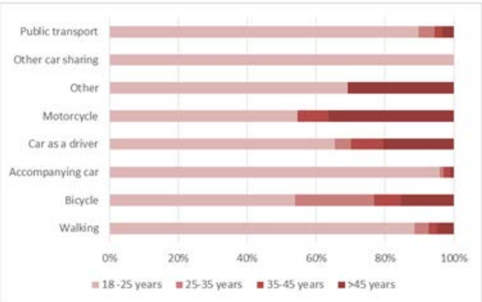
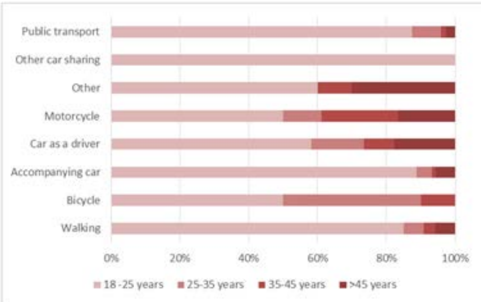


Chart 12. Mobility & Year - URJC-



5.2.3. Income mobility variables

Chart 13. Mobility & Income - UPM -

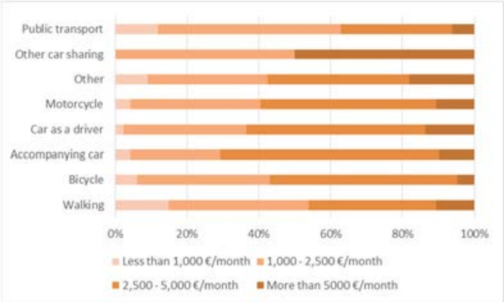


Chart 14. Mobility & Income - UCM -

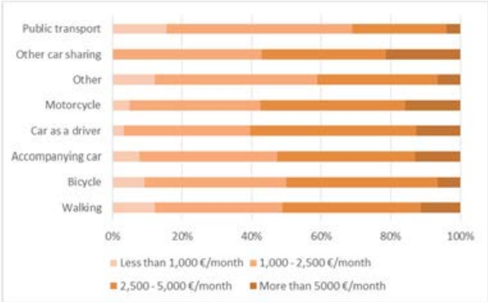


Chart 15. Mobility & Income - UAH -

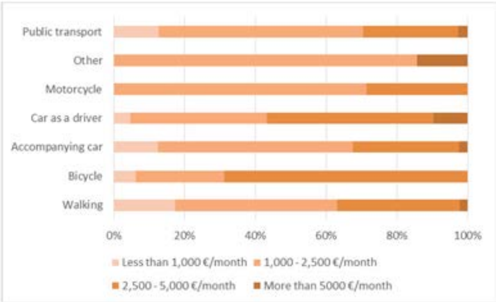


Chart 16. Mobility & Income - UAM -

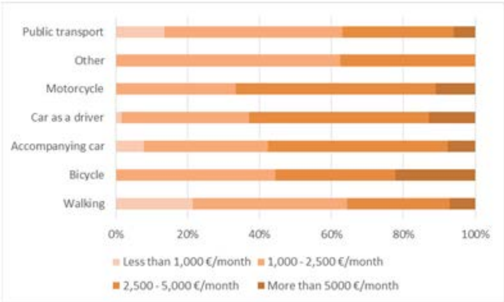


Chart 17. Mobility & Income – UC3M -

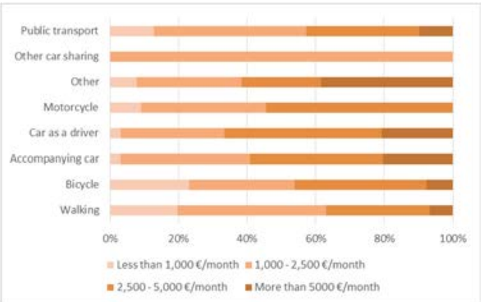
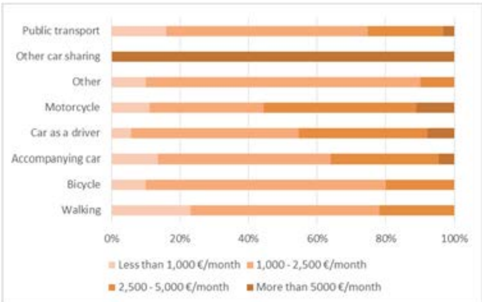


Chart 18. Mobility & Income – URJC -

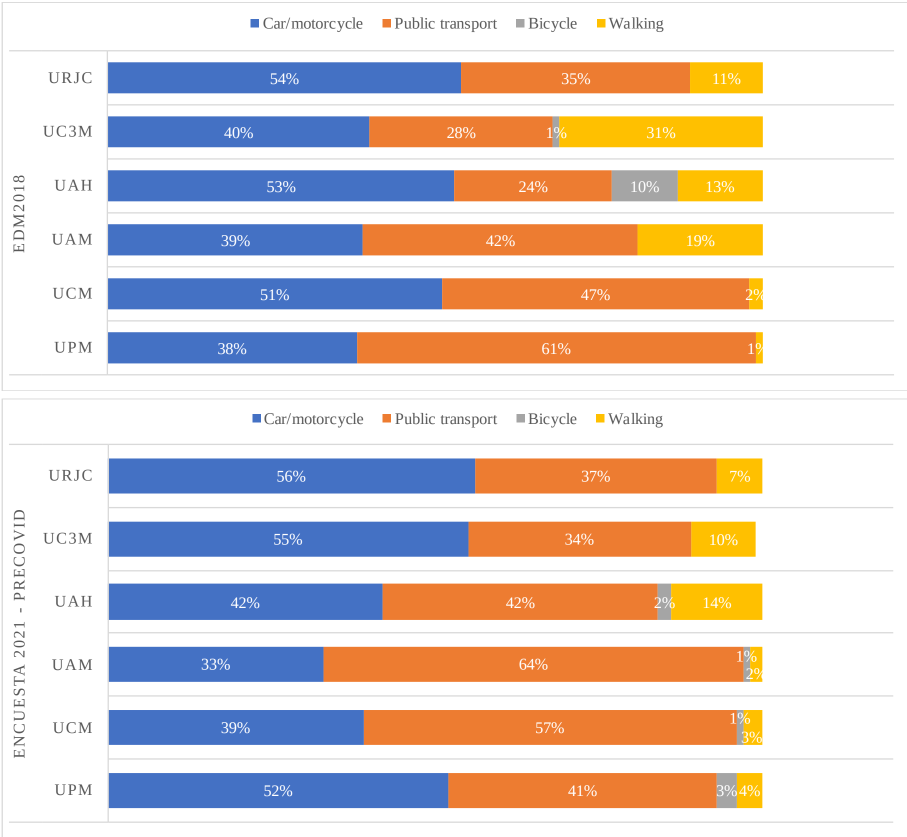


5.3. Quality of service environment

In this section a comparison will be made between the 2018 mobility survey and the 2021 mobility survey in terms of modal split, and the impact of Covid on modal choice and users' perception of their mobility and how they think it will be in the future will be analysed.

5.3.1. EDM2018 & Mobility Survey 2021

Comparison between the results of the edm2018 and those of the mobility survey 2021.



5.3.2. Impact of COVID-19 on mobility

Chart 19. Impact Covid - UPM -

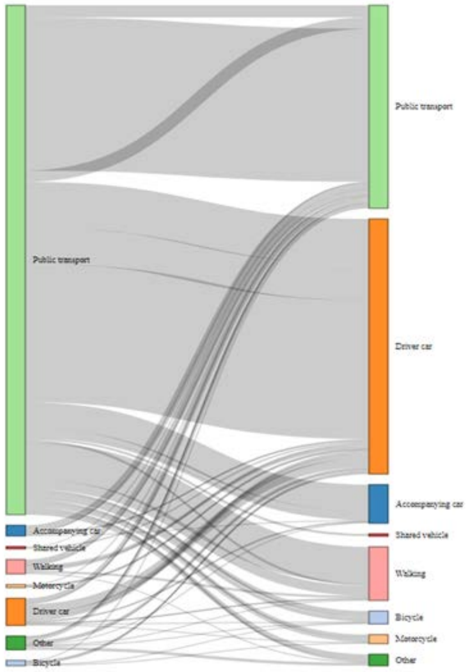


Chart 20. Impact Covid - UAM -

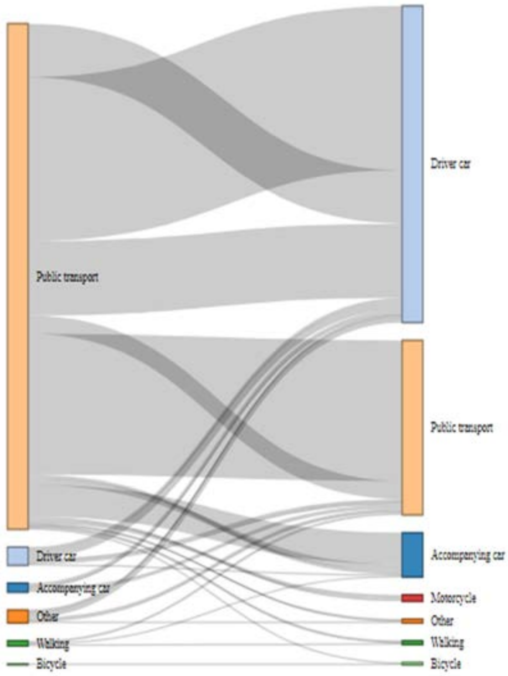


Chart 21. Impact Covid - UCM -

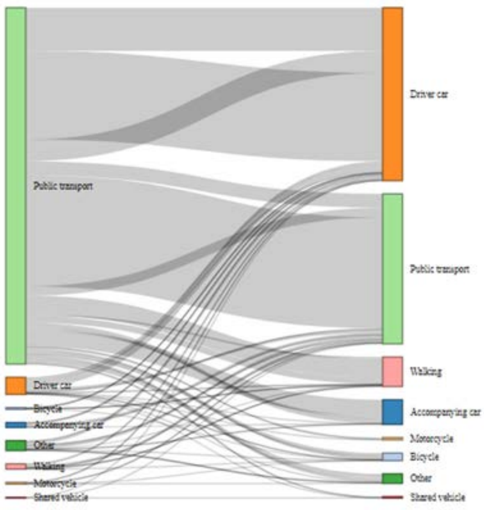


Chart 22. Impact Covid - UAH -

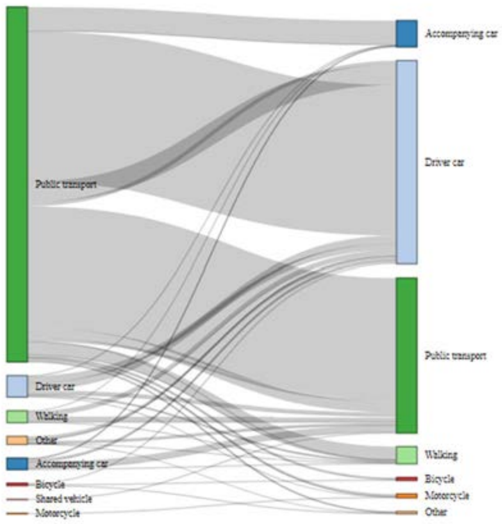


Chart 23. Impact Covid - UC3M -

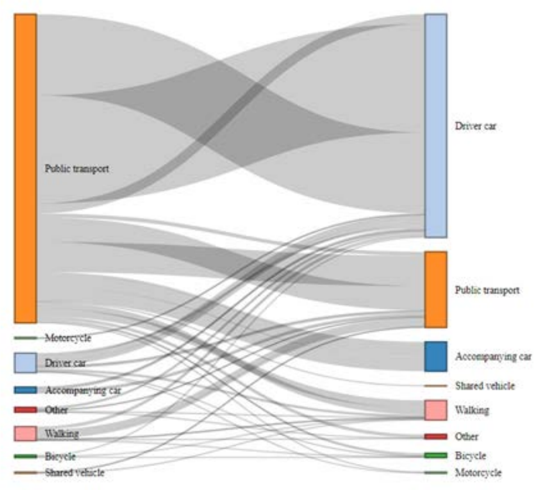
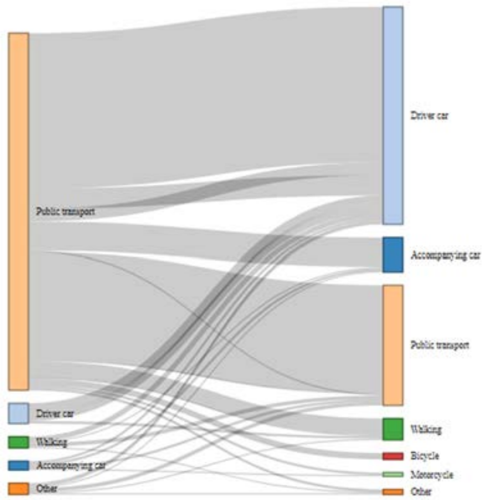


Chart 24. Impact Covid - UC3M -



5.3.3. Perception of mobility and future

Criteria	*Variables*	*UPM*	*UCM*	*UAM*	*UAH*	*UC3M*	*URJC*
Preferences and satisfaction	**1. Future mobility (1-6)**						
	more trips by public transport	4.28	4.40	4.52	4.18	4.22	4.43
	More bike trips	3.42	3.52	3.40	3.45	3.19	3.39
	More car travel	2.55	2.53	2.52	2.94	2.82	3.06
	I will share travel	2.22	2.16	2.11	2.15	2.18	2.30
	Use of shared modes	2.95	3.24	3.26	3.79	3.52	3.51
	I will reduce commuting	2.08	2.05	2.03	2.06	1.98	2.25
	I will work remotely	2.36	2.17	2.25	2.06	2.27	2.40
	2. Satisfaction (1-6)						
	General	4,11	4,06	4,15	3,61	4,08	4,00
	2.1. Groups						
	Students	3.99	3.91	3.97	3.43	4	3.90
	Service staff	4.20	4.26	4.60	4.5	4.40	4.45
	Teachers	4.35	4.42	4.45	4.1	4.35	4.82
	2.2. Gender						
	Mas	4.17	4.16	4.26	3.83	4.08	4.11
	Woman	4.09	4.02	4.09	3.51	4.08	3.94
	Unspecified	3.61	3.78	4	3.79	3.87	4.08
	2.3. Travel time						
	0-15min	5.03	5.05	5.27	4.95	5.36	5.03
	15-30min	4.62	4.59	4.61	4.38	4.54	4.56
	30-60min	3.97	3.94	3.99	346	3.69	3.80
	>60min	2.95	3.10	3.14	2.52	2.72	2.89

	3. Assessment of the transport service (1-6)						
	Access by car	4.86	4.73	4.97	4.38	4.67	4.99
	Access by public transport	4.60	4.82	4.74	3.84	4.43	4.85
	Access by bicycle	3.99	4.23	3.9	3.84	3.83	4.05
	Security in access and parking	4.26	4.21	4.65	3.98	4.42	4.33
	4. Improvement measures (1-6)						
	Car access restriction	3.01	3.24	2.91	2.99	3.34	3.05
	Incentivise car sharing	3.96	3.90	4.33	4.19	4.24	4.24
	Increase frequency of public transport	4.96	5.17	5.36	5.40	5.09	4.96
	5. Mobility relevant to university choice (%)						
	Yes	37	52	40	52	39	54
	No	63	48	60	48	61	46
	6. Use electric vehicle if reserved spaces are available (%)						
	Yes	43	77	41	38	40	45
	No	57	23	59	62	60	55
	7. Carpooling with others (%)						
	Yes	68	70	72	70	72	72
	Already carpooling	6	6	6	10	9	7
	No	26	23	22	20	19	21

6. CONCLUSIONS AND RECOMMENDATION

Recommendations based on the characteristics of the campus, where to decide on which campus it would be appropriate to:

- Restrict the access and circulation of private vehicles.
- Promote the electric vehicle, placing recharging points or excluding them from the restrictions of the private vehicle.
- Facilitate the use of the bicycle, or active modes by building more infrastructure or improving the existing one.
- Encouraging the use of dissuasive car parks and the use of shared vehicles.
- Making study and work hours more flexible to reduce the demand curve in public transport at rush hour.

6.1. Key factors improving sustainable mobility (influencing variable in decision making)

The key factors that enhance mobility to universities are: the income of each group, the location and accessibility of the universities, the existing facilities for carpooling.

This analysis shows that it is key to promoting sustainable mobility to know the socio-economic characteristics of university users, which will facilitate access to new, more sustainable modes of transport. The trend and acceptance of the initiatives shown towards the use of bicycles is quite acceptable, which encourages us to continue along this path.

ACKNOWLEDGMENTS

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OPPORTUNITIES FOR SUSTAINABLE AND INTELLIGENT MOBILITY IN THE RESPONSIVE CITY

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ABSTRACT

The growth of the world population indicates that about 70% of the inhabitants will live in cities by 2050. This implies the need for infrastructure, resources, basic services, and transportation available to serve this population and guarantee their quality of life.

To meet these requirements, some cities have adopted technology to obtain data and information that allow for the analysis of these new dynamics from the perspective of smart cities.

Other cities have also involved criteria focused on the well-being of the community-environmental system from the perspective of sustainable cities. There are other cities that transcend the sustainable and intelligent status to become responsive cities where the interpretation and analysis of data is provided by and for citizens. This allows them to become key in the planning and development of their city and the construction of these cities in the future.

Mobility in the development of cities is important and in a responsive city it is no different. It allows for the dynamic action of the population to satisfy their needs. Mobility worldwide is based on the private car and infrastructure grows as a function of this. The associated environmental, economic, and social impacts have wide ranging consequences.

Likewise, the COVID-19 pandemic has revealed an additional motivation to opt for public transport, cycling, or walking instead of the private car. This requires rethinking cities and adapting their physical, technological, and social infrastructure to facilitate this transition.

The evaluation of mobility in cities is based on indicators that allow the monitoring of important aspects from specific practices in each territory. However, the framework of responsive cities is not clearly or comprehensively identified resulting in the need for an investigative process aimed at forming a citizen-centered mobility evaluation model, integrating the holistic precepts of smart and sustainable cities.

1. PLANNING CITIES FOR THE FUTURE

The dynamics of the cities are accelerating their pace according to the urbanization process increase. The emerge of new settlers implies the supply of infrastructure, basic services, transport, employment, dwelling and additional resources that will allow them to improve their quality of life, thus, the conventional planning models are inadequate for the attention of new requests.

Currently, management instruments have been developed which provide a framework to the cities to modify their planning approach, on one hand, to achieve the sustainable urban development (United Nations, 2017), and on the other hand, supported by technology, to attain smart cities (ECLAC, 2020a).

The need to connect the community participation in the city development process has aroused the chance to address a more inclusive urban planning approach that allows to have responsive cities.

Below, the sort of stated cities are contextualized:

1.1 Smart and sustainable cities

The smart city is a concept that implies different meanings, although, it is generally connected with those cities in which information and communication technology – ICT are widely used. A first definition assumes the smart city as a construct to improve the quality of life, it is formulated bearing in mind three concepts: digital city, green city and city of knowledge, which are characterized by the use of data center technology in an ecological sight and a data value-based, information and knowledge production, respectively (Yin et al., 2015).

Another view relates to smart city with a prospective achievement in terms of economy, population, government, mobility, environment and livability (Aletà, Alonso, & Ruiz, 2017), (Albino, Berardi, & Dangelico, 2015), (Manville et al., 2014), therefore, the city is smarter if it is more competitive, preserves natural resources, the community is participatory, generates quality of life, integrates transport and ICT and promotes social and human capital.

The smart city is based on the creation and interaction of human capital, social capital and information and communication technology (ICT) infrastructure to generate greater economic and sustainable development and a better quality of life (Manville et al., 2014).

En este sentido, muchas ciudades están mejorando la calidad y el rendimiento de los servicios urbanos al ser digitalizadas e inteligentes (Kumar et al., 2020). However, “a city may also be smart when investment in social capital and infrastructure are made with a rational management of the natural resources and through a participatory governance” (Schaffers et al., 2011), which does not necessarily mean high investments in technology, bearing in mind resources availability according to the large city. (Manville et al., 2014).

Thus, it is clear that there is a variety of definitions about smart city and it is not possible to establish a universal meaning, nor there is a single way to measure it (Albino et al., 2015).

According to the International Telecommunication Union (ITU) and the Economic Commission for Europe (ECE), “a smart and sustainable city is an innovative city that uses ICT to improve the quality of life, the efficiency of operations, urban services and the competitiveness, at the same time that meets the needs of the current and future generations in economic, social, environmental and cultural features”. Smart and sustainable cities are provided with indicators to determine goals, gather data and evaluate their achievements, they are supported by a telecommunications infrastructure that is stable, secure, reliable and interoperable to provide support ICT-based applications and services (UIT-CEPE, 2016).

In the context of smart and sustainable cities, it is possible to identify the contribution of ICT in the urban setting, which is focused on: i) The advantages of the effectiveness in the operations and urban services, ii) the means to improve the quality of life and iii) encouragement of environmental sustainability (UIT, 2020). It is highlighted the need of smart cities to face challenges such as inequality, insecurity, unemployment and ageing population to contribute to the achievement of the sustainable development goals. (Sharifi, 2019), (Ahvenniemi et al.,2017).

The conceptual evolution of the smart city allows to evidence a different approach, from the use of ICT to maximize the effectiveness of hard urban infrastructure to a style focused on the human being and soft infrastructure (Sharifi, 2019). This is the basis of the responsive city.

1.2 Responsive cities

Taking into account the technological perspective, smart cities are supplied with data to promote information units that support decision-making and the governance (McKenna, 2019a), (von Richthofen et al., 2019), (McKenna, 2019b), such a way to promote knowledge generation in the different actors of the city itself.

At this point, the technological genesis of smart cities has been hatched. However, recent trends based on concepts such as Society 5.0 or people-centered smart society (Hitachi-UTokyo, 2020) urge to advance to citizen-centered cities, thus, “smart” becomes a infrastructure layer in which technological contributions are enclosed by the empowerment of citizens to contribute with their welfare, health, mobility, and other essential criteria of their condition as members of society and inhabitants of the territory; this is the base of responsive cities.

Goldsmith y Crawford (Goldsmith, 2014) established the concept of responsive city based on the citizens commitment and governance during the digital age to encourage cities characterized by their agility, competitiveness and economic resilient, based on the contributions brought by information technologies. The responsive city gives citizens the chance to use smart technology to contribute to the planning, design and management of the city (Yigitcanlar et al., 2019).

The perspective of responsive city is focused on the citizen, so, the processes of the city are supported by technological resources to improve their performance and be more involved with the citizen, decision makers guide their decisions toward problem analysis and opportunities to promote the quality of life in the communities; and finally, local managers use the predictive value of data to make accurate decision. The responsive concept frames a synergy among decision makers, thoughtful citizens and 21st century technologies (Goldsmith, 2014).

While common cities are based on classical planning models where data is emerged, smart cities lay the foundation on technology, proving information; responsive cities are centered on the citizen, building knowledge themselves (Schmitt, 2017).

The responsive city tends to “return the city to its citizens, so, they get involved directly in the planning and management of their habitat. Thus, the citizen responsibility becomes the basis of a responsive city” (Schmitt, 2017).

Bearing in mind the characterization of modern cities, challenges and opportunities that arise regarding mobility will be addressed.

2. MOBILITY IN THE 21ST CENTURY

An increasing trend of population in cities has grown distance journeys (Guasch, 2002) due the expansion of the urban border because of the peripheries settlement and the low coverage of public transport service (Cervero, 2000).

The implementation of encouragement policies to use private vehicles and their reduction prices have caused the increase of motor vehicles (Lizárraga, 2006), (Despacio y ITDP,

2013) and for that reason, problems such as traffic jam, pollution and accident rate have been accentuated (Vasconcellos et al., 2016).

Besides, there are failures in affordability, so, people with lower incomes must assign a high percent of their economic sources to get around (Vasconcellos, 2001), it has a directly impact on social inequity.

Other problems related to transport are connected to security, equity and inclusion, in the same way, the air pollution causes illnesses that can cost around 15% of a person's income (Hidalgo & Huizenga, 2013).

In response to this scenario, the conventional planning mobility approach has been changing toward sustainable smart mobility, where preferences of investments on private vehicle infrastructure are discouraged and active transport modes such as walk or pedal take place articulated with a service quality in the public transport system to guarantee the participation of all social groups and reduce the effects associated with transport such as energy consumption, CO2 release, air quality or wasted space in the streets. (Gillis et al., 2015).

2.1 Sustainable Smart mobility

Mobility makes part of the smart city agenda which is supported by the adoption of sustainable transport practices (Yigitcanlar & Kamruzzaman, 2019).

The context of sustainable mobility includes the objectives of smart mobility: i) reduce pollution, ii) decrease traffic jam, iii) increase people safety, iv) lessen noise and v) improve speeds and cost of movement, which is doable if they are joined to this sort of city (Benevolo et al.,2016). Sustainable mobility also includes four smart perspective which deal with the design, system, infrastructure and usage (Lyons, 2018).

The appropriate proposal about mobility framed within smart cities allows the implementation of projects that aim to answer community needs and tend towards sustainable (Battarra et al., 2018). Thus, sustainability has left to consider specific problems such as resource depletion and pollution to involve economic, social and environmental relations and their impact on solving problems (Litman, 2021).

The sustainability approach is given in mobility addressing the increase of urban congestion and pollution based on substantial changes in terms of logistic and transport affairs, private and public vehicles, as well as behavior and habits changes in order to keep in mind the quality of life, short and long-term impacts, affected population and the city planning (Mozos-Blanco et al.,2018).

According to Banister, sustainable mobility “supplies an alternative paradigm within with the complexity of cities is investigated and links between land use and transport are strengthened”. This requires actions to reduce the number and duration of journeys, promote modal change and encourage greater efficiency transport system. (Banister, 2008).

The main characteristics of the sustainable mobility approach are: i) it focuses on people, ii) it prioritizes accessibility, iii) it is proposed on a local scale, it recognizes the street as a useful space and not only as a vehicular road, v) it finds relevant the inverted mobility pyramid where pedestrians and cyclists are privileged in the upper part and the automobile drivers are placed in the lower part, vi) it is supplied with multi-criteria analysis to contemplate environmental and social concerns, it is focused on management, viii) it has a tendency to integrate people and traffic and, ix) it allows healthy benefits (Holden et al., 2019).

Currently, cities must assume smart and sustainable mobility, not only as a challenge but also as a necessity, taking into account the new requirements imposed by the Covid-19 pandemic.

2.2 COVID 19 and mobility

Coronavirus (COVID 19) has changed the environment sense and new vulnerabilities have emerged, for this reason, territory, distance, time, space and social relationships concepts must be rethought. The actual pandemic has exposed the need to modify people lifestyles as to the risks to health and life of the population, especially in urban areas (Moreno, 2020), this entails changes in city planning and, especially, in the mobility topic.

In this pandemic time, the communities have changed the people displacement modes, caused by virtuality that replaces many journey needs. Thus, technology and connectivity have been increasing to correspond with social distancing. According to this, ECLAC indicates that the Latin American and Caribbean region has the conditions to strengthen its technological capacity to face the consequent challenges through resilience, especially, in the transport, mobility, logistics and energy sectors. (ECLAC, 2020b).

The territory will be the character in these projected changes, then basic transport modes such as bicycles will be promoted, that will require the necessary infrastructure to be developed properly, in this case, bikeways and parking spaces are needed (Universidad de Los Andes, 2020). Likewise, walked displacements will have relevance in the new vision of post-pandemic mobility, it implies the adaptation of areas for the citizens circulation, the public space for its enjoyment and a pleasant environment that motivates them (ECLAC, 2021).

In conclusion, the pandemic has not necessarily had negative effects, as it has undeniably led organizations, families and people to redefine the mobility concept, for example, their transport modes, needs and time value used to fulfill their daily lives; that constitutes in a forced and disruptive process of adaptation for existing models that describe, model and implement sustainable mobility systems.

2.3 Sustainable mobility goals

Mobility in the current context is based on the pillars of sustainability: the social, economic and environmental features; in addition, with the scenario of responsive cities, it is necessary to articulate additional components: planning and governance, that allow to achieve the goals of sustainable and intelligent mobility.

In general terms, the mobility goals of the 21st century are presented as follows. The economic component focuses on the productivity and economic local development, energy efficiency, affordability, and operational efficiency.

The social component includes the equity, safety and human health, as well as, the community cohesion with the preservation of cultural heritage. The environmental component considers the reduction of emissions that contribute to climate change, the prevention of air, water and sound pollution, the reduction of hydric resource damage, the conservation of natural resources, the protection of the biodiversity and open spaces.

The good governance and planning component addresses inclusive, comprehensive and integrated planning (Litman, 2021).

3. MOBILITY EVALUATION

Mobility evaluation for urban context is commonly carried out from indices -or indicators- that consider different aspects of economic, social, environmental and operational issues. Currently, the evaluation models emphasize on sustainability requirements and integrate evaluations of technological types to involve the intelligent aspect in the assessment, to determine a sustainable and smart mobility.

Next, the main characteristics of conventional mobility evaluation models are presented and the most relevant characteristics of a participatory evaluation proposal model are planned in the context of responsive cities, they are obtained from methods focused on documentary research (Geerts, 2011) and bibliometric analysis techniques (Cobo, 2011).

3.1 Conventional evaluation models

Some authors have studied the feasibility to analyze urban mobility based on indicators to: i) transport planning and infrastructure provision (Mihyeon & Parsons, 2016), ii) quality measurement of the public transport network (Zegras, 2006), iii) determination of the relationships between urban planning and transport (Zhang & Guindon, 2006), iv) sustainability measurement of urban transport in different continents (Litman, 2008), (Litman, 2011), (Litman, 2021), (Tanguay et al., 2010), v) measurement of the three dimensions of sustainability (Haghshenas & Vaziri, 2012).

The mobility assessment is carried out by the significant contribution of the transport area through reduced environmental quality of a city. Thus, the transition towards sustainable mobility will contribute to the mitigation of negative impacts, optimization of the transport system and integration with urban planning policies (Battarra et al., 2018).

Since of the 20th century ending, initiatives aimed at achieving sustainable urban mobility were already identified (Commission of the European Communities, 1998). In order to measure and compare the state of urban transport systems in terms of sustainability, the indicators were created, so that different initiatives emerged for reducing the urban mobility effects on human health, environment and economic productivity, in terms of a sustainable development (Alonso & Monzón, 2011).

Sdoukopoulos et al. (2019), proposed a categorization of evaluation indicators for transport sustainability and formulated an index evaluation; however, this research highlights the difficulty in the use of this indicators due to a great variety of indicators that are available, as well as, their structure, the constant monitoring needs and the use context (countries of the First World) (Sdoukopoulos et al., 2019).

Based on the Sdoukopoulos' findings, other related researches about use of indices or indicators to assess sustainable mobility was documented. The number of indicators used by each identified author is presented in Figure 1.

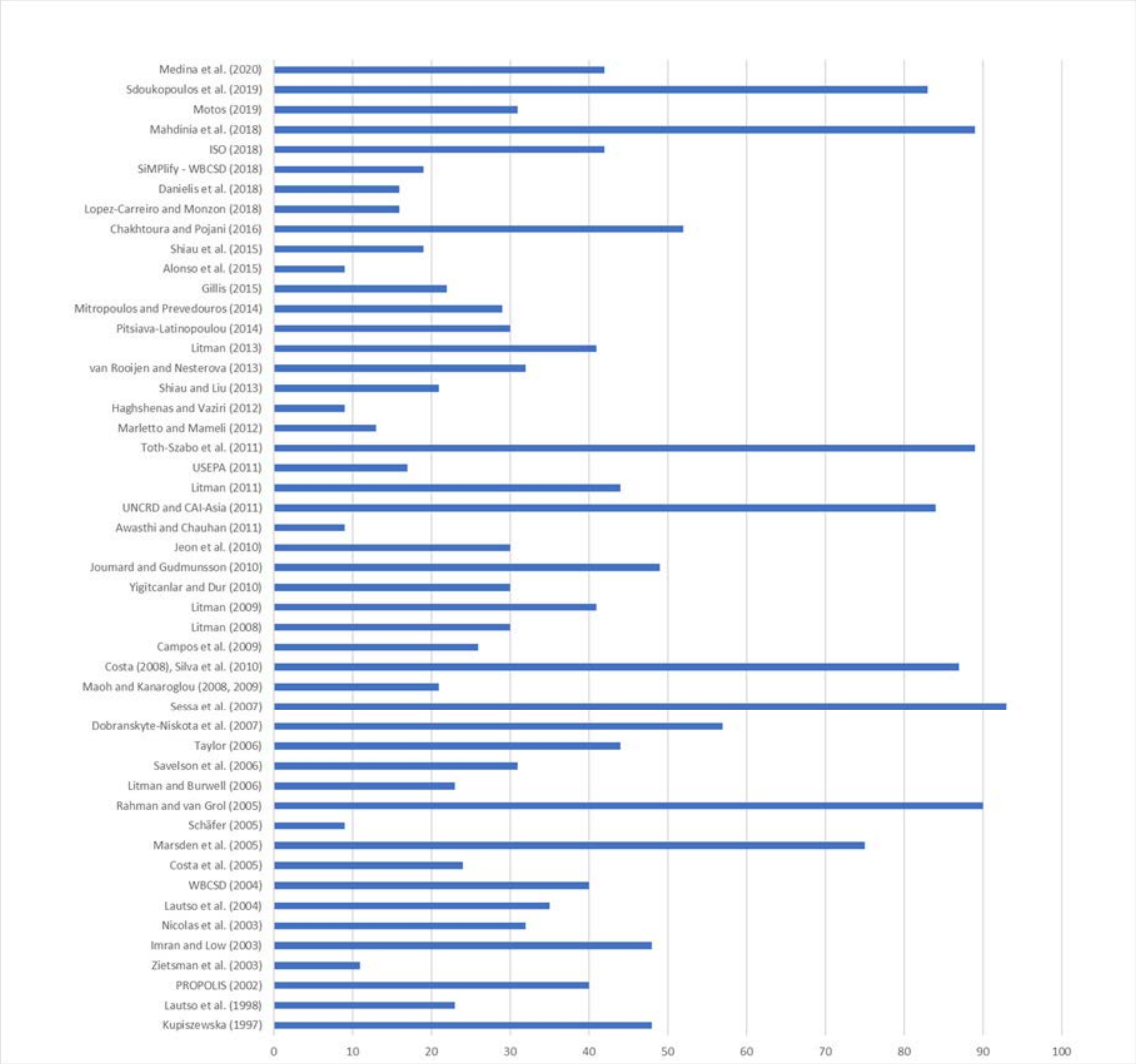

Figure 1: Roadmap regarding the indicator’s quantification in sustainable mobility assessment initiatives

In conclusion, there is a considerable number of alternatives for evaluating the different constitutive aspects of cities, including mobility. These tools allow the evaluation of the main functions of conventional and smart cities. It is expected to obtain a strategy that involves a transition from this type of cities to responsive cities, where the citizen becomes the direct identifier of their needs, besides an information and knowledge contributor through the research solutions, using digital tools or smart technologies that he/she may have at his/her willingness (Levenda et al., 2020).

In order to contribute in the transition towards a smart and sustainable city, the sustainable mobility evaluation is an important factor, because the existing models to achieve this type of city still do not fully include all the aspects that must be taken in this high-level process, this constitutes a knowledge gap (Ibrahim et al., 2018).

3.2 Participatory evaluation model

According to sustainability indicators that can be applied in transport and planning assessment (Litman, 2021), actually, their use is been expanded. However, despite involving economic, social and environment issues like the pillars of sustainability in the environmental mobility evaluation, it is evident that urban dynamics have changed, and both, the active participation of citizens and a greater concern for environmental issues are indispensable in the planning of the future cities.

As evidenced in different worldwide experiences, citizens have the opportunity to change mobility patterns in their cities, promoting an active mobility and demanding changes in that sense (van Laake & Pardo, 2018). Thus, the citizen empowerment allows them to achieve a proactive participation in sustainable and equitable projects, facilitating political changes in their favor to improve their quality of life (Moscoso et al.,2020).

The 2030 agenda also emphasizes two challenges to improve the quality of life in cities: i) not repeating public policies patterns that have not generated a desired impact and ii) include citizens in order to guarantee their rights access. (Naser et al., 2021).

One of the fundamental citizen rights is the right to participation, as part of decision-making in their interest areas. Therefore, the citizenry transition that acts as an observer of their reality is necessary, towards an active and committed citizenry that participates in their city changes processes (Salazar, 2019).

To achieve a participatory evaluation proposal for sustainable and smart mobility, it is necessary to look upon the fundamental principles of citizen participation: Transparency and access information, Voluntariness, Non-exclusion, Equity, Responsiveness, Recognition and respect for the diversity, (Naser et al., 2021).

Likewise, it is necessary to determine a desired level of participation, since it is expected in responsive cities that have an important commitment from citizens, so, they can contribute with their knowledge and live experiences to achieve more effective, efficient, relevant and sustainable to the future.

The first participation level is the informative one, where there is no dialogue with people and a purely information is delivery by the authority. A second level is consultative, where opinions, proposals and interests of citizens are obtained in relation to a public interest subject. The third level is decision-making, where citizens directly influence decision-making on an interest subject. Finally, the fourth level corresponds to co-management, where an articulation between the citizenry and the authority is expected, with the purpose to involve in the design, implementation, control and evaluation of a public interest activity and to influence in an associated decision-making. (Naser et al., 2021).

Currently, research is in progress and it proposes an evaluation model for urban mobility with a participatory approach, it emphasizes in social and environmental mobility aspects, that tries to achieve sustainable and smart mobility. Mobility is being analyzing in the context of sustainable and smart cities that is also responsive, therefore, the importance of the citizens quality of life is highlighted from the new planning of urban mobility.

To achieve this, the need to invest in mobility priorities is accentuated: the first priority is the pedestrian, followed by non-motorized modes, other transport modes, an optimized public transport system and, finally, the private vehicle.

The global context and environmental quality mean a determining aspect in the mobility evaluation, with the criterion that they directly affect the population health and their quality of life. The importance of ecological restoration to achieve green spaces throughout cities to promote active mobility is highlighted.

The built environment constitutes a relevant aspect for evaluation, as the quality public space is required to offer the enough infrastructure for all transport modes and the enjoyment for all social groups.

Connectivity is another important aspect to link-up, because it enables access to the city and its services, regardless of the transport mode used. The purpose is to achieve proximity, balance between time and space, affordability and accessibility.

Urban design becomes relevant, because it allows recovering the social meaning of the city; where safety aims to have streets and safe transport modes, further, urban corridors restored from an ecological point of view, structures and heritage recovered and integrated with the city mobility, where forgotten cultural and historical places are recovered and can be enjoyed on travel routes.

Transport centered on sustainable communities implies the permanent participation of the community in decision-making related to urban mobility and the possibility of discouraging the dependence on private vehicle, searching that infrastructures investments associated with it are reduced.

Financial management is another aspect to consider when evaluating mobility, especially regarding to public transport, that should consider all social groups, including people with physical disabilities, women, people of all ages and low-income people, with the purpose to facilitate their accessibility to the system.

The use of technology to measure some environmental, operational and social parameters is another aspect to consider in the urban mobility evaluation model, where, in participatory processes, the community will be permanently articulated with the local authority to contribute in the decision-making that are necessary, this can be facilitated with this type of technological instruments.

The finished model is expected to be disseminated in 2022 to contribute to the knowledge basis regarding sustainable and smart mobility and to contribute to the transition towards achieving responsive cities based on citizen participation.

4. CONCLUSIONS

Increasing population in cities and its consequent increase in infrastructure, basic services, transportation, employment, housing and those additional resources that allow them to improve their quality of life, make a necessary change in conventional urban planning models, that are insufficient to attend the new requirements.

The need to link-up the community participation in city development processes has given rise to the opportunity to determine an even more inclusive approach to urban planning, which, together with the previous ones, allows achieving responsive cities, that is, centered on the citizen.

For the mobility case, a transition has been taking place in the conventional mobility planning models towards sustainable and intelligent mobility, to guarantee the participation of all social groups and reduce the effects associated with transport, such as the consumption of electricity. energy, CO_2 emissions, air quality, street loss spaces or the impact on public health.

In the current context, Covid-19 pandemic has made it possible to redefine mobility, from transport modes, their needs and the time value used to comply with daily life, that constitutes a forced and disruptive adaptation process of existing models that describe, modeling and implement sustainable mobility systems.

Nowadays, the mobility evaluation in the context is based on the pillars of sustainability: social, economic and environmental issues; furthermore, in the responsive cities’ scenario, it is necessary to articulate an additional component: planning and governance, where the technology integration, knowledge and people participation will make it possible to achieve the goals of sustainable and smart mobility.

To achieve a participatory evaluation proposal for sustainable and smart mobility, it is relevant to bear in mind the fundamental principles of citizen participation and determine the desired level of participation, that in responsive cities the greatest citizen commitment is expected, they can contribute with their knowledge and life experiences to achieve more effective, efficient, relevant and sustainable results over time.

Finally, some of the aspects registered in this proposal for the urban mobility evaluation are related to the invert mobility priorities, the global context and environmental quality, the built environment, connectivity, urban design, and transport-oriented sustainable communities, financial management, the use of technology in the city, among others, to contribute to the proposed objective.

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IMPACT OF COVID-19 ON URBAN TRANSPORTATION HABITS IN THE CITY OF GIJÓN

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ABSTRACT

The COVID-19 pandemic, which has been ravaging the world since the beginning of 2020, has greatly changed daily habits in terms of mobility, particularly in cities. The fear of prolonged contact with other users on public transport, may cause great changes in citizens' preferences towards transport in private vehicles, motorized or not, and sharing. The aim of this study was to assess the changes in mobility habits based on an online survey in Gijón (Spain) taken at the end of summer 2020, after the first wave, and generation of the so-called "new normality". This document presents a preview of the main results, related to the vehicles most used by Gijon's population. The results have allowed us to observe an increase in the use of private vehicles and, consequently, decrease in use of the bus. In addition, the survey sample also demonstrated the scant insertion of PMVs, motorcycles and bicycles in citizens' preferences. Finally, they also showed gender and age differences in urban mobility.

1. INTRODUCTION AND OBJECTIVE

At the beginning 2020, the virus later known as SARS-CoV-2 began to spread through the city of Wuhan, China. On March 11, 2020, the WHO determined that the situation of the COVID-19 disease caused by SARS-CoV-2 was pandemic. Days later, and in harmony with what occurred in surrounding countries, on March 14th, the Spanish government decreed a state of emergency and home confinement until June 20th.

The effects of this pandemic, and of confinement, caused substantial changes in the habits of millions of people in all walks of life; among others, there are signs that the preferences for use of different means of transportation have been profoundly affected. This relationship is not exclusive to COVID-19, as after a detailed analysis of extant literature, Muley et al. (2020) found a strong relationship between the appearance of contagious diseases and a series of significant changes in the transportation sector, demonstrated by other pandemics in the 21st century before COVID-19: SARS (2003), influenza A (2009) and MERS (2012). However, during the past year, interest in knowing the effect of COVID-19 on mobility habits has generated an enormous amount of information. This was emphasized in surveys and indicators such as Apple's reports on trends in mobility (Apple Maps, 2020); and the Nextdoor app noted that in cities like Madrid and Barcelona, over half of the population has changed its customs for going from place to place (Interempresas, 2020), and other services, such as the Moovit platform (Moovit, 2020) have also suggest this. Likewise, with tremendous immediacy, scientific journals began to publish a considerable number of studies that analyzed the effect of the pandemic on transportation habits in different countries (Awad-Núñez, Julio, Moya-Gómez, Gomez, y Sastre González, 2021; Cartenì, Di Francesco, y Martino, 2020; Gunthe y Patra, 2020; Linka, Peirlinck, Sahli Costabal, y Kuhl, 2020; Orro, Novales, Monteagudo, Pérez-López, y Bugarín, 2020; Tian, An, Chen, y Tian, 2021), and databases focused on future studies of mobility during the pandemic (Barbieri et al. 2020).

The methods for evaluating these changes have been diverse. Thus, Aloi et al. (2020) collected data from traffic counters, ITS public transportation, and recordings from traffic control cameras and environmental sensors, to evaluate the effect in Santander (Spain); Bucsky (2020) took data from official sources to measure the changes in Budapest; Klein et al. (2020) used mobility data from the Cuebiq platform; Brough et al. (2021) combined data from government administrations and own surveys; Khaddar and Fatmi (2021) used data from the 2020 COVID-19 Survey for Assessing Travel Impact (COST); and Bartuska and Masek (2021) analyzed data from traffic surveys.

Along with these methods, some research teams and individuals have chosen to take surveys of their own. Logically, the survey method is widely used for acquiring information on transportation (Ampt y Ortúzar, 2004; Ortúzar, Armoogum, Madre, y Potier, 2011; Plasencia-Lozano, 2021). Table 1 shows a diversity of studies carried out in different places. In general, strong changes in urban mobility are observed in all of them in line with what was noted in the abovementioned study by Muley, who found the following effects on travel behavior: Decrease in the number of trips, in the use of public transportation and in distances covered, and an increase in the use of private vehicles, bicycles and walking. All of them were done before the summer of 2020 and analyzed the effect of COVID-19 during its most complicated moment, due to its novelty, and therefore more in contrast to the prepandemic situation.

Source	Place	Sample size	Dates
(Campisi et al., 2020)	Sicily (Italy)	431	March 13 - April 13, 2020
(Mogaji, 2020)	Lagos (Nigeria)	329	May 18 - May 24, 2020
(Beck y Hensher, 2020)	Australia	1,073	March 30 - April 15, 2020
(Shamshiripour et al., 2020)	Chicago (USA)	1,200	April 25 - June 2, 2020
(König y Dreßler, 2021)	Altmarkkreis Salzwedel district (Germany)	117	April - May, 2020
(Irawan et al., 2021)	Indonesia	1,062	March – April, 2020

Table 3 - Survey studies on variations in mobility habits related to COVID-19.

At the end of spring and beginning of summer 2020, there was a strong descent in contagion, and the authorities in Spain began to talk about remission of the pandemic in a context baptized as “the new normality”. On June 20th, “reconquering mobility” was expressly suggested, and on July 4th, citizens were encouraged to “recover the streets” (Benito, 2021). Although we now know that this first wave was followed by several more, at that moment between the first and following waves, which coincided with the summer of 2020, is of interest for studying mobility habits, at least in Spain, because on those dates, society (or part of it) made decisions within a context of “reconquered mobility” and “recovered streets”. Therefore, it could give us a clue to what were going to be the mobility habits in the final scenario mentioned, when it occurs. With this in mind, on those dates, during the summer and beginning of autumn 2020, we conducted a study using an online survey to evaluate the effect of the pandemic on the mobility habits of the population of Gijón, a middle-sized Spanish city with several transportation options.

2. MATERIALS AND METHODS

2.1. Description of the Case Study

Our study focused on the city of Gijón (Spain), which currently has a population of 271,780 and an area of 181.7 km^2. It is a city with a large urban bus system, with 16 lines with different routes, plus one special line only for workdays and five night-service routes, operating daily from 06:30 to 00:00 making 80,611 trips daily (Gijón City Council, *Plan de movilidad urbana municipal sostenible* [Sustainable Municipal Urban Mobility Plan]). Since 2019, a car-sharing and moped-sharing service has also been in growing demand in the city, and since 2018, the Tucycle e-bike service.

2.2. Procedure

A survey was designed for the study (Table 2) and distributed to the population of Gijón in an online form from August 15, 2020 to November 5, 2020 (date the state of emergency that officially determined the beginning of the second wave was declared) related to mobility habits. A link to the survey was distributed by email, in social networks and in QR codes linked to the form at several different points in the city.

A statement clarified that only those inhabitants of the city aged 18 to 99 who must move around it and need to use a vehicle to do so could answer. Descriptive statistics were used in data processing, although in future these data could be used for developing an inferential statistics research.

	Question	Answer choices
1	State your age	Open answer
2	State your sex	Female, Male
3	Before March 2020, what type of transportation did you mostly use to get around?	Private car, Bicycle, Motorbike (own or sharing), Scooter, Bus, Taxi
4	Before March 2020, did you have a bicycle, motorbike or electric scooter?	Yes, traditional bicycle. Yes, e-bike, Yes, e-scooter. Yes, traditional motorbike. Yes, e-moped. No.
5	After March 2020, what type of transportation did you mostly use to get around?	Private car, bicycle (own or sharing). Motorbike (own or sharing). Scooter. Bus. Taxi.
6	After March 2020, have you acquired some type of bicycle or e-scooter?	Yes, traditional bicycle. Yes, e-bike. Yes, e-scooter. Yes, traditional motorbike. Yes, e-moped. No.
7	Related to the e-bike sharing service “TuCycle”	I was a member and still am. I was a member before March 2020 but am not now. I was not a member before March 2020 and am still not. I was not a member before March 2020, but now I am.
8	Related to the e-moped sharing service “HiMobility”	I was a member before March 2020 and still am. I was a member before March 2020 but am not now. I was not a member before March 2020 and am still not. I was not a member before March 2020, but now I am.

Table 4 – Questions and answer choices in the online form

2.3. Sampling

After the survey was distributed, a total of 630 responses were received as of November 5, 2020, all of them valid. Of these 55.6% were women (350) and 44.4% were men (280); these figures are similar to the social reality of Gijón (Table 3). There were strong differences with respect to reality in age groups, as people aged 18–25 are hardly represented at all, while there is a significant overrepresentation of people over 65.

Category		Sample		Gijón
		Frequency	Percentage	
Gender	Female	350	55.6%	53.5%
	Male	280	44.4%	46.5%
Age	18-25	159	25.2%	7.7%
	26-65	450	71.4%	63.9%
	>65	21	3.4%	28.4%

Table 3. Respondents by gender and age, and comparison with real population in Gijón 18 years and over

The margin of error was found applying the following formula:

$$n = \frac{N \cdot z_{\frac{\alpha}{2}}^2 \cdot p \cdot (1-p)}{e^2 \cdot (N-1) + z_{\frac{\alpha}{2}}^2 \cdot p \cdot (1-p)} \quad (1)$$

The values entered were: size of the population of Gijón over 18 years of age, $N = 235{,}075$; sample size $n = 630$; $p = 0.5$. Following a normal distribution, $z_{\frac{\alpha}{2}} = 1.96$, for a confidence level of $(1 - \alpha) = 95\ \%$. The margin of error was therefore $e = \pm 3{,}9\ \%$.

4. RESULTS

The answers to Question 3 (Table 4) show that the means of transportation most used in Gijón before the pandemic by over 50% of the users, excluding pedestrians, was private vehicle. The bus was used by 36.8% of users, and the rest were hardly used at all.

Comparing this to the answers to Question 5 (Table 5), it may be observed that private car users increased greatly (14.1 points) as did bicycle users (3.8 points), while use of bus diminished (19.5 points). The rest of vehicles increased slightly.

There was an unequal evolution of data by gender: before March 2020, women used private cars less than men, but used the bus to a similar extent. However, after the first wave of the pandemic, their use of the private car was practically the same as men. Men in turn, have chosen to use alternative private vehicles more than women: the set bicycle+moped+scooter rose among men from 12.1% to 17.5%, while in women it went from 2.3% to 5.5%. By age range, the private car was observed to increase greatly in the 18-25 group by 36.1%, and 7.6% in the 26-65 age range, while over 65 remained the same, and this rise was due to the drop in use of the bus, in the group of 18 to 25 by 44.2%, in the 26.65 group by 12.1%, and in the group over 65, the drop is 5.1%.

		Private car	Bicycle	Motorbike (own or sharing)	Scooter	Bus	Taxi	Total
Women	Responses	171	4	2	2	171	0	350
	Percentage	48.9%	1.1%	0.6%	0.6%	48.9%	0.0%	100.0%
Men	Responses	183	14	17	3	61	2	280
	Percentage	65.4%	5.0%	6.1%	1.1%	21.8%	0.7%	100.0%
18-25	Responses	34	3	1	0	117	0	155
	Percentage	21.9%	1.9%	0.6%	0.0%	75.5%	0.0%	100.0%
26-65	Responses	303	15	18	5	111	2	454
	Percentage	66.7%	3.3%	4.0%	1.1%	24,4%	0.4%	100.0%
>65	Responses	17	0	0	0	4	0	21
	Percentage	81.0%	0.0%	0.0%	0.0%	19.0%	0.0%	100.0%
Total	Responses	354	18	19	5	232	2	630
	Responses	56.2%	2.9%	3.0%	0.8%	36.8%	0.3%	100.0%

Table 4: Question 3. Before March 2020, what type of transportation did you mostly use to get around?

		Private car	Bicycle	Motorbike (own or sharing)	Scooter	Bus	Taxi	Total
Women	Responses	244	16	2	1	80	7	350
	Percentage	69.7%	4.6%	0.6%	0.3%	22.9%	2.0%	100.0%
Men	Responses	199	26	19	4	29	3	280
	Percentage	71.1%	9.3%	6.8%	1.4%	10.4%	1.1%	100.0%
18-25	Responses	92	11	1	2	50	3	159
	Percentage	57.9%	6.9%	0.6%	1.3%	31.4%	1.9%	100.0%
26-65	Responses	334	31	20	3	56	6	450
	Percentage	74.2%	6.9%	4.4%	0.7%	12.4%	1.3%	100.0%
>65	Responses	17	0	0	0	3	1	21
	Percentage	81.0%	0.0%	0.0%	0.0%	14.3%	4.8%	100.0%
Total	Responses	443	42	21	5	109	10	630
	Percentage	70.3%	6.7%	3.3%	0.8%	17.3%	1.6%	100.0%

Table 5: Question 5. Since March 2020, what type of transportation do you mostly use to get around?

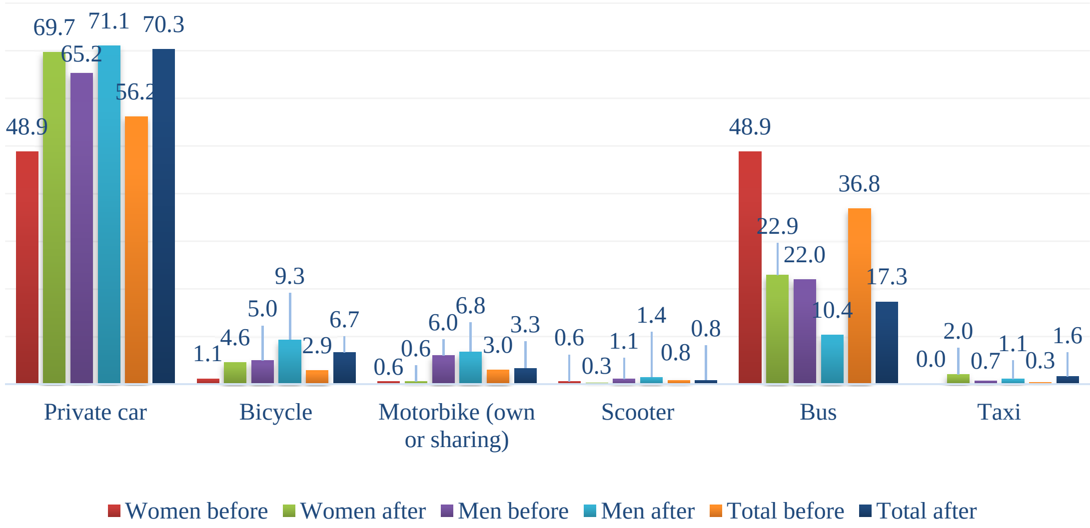

Figure 1. Comparison, in percentage, of means of transportation used before and after March 2020 by gender.

Questions 4 and 6 referred to the evolution of the private vehicle pool other than cars.

Before 2020, over 42% of the population owned some type of vehicle of the following types: bicycle or e-bike, e-moped or motorbike, e-scooter. After March 2020, 6.3% of the population claimed to have acquired a vehicle of this kind. An analysis by gender showed that before the pandemic, a higher percentage of men and women had vehicles of this type (57% vs 30%); after the pandemic, the percentage of men who acquired these vehicles was higher than women (8.9% vs 4.3%). Analyzing these data by age range, over 44% of the group of young people (18-25) had one of the vehicles mentioned, and similar in the 26-65 group (42%), however in the group over 65, only 18% had one of these vehicles. After March 2020, in all of the groups, over 93% had not acquired any of the vehicles mentioned above.

		Yes, traditional bicycle	Yes, e-bike	Yes, e-scooter	Yes, motorbike	Yes, e-moped	No	**Total**
Women	Responses	88	3	3	12	1	249	**356**
	Percentage	24.7%	0.8%	0.8%	3.4%	0.3%	69.9%	**100.0%**
Men	Responses	126	5	11	25	0	126	**293**
	Percentage	43.0%	1.7%	3.8%	8.5%	0.0%	43.0%	**100.0%**
18-25	Responses	62	0	6	3	0	89	**160**
	Percentage	38.8%	0.0%	3.8%	1.9%	0.0%	55.6%	**100.0%**
26-65	Responses	149	8	8	34	1	268	**468**
	Percentage	31.8%	1.7%	1.7%	7.3%	0.2%	57.3%	**100.0%**
>65	Responses	3	0	0	1	0	18	**22**
	Percentage	13.6%	0.0%	0.0%	4.5%	0.0%	81.8%	**100.0%**
Total	Responses	214	8	14	37	1	375	**649**
	Percentage	33.0%	1.2%	2.2%	5.7%	0.2%	57.8%	**100.0%**

Table 6: Question 4. Before March 2020, did you have a bicycle, moped or e-scooter?

		Yes. traditional bicycle	Yes. e-bike	Yes. e-scooter	Yes. motorbike	Yes. e-moped	No	**Total**
Mujeres	Responses	11	1	2	1	0	335	**350**
	Percentage	3.1%	0.3%	0.6%	0.3%	0.0%	95.7%	**100.0%**
Hombres	Responses	17	2	1	5	0	256	**281**
	Percentage	6.0%	0.7%	0.4%	1.8%	0.0%	91.1%	**100.0%**
18-25	Responses	6	1	1	2	0	150	**160**
	Percentage	3.8%	0.6%	0.6%	1.3%	0.0%	93.8%	**100.0%**
26-65	Responses	23	2	2	5	0	420	**452**
	Percentage	5.1%	0.4%	0.4%	1.1%	0.0%	92.9%	**100.0%**
>65	Responses	0	0	0	0	0	21	**21**
	Percentage	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	**100.0%**
Total	Responses	28	3	3	6	0	591	**631**
	Percentage	4.4%	0.5%	0.5%	1.0%	0.0%	93.7%	**100.0%**

Table 7: Question 6. Since March 2020, Have you acquired a bicycle, moped or e-scooter?

Questions 7 and 8 asked about bicycle and e-moped sharing services. With regard to e-bikes, new and leaving members led to lack of variation in the number of members. e-mopeds went from 2.1% of the population before the pandemic to 3.6% afterwards, for a relative increase of 71%. By age group, in the group of young people, there were 0.6% fewer, while in the group 26-65 there was a 0.4% increase.

		I was a member and still am	I was a member, but am not now	I was not a member and am still not	I was not a member, but now I am.	**Total**
Mujeres	Responses	6	2	339	3	**350**
	Percentage	1.7%	0.6%	96.9%	0.9%	**100.0%**
Hombres	Responses	12	6	257	5	**280**
	Percentage	4.3%	2.1%	91.8%	1.8%	**100.0%**
18-25	Responses	1	4	151	3	**159**
	Percentage	0.6%	2.5%	95.0%	1.9%	**100.0%**
26-65	Responses	17	4	424	5	**450**
	Percentage	3.8%	0.9%	94.2%	1.1%	**100.0%**
>65	Responses	0	0	21	0	**21**
	Percentage	0.0%	0.0%	100.0%	0.0%	**100.0%**
Total	Responses	18	8	596	8	**630**
	Percentage	2.9%	1.3%	94.6%	1.3%	**100.0%**

Table 8: Question 7. Related to the e-bike sharing service "TuCycle"

		I was a member and still am	I was a member, but am not now	I was not a member and am still not	I was not a member, but now I am.	Total
Women	Responses	2	1	343	4	350
	Percentage	0.6%	0.3%	98.0%	1.1%	100.0%
Men	Responses	11	3	257	9	280
	Percentage	3.9%	1.1%	91.8%	3.2%	100.0%
18-25	Responses	1	1	155	1	158
	Percentage	0.6%	0.6%	98.1%	0.6%	100.0%
26-65	Responses	12	3	424	12	451
	Percentage	2.7%	0.7%	94.0%	2.7%	100.0%
>65	Responses	0	0	21	0	21
	Percentage	0.0%	0.0%	100.0%	0.0%	100.0%
Total	Responses	13	4	600	13	630
	Percentage	2.1%	0.6%	95.2%	2.1%	100.0%

Table 9: Question 8. Related to the e-moped sharing service "HiMobility"

5. DISCUSSION

The main conclusion arrived at from the survey responses is that, although the majority of users already used private vehicles as their usual means of transport before the pandemic, there was a large increase in their use, by both men and women, in a higher percentage than the margin of error mentioned above (total of 56% to 70%); at the same time, bus fare increased, and its use fell drastically (from 36% to 17%). In the rest of the means of transport no significant variations were observed (higher than margin of error).

It is also observed that those surveyed acquired one of the following types of vehicle: e-bike or bicycle, e-moped or motorbike, or e-scooter. Only 6.3% said they had acquired one after the pandemic began, and 4.4% were bicycles. Neither is there an increase in sharing services, as only 1.3% said they had become members of the city's bicycle sharing service, and 2.1% of the moped sharing service.

Furthermore, gender was important both before and after the pandemic, observing more use of the bus by women, and more use of private cars, bicycles and motorbikes by men.

This effect has been widely analyzed in the literature (Figueroa Martínez y Waintrub Santibáñez, 2015; Law, 1999) and even related to cities with mild climates (Williams y Larson, 1996) as is the case of Gijón. The gender effect in the city could also be related to women's employment sectors. Before the pandemic, most women worked in sales, healthcare, education and restaurants/hotels (INE, 2019). These establishments are usually in city centers or zones easily accessible by bus, which could be why those workers habitually make use of public transportation.

The reason for the increase in mobility by private vehicle may be fear of contagion in public transportation due to prolonged contact with other riders, especially at rush hour, as well as occasional drop in service level. Users decided to use private vehicles before using a personal mobility vehicle or a sharing service, which reflects the lack of safety of these vehicles, their price or the city's climate, which could be reasons for this deficit of users.

The results of this study are in line with what those cited in the introduction, which were done just before this one. As the Apple and Nextdoor app mobility reports demonstrated, in cities like Madrid and Barcelona, over half of the population had modified their mobility habits. In Gijón, a change in means of transport was also observed, although not as drastic as in Madrid or Barcelona, which are larger cities with more traffic and more public transportation choices. In this case, half of those surveyed were already usually using a private vehicle, so their habits were not modified; nevertheless, the 36% of users who traveled by bus before the pandemic was reduced to 17% after March 2020.

This study had some limitations. In this case, the main problem with the methodology used is the limitation in generating questions asked in the survey, because the form cannot be very long, or respondents will lose interest. This may have led to the omission of some interesting questions, such as those related to users who shared vehicles before and after the pandemic or the usual destination of the respondents, as their usual means of transportation would vary depending on where they work or study, in the city center or in the outskirts or even in another city in the region. Furthermore, the representativeness of the sample was not the most suitable in terms of age, which could affect the results in the 18 to 25 age group.

One of the results that might have been expected was a large increase in the number of users of the bicycle as their usual means of transportation after the pandemic, because the city has a bike lane. This did increase from 2.9% to 6.7%, although this difference is perhaps not as wide as could have been expected: the lack of connectivity between bike lanes in the city might be the reason why this does not seem a safe choice for regular transportation. In fact, at present, the city is working on a Mobility Plan to solve the problems in the current network's continuity (Grande, 2020), and in March 2021 approved a Mobility Ordinance promoting active mobility stead of private vehicles (Ayuntamiento de Gijón, 2021).

Future studies on mobility since the beginning of the pandemic could consider other factors, such as finding out whether people who usually share cars continue to do so or whether on the contrary, many users of public transportation have now decided to share a vehicle; whether there is any difference between mobility in the different waves of the pandemic, since in this case only the period after the first was evaluated; or include pedestrian mobility in the study to quantify its increase. It might also make sense to study a second wave a year after it, or in successive years; and likewise, the results could be combined with changes in the labor market (increase in telecommuting) or unemployment scenarios arising.

6. CONCLUSIONS

This study analyzed the effect of the appearance of the pandemic associated with COVID-19 on mobility habits in the Spanish city of Gijón, with a population of 270,000, where there is currently a good city bus system, and car-sharing, moped-sharing and bike-sharing services. Therefore, a survey was taken from August 2020 to early November 2020. We think that a large part of the value of this study is that it shows a snapshot of a particular moment: that moment at which there was a certain return to normality, in order to evaluate the changes that occurred between the situation before the pandemic and the situation in the summer of 2020, after the first wave.

The survey included eight questions focusing on finding out the variation in type of transportation most used for everyday travel, about possible acquisition of personal mobility vehicles, and joining and leaving bike-sharing and moped-sharing services. This is a pioneer study of the mobility habits related to the pandemic in Gijón, and the results were analyzed based on descriptive statistics.

The main conclusion is a strong increase in the habitual use of the private vehicle, by both men and women, and a decrease in use of the bus. In the rest of the means of transportation, no significant variation was observed.

After the first wave of the pandemic, a certain renewed high in acquisition of personal mobility vehicles by those surveyed was observed. Finally, in regard to shared vehicles, it could only be deduced that there were no important variations.

Gender was demonstrated to affect mobility. Both before and after the pandemic, women used the bus more, and men used private car, bicycle and motorbike more. With regard to the vehicles owned, before the pandemic, more men than women had personal mobility vehicles; after the pandemic, the percentage of men who acquired these vehicles was also higher than women (8.9% vs 4.3%). More people went from public transportation to private in the group of young people (18-25); the group over 65 did not change their habits, because most of them were already using a private vehicle for getting around before the pandemic. Similarly, in regard to owning a PMV, a sharp generational change was observed among those up to 65 years of age compared to those over, as over 42% of the first had a PMB before the pandemic compared to 18% of the latter.

The main limitations of the study were the underrepresentation of young people from 18 to 25, along with the short survey, which did not go into detail so the questionnaire could be answered quickly.

Finally, this study could be a model (both in how it acquired data and the brevity of the survey) for analyzing future modification of mobility habits, as the number of responses was representative (except for underrepresentation of young people), and interesting conclusions were arrived at concerning the objectives set. The possibility of following surveys on the same city to acquire a dataset that can be used to analyze evolution over time of urban mobility habits in Gijón remains open.

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LA REGULACIÓN MUNICIPAL COMPARADA SOBRE EL USO DE LOS VEHÍCULOS DE MOVILIDAD PERSONAL (VMP): ANÁLISIS SOBRE EL DESARROLLO NORMATIVO DE GIJÓN, VALLADOLID, VIGO, HOSPITALET DE LLOBREGAT Y VITORIA

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RESUMEN

El crecimiento del uso de los vehículos de movilidad personal (VMP) en el espacio urbano ha obligado a realizar adaptaciones normativas en distintos niveles de regulación. El tráfico es una materia donde intervienen poderes públicos de ámbito estatal, autonómico y local, con diferentes herramientas de limitación, fomento o servicio público. El retraso en dotarse de unas reglas precisas de ámbito estatal (2020) sobre las características lícitas de producción y uso en el entorno urbano ha provocado un desarrollo desigual de la regulación municipal, cuyas autoridades han tratado de anticiparse, en ocasiones, a los desafíos que este nuevo sistema de movilidad ha provocado: uso de las vías públicas, habilitación de los conductores, interacción con otras formas de movilidad, etc.

El objetivo del estudio ha sido identificar y analizar el régimen jurídico vigente en cinco municipios españoles de similar población (Gijón, Valladolid, Vigo, Hospitalet de Llobregat y Vitoria). Sus normas (también sus proyectos normativos) han sido objeto de la descripción sistemática, y se han contrastado con la regulación estatal adoptada en 2020, y con la normativa generada por las autoridades autonómicas respectivas.

El resultado es una exposición profunda de tres aspectos: el ordenamiento vigente en España a propósito de estos vehículos (VMP), sus principales novedades vigentes a partir de enero de 2021 y el impacto que puede tener en la regulación municipal preexistente; el conjunto de las reglas que podrían resultar de aplicación dadas por los cinco poderes públicos autonómicos que afectan a las ciudades elegidas, con sus principales fortalezas y debilidades actuales; y la comparación específica sobre cómo afrontan los cinco municipios (con sucintas referencias a las normas de otras ciudades españolas) los desafíos en materia de habilitación y permisos de los conductores de VMP, las exigencias materiales sobre los vehículos y las reglas para su uso.

1. INTRODUCCIÓN

El desarrollo de la innovación para el desplazamiento de las personas en el entorno urbano se ha concretado, en los últimos años, en el auge de nuevas herramientas de movilidad alternativas a los vehículos a motor convencionales, que transitan entre la tracción humana (bicicletas tradicionales o con la asistencia de motores eléctricos, patines o patinetes sin motor, etc.) y la total tracción eléctrica, creando una nueva categoría de vehículos que diversifican las formas de utilizar las vías de circulación urbana.

Parte de los nuevos instrumentos para el desplazamiento han sido denominados en España como "vehículos de movilidad personal" (en adelante, VMP), en función de una serie de características técnicas comunes. Morell Aldana (2020) alude a fuentes que cifrarían en alrededor de 20.000 vehículos de estas características los que circularían en España hasta poco antes de la epidemia de la Covid-19. Estos VMP no han sido realmente definidos de forma clara, mediante instrumentos jurídicos que ofrecieran certidumbre, hasta una reciente regulación normativa de ámbito estatal, parcialmente vigente desde enero de 2021.

Hasta entonces, gran parte de las reglas sobre su manejo, sus características y su circulación quedaban en el margen de ordenación de los más de ocho mil municipios.

Cuando iniciamos este estudio aún no se había promulgado la reforma del Reglamento General de Circulación y del Reglamento General de Vehículos, por lo que la mayor parte de las decisiones jurídico-técnicas del uso de los VMP en la vía pública urbana, en España, era competencia municipal, con directrices de la Administración estatal de tráfico manifiestamente insuficientes y de validez jurídica discutida (Vestri, 2018). Tras la reforma de estos reglamentos ejecutivos estatales, se ha elevado el mínimo común denominador de las reglas que afectan al uso urbano de estos vehículos. Nuestro objetivo ha evolucionado con la transformación normativa. Al principio fue solo la identificación y el análisis de las distintas soluciones técnico-jurídicas adoptadas por varias autoridades municipales en España con el fin de ordenar en su ámbito la circulación de los VMP. Sin embargo, la irrupción de las reformas justifica una ampliación del ámbito de estudio, que plantee, primero, cuál es la concreta responsabilidad de los distintos poderes públicos territoriales en la regulación de los VMP, para situar después de forma orientada cuál ha sido el desarrollo específico en los municipios inicialmente seleccionados.

Para desarrollar un análisis comparado eficiente, el ámbito territorial del estudio se ha circunscrito a la comparación entre la regulación (mediante ordenanzas) y la programación (mediante planes de movilidad urbana sostenible) de cinco ciudades de dimensión poblacional equivalente (entre 250.000 y 300.000 habitantes): Gijón, Valladolid, Vigo, Hospitalet de Llobregat y Vitoria. Sus normas y programas serán, además, contrastados con el contenido de las normas europeas, estatales y autonómicas que les son de aplicación específica.

2. MARCO COMPETENCIAL GENERAL

En el sistema político español, los municipios constituyen uno de los tipos de entidades locales (junto a diputaciones provinciales, mancomunidades, cabildos, etc.) que representan el tercer nivel de administración territorial, tras las comunidades autónomas y el Estado.

La Constitución española de 1978 (en adelante, CE) no contiene referencias explícitas a la movilidad ni a la sostenibilidad, aunque aborda tangencialmente estas materias al referirse a las competencias públicas sobre el transporte (por ejemplo, el art. 149.1.21ª CE) o la protección del medio ambiente (arts. 45, 148.1.9ª y 149.1.23ª CE). El enfoque constitucional de estas cuestiones, limitado por el contexto histórico en el que se promulga la Carta Magna (propio de finales de la década de los setenta) no impide un desarrollo normativo inferior acorde a las nuevas realidades y evidencias en estos ámbitos, más de cuarenta años después. La proliferación del uso de los ahora denominados “vehículos de movilidad personal” es una de estas realidades que el Derecho español contemporáneo aborda, aún con notables zonas de incertidumbre.

En todo caso, sobre la movilidad y el uso de medios de transporte, en general, las administraciones públicas de los tres niveles territoriales (Estado, comunidades autónomas y entidades locales –y, entre estas, especialmente los municipios–) disponen, respectivamente, de distintas competencias propias. Este sistema, avoca a una cierta complementariedad de intervenciones, y es el resultado de las previsiones del sistema constitucional.

2.1. Las competencias estatales

El Estado se ha dotado del Real Decreto Legislativo 6/2015, de 30 de octubre, por el que se aprueba el texto refundido de la Ley sobre Tráfico, Circulación de Vehículos a Motor y Seguridad Vial (en adelante, Ley de Tráfico). Esta Ley invoca como título competencial de su contenido lo dispuesto en el artículo 149.1.21ª de la Constitución española de 1978, es decir, la competencia exclusiva del Estado sobre la materia de “tráfico y circulación de vehículos a motor”. En consonancia con la legislación reguladora de las bases del régimen local, y al carácter “bifronte” de la regulación de competencias municipales, esta Ley de Tráfico alude no solo a las competencias ejercidas por la Administración del Estado, sino también al reconocimiento estatal explícito de competencias que corresponden a los municipios sobre las materias objeto de esta norma. En concreto, la Ley de Tráfico dedica su Título I al “(E)jercicio y coordinación de las competencias sobre tráfico, circulación de vehículos a motor y seguridad vial”, y el primer Capítulo de este Título está dedicado a la distribución de las “(C)ompetencias” entre la Administración General del Estado (art. 4) y los municipios (art. 7).

Las competencias que el legislador estatal atribuye a la Administración central del país, a los efectos que interesan en este estudio, pivotan en torno a la potestad para dictar reglamentos administrativos y los actos que correspondan sobre: 1º) la normativa técnica básica en materia de seguridad vial; 2º) las exigencias de homologación previa de los elementos de los vehículos y las directrices en materia de inspecciones técnicas; 3º) la determinación de las condiciones de los sujetos para la conducción de vehículos (reglas y controles sobre consumo de sustancias, causas de inhabilitación, etc.); 4º) la eventual expedición de permisos y licencias, y la determinación de los requisitos para su obtención o pérdida; e) las autorizaciones o permisos (permanentes o temporales) para la circulación de vehículos; 5º) la vigilancia, la disciplina y la regulación (en sentido amplio) del tráfico, en vías interurbanas y en travesías cuando no exista policía local; y 6º) la garantía de la igualdad de oportunidades, no discriminación y accesibilidad universal de las personas con discapacidad, en los ámbitos regulados por la Ley de Tráfico.

Aun cuando veremos que los VMP han sido reconocidos como vehículos propulsados con apoyo motorizado, no son considerados estrictamente "vehículos a motor" en sentido estricto. Pero ello no ha sido obstáculo para que el mencionado Título I de la Ley de Tráfico confiera cobertura a la regulación posterior de los VMP en los reglamentos ejecutivos de desarrollo, conforme a las competencias estatales descritas, quizá asumiendo la inclusión conceptual de los VMP como "vehículos a motor" en un sentido *lato*, o bien porque la circulación de los VMP inciden, de forma notable y obvia, sobre la seguridad vial y el tráfico, aun sin ser estrictamente tal tipo de "vehículos a motor".

Como consecuencia de todo lo expuesto, el Ejecutivo ha podido adoptar una reciente regulación sustantiva explícita (a finales de 2020, parcialmente vigente desde el 2 de enero de 2021) a propósito de los VMP en el Reglamento General de Circulación y en el Reglamento General de Vehículos, sobre la que nos detendremos en el epígrafe siguiente.

En todo caso, tanto las comunidades autónomas como los municipios disponen, también, de un ámbito competencial propio que da pie a una regulación parcialmente diferente en cada territorio autonómico y municipal.

2.2. Las competencias autonómicas con incidencia en la ordenación local

Las comunidades autónomas se ajustan, para regular aspectos que inciden en el uso de los VMP, a lo que prevean sus respectivos estatutos de autonomía en materia de ordenación del tráfico y de las vías para la movilidad terrestre (aun empleando términos distintos). Por el emplazamiento de los municipios que han sido elegidos para el concreto análisis de este estudio, resultan de interés los regímenes competenciales, y el ejercicio de las correspondientes potestades, en las comunidades autónomas del Principado de Asturias (por Gijón), Castilla y León (por Valladolid), Galicia (por Vigo), Cataluña (por Hospitalet de Llobregat) y el País Vasco (por Vitoria).

A título ilustrativo, es frecuente encontrar (en todos los estatutos autonómicos) cláusulas semejantes a las que confieren a la Comunidad Autónoma del Principado de Asturias la competencia exclusiva sobre los "ferrocarriles, carreteras y caminos cuyo itinerario se desarrolle íntegramente en el territorio de la Comunidad Autónoma, y en los mismos términos el transporte terrestre, fluvial, por cable o tubería" (artículo 10.1.5 de la Ley Orgánica 7/1981, de 30 de diciembre, de Estatuto de Autonomía para Asturias). En términos similares se expresa el Proyecto de Ley de Movilidad Sostenible de Euskadi, que señala la "atribución a la Comunidad Autónoma del País Vasco de la competencia exclusiva" en materia de transportes que discurran íntegramente en el territorio del País Vasco, "conforme a lo previsto en el artículo 10.32 del Estatuto de Autonomía para el País Vasco". Previsiones semejantes recoge el artículo 70.1.8º de la Ley Orgánica 14/2007, de 30 de noviembre, de reforma del Estatuto de Autonomía de Castilla y León, o el artículo 27, apartado Ocho, de la Ley Orgánica 1/1981, de 6 de abril, de Estatuto de Autonomía para Galicia.

Sin embargo, merece una atención particular la Ley Orgánica 6/2006, de 19 de julio, de reforma del Estatuto de Autonomía de Cataluña. Este es el único de los estatutos de autonomía que aquí nos interesan que recoge una alusión explícita a la finalidad u orientación que debe guiar el ejercicio de las competencias sobre movilidad sostenible desde los diversos poderes públicos (en este caso, de Cataluña –ya sean poderes públicos autonómicos o locales–), como específico criterio de intervención en materia de las políticas de transporte (el apartado primero del artículo 48 indica que los "poderes públicos deben promover políticas de transporte y de comunicación, basadas en criterios de sostenibilidad", entre otros). Pero, además, el artículo 84.2.h) del estatuto catalán recoge de manera expresa la competencia municipal en esta materia, aun cuando añade poco valor sustantivo directo a las alusiones de la normativa estatal antes mencionada. Este último precepto indica que es de competencia municipal "la circulación y los servicios de movilidad y la gestión del transporte de viajeros municipal".

2.3. El reconocimiento de la competencia municipal

Los municipios pueden regular diversos aspectos del uso directo de los VMP en virtud de sus competencias propias. Estas atribuciones competenciales pueden provenir de tres fuentes distintas, principalmente: a) la legislación básica del Estado en materia de régimen local; b) los expresos reconocimientos de la Ley de Tráfico; o c) de forma matizada, gracias a las previsiones de las normas de ordenación autonómica con efectos sobre las competencias de ámbito municipal.

En primer lugar, la Ley 7/1985, de 2 de abril, Reguladora de las Bases del Régimen Local (LBRL), en su artículo 25.2.g), reconoce de forma expresa que el tráfico, el estacionamiento de vehículos y la movilidad [urbana] son materias sobre las que los municipios ejercen competencias propias. Esta atribución opera con carácter general en todas las Administraciones municipales en el ámbito estatal, aun sin perjuicio de una posible ampliación o precisión de las competencias, por atribución o delegación de la normativa autonómica en cada caso. Aunque el texto de la LBRL no recoge mayor contenido sustantivo sobre el asunto que nos ocupa, esta norma estatal es indispensable para precisar las herramientas de las que disponen los municipios para afrontar esta y las demás competencias propias. Esta Ley marca, precisamente, el instrumento de regulación utilizado con mayor frecuencia por los Ayuntamientos para especificar la regulación del uso de los VMP en sus respectivos términos municipales: las ordenanzas municipales –*vid*. arts. 84.1.a) y 123.1.d) LBRL–. Tales normas delimitan las reglas de la potestad sancionadora atribuida a los alcaldes –art. 21.1.n) LBRL–. No debe obviarse, en cualquier caso, el creciente impacto de la potestad planificadora de los municipios –art. 4.c) LBRL–, que ha favorecido la expansión de los instrumentos denominados Planes de Movilidad Urbana Sostenible (PMUS), bajo el marco de referencia que supuso la Estrategia Española de Movilidad Sostenible de 2009, y la recomendación gubernamental de que todos los municipios de más de 50.000 habitantes se dotaran de su propio PMUS (Movilidad Sostenible: 2019).

En segundo lugar, la Ley de Tráfico, en su artículo 7, indica que "corresponde a los municipios", entre otras competencias: 1º) la "regulación, ordenación, gestión, vigilancia y disciplina (…) del tráfico en las vías urbanas" –art. 7.a)–; 2º) "la regulación mediante ordenanza municipal de circulación, de los usos de las vías urbanas, haciendo compatible la equitativa distribución" del tráfico, las zonas de aparcamiento y "el uso peatonal de las calles" –art. 7.b)–; 3º) la potestad para "la retirada de vehículos de las vías urbanas y su posterior depósito" cuando sean un obstáculo o un peligro para la circulación –art. 7.c) *in fine*–; y 4º) la "restricción de la circulación de determinados vehículos en vías urbanas por motivos medioambientales" –art. 7.g)–.

En tercer lugar, resulta más compleja la identificación de las heterogéneas alusiones de la normativa de proyección autonómica sobre la forma de ejercer estas competencias municipales, que marcan las diferencias entre unos territorios y otros. En las normas estatutarias solo se recoge la referencia del tipo a la ya anticipada del artículo 84.2.h) del Estatuto catalán. Sin embargo, la legislación autonómica específica sobre movilidad o transportes, con independencia de su concreta denominación, también dicta marcos competenciales en los que las comunidades autónomas atribuyen un determinado ámbito de actuación a las administraciones municipales.

Un caso peculiar es el de la Ley 9/2018, de 20 de diciembre, de transporte público de viajeros por carretera de Castilla y León. Esta norma, a pesar de su título alusivo al transporte público, realmente recoge disposiciones relativas a la movilidad personal, ajena a los medios de transporte colectivos. Por ello, su análisis será pertinente en las disposiciones sustantivas. Pero en términos competenciales, el artículo 6 de esta (referido expresamente a las "competencias municipales") carece de relevancia para las potestades de ordenación de los municipios sobre los VMP.

Y, sin embargo, los planes de movilidad sostenible aparecen como una herramienta exhaustivamente regulada (arts. 50 a 59), y en la que las Administraciones municipales desempeñan un papel nuclear.

La Ley asturiana 12/2018, de 23 de noviembre, de Transportes y Movilidad Sostenible no es especialmente generosa en sus previsiones hacia los VMP, ni los denomina así, pero recoge, en su ámbito de aplicación (art. 2), "los transportes activos realizados a pie, en bicicleta, patines u otros de similares características". Esto constituye, a todas luces, una descripción abierta y anticipada de este tipo de vehículos.

3. REGULACIÓN SUSTANTIVA MULTINIVEL EN EL ÁMBITO SUPRAMUNICIPAL

Fruto del esquema competencial antedicho, es imposible determinar con precisión un único ámbito territorial en el que los poderes públicos desplieguen normas jurídicas con efecto directo. Esto, en parte, es habitual en la mayoría de materias que hoy en día son objeto de regulación jurídica. Sin embargo, cobra especial trascendencia en algunas de ellas, cuya ordenación requiere, necesariamente, una complementariedad de normas técnicas industriales y de certificación de productos complejos, y su uso en territorios principalmente acotados a la movilidad en el espacio urbano. Tal es el caso de los VMP.

Aun cuando existe un amplio margen de concreción y discrecionalidad en manos de los Ayuntamientos u otras autoridades municipales para la regulación de la movilidad a través de los VMP, es innegable la incidencia de marcos reguladores de alcance territorial superior. Estos niveles supramunicipales incluyen, a los efectos de este estudio, las disposiciones de la Unión Europea, las normas dictadas por los poderes públicos del Estado en el ejercicio de sus potestades (de legislar, el Parlamento, o de reglamentar, el Ejecutivo), y las comunidades autónomas, en el ámbito de sus respectivas competencias.

3.1. La normativa de la Unión Europea

La principal norma europea digna de ser considerada sobre los VMP es el Reglamento (UE) n ° 168/2013 del Parlamento Europeo y del Consejo, de 15 de enero de 2013, relativo a la homologación de los vehículos de dos o tres ruedas y los cuatriciclos, y a la vigilancia del mercado de dichos vehículos (en particular, este Reglamento de la UE se aplica a los «vehículos de categoría L» definidos en su Anexo I, y que pueden resumirse, a grandes rasgos, como los ciclos de motor y ciclomotores, triciclos de motor y cuatriciclos. La principal diferencia perceptible por sus rasgos externos, al margen del tipo de propulsión del motor y otras características técnicas, es la existencia o no de un sillín –y con o sin sistema de autoequilibrado–).Veremos, más adelante, que esta disposición comunitaria ha sido utilizada como herramienta de delimitación negativa para la definición de los VMP en la normativa estatal española, haciendo que los vehículos objeto de regulación en este Reglamento europeo sean algunos de aquellos que quedan expresamente excluidos de la aplicación de las normas estatales sobre VMP (en el Reglamento General de Vehículos y en el Reglamento General de Circulación, principalmente). Es una distinción que justifica de forma lógica el mismo Reglamento de la UE, en los apartados 2.i) y 2.j) de su artículo 2. No existen otras normas europeas que incidan de forma directa en la regulación del uso de los VMP en el territorio, sin perjuicio de las reglas sobre su producción (SAV-DGT, 2019).

Por tanto, la regulación europea que deben considerar las autoridades municipales es escasa. Ello es acorde al marco competencial de la Unión Europea, que en este ámbito centra el ejercicio de sus potestades normativas en la adopción de "medidas relativas a la aproximación de las disposiciones legales, reglamentarias y administrativas de los Estados miembros que tengan por objeto el establecimiento y el funcionamiento del mercado interior" (art. 114.1 TFUE), y no en la ordenación del uso de vehículos en la específica movilidad "intra-urbana".

3.2. La normativa estatal

La ordenación estatal de los vehículos de movilidad personal se encuentra contenida en varias normas de distinto rango jurídico. Sobresalen una Ley con incidencia directa y sus reglamentos ejecutivos de desarrollo (recientemente reformados en 2020), pero no deben pasar desapercibidas otras disposiciones legales tangenciales, ni una importante iniciativa gubernamental de legislación sobre movilidad sostenible.

Romero *et al*. (2019) señalaban que, en el plano de los Estados europeos, los Países Bajos fueron pioneros al dotarse de una regulación nacional sobre esta cuestión en 2008, si bien han precedido también a España las normas estatales en Alemania, Finlandia, Reino Unido o Suiza (no así Francia, que hasta 2019 seguiría remitiendo la regulación a las normas municipales).

Las reglas de los poderes públicos de ámbito estatal despliegan efectos sobre el marco de competencias sustantivas de todas las autoridades municipales del país. La actual ordenación se encuentra en un momento de transformación: se han adoptado recientes reglas nuevas que inciden en la preservación de la seguridad, que obligan a reconsiderar algunas disposiciones previas dadas por los Ayuntamientos para la circulación en sus ámbitos urbanos.

Al mismo tiempo, está pendiente la adopción de nuevas normas, que pueden incidir en las funciones de fomento de las Administraciones Públicas en materia de movilidad sostenible. Por tanto, es muy probable que los próximos años asistamos a una profunda transformación de la actividad administrativa española en todos los niveles (normativa y planificadora, principalmente) hacia los vehículos de movilidad personal y otras formas de desplazamiento humano considerado "sostenible".

3.2.1. Un esquema básico normativo: leyes y reglamentos estatales que afectan a la ordenación municipal de los VMP

En primer lugar, destacan las previsiones de organización del sector público contenidas en la ya mencionada Ley de Tráfico (el Real Decreto Legislativo 6/2015, de 30 de octubre, por el que se aprueba el texto refundido de la Ley sobre Tráfico, Circulación de Vehículos a Motor y Seguridad Vial).

A raíz de este texto legal (y, en segundo lugar), el Gobierno ha dictado varios reglamentos que concretan las normas aplicables a esta materia. Sobresalen, por la importancia para los VMP de algunos de sus preceptos, dos textos principales: 1) el comúnmente denominado Reglamento General de Circulación (RGC), y 2) el conocido como Reglamento General de Vehículos (RGV).

Ambos reglamentos han sido modificados de forma reciente, precisamente para ser adaptados a la realidad emergente de los vehículos de movilidad personal. Para ello se ha aprobado el Real Decreto 970/2020, de 10 de noviembre [por el que se modifican el Reglamento General de Circulación, aprobado por Real Decreto 1428/2003, de 21 de noviembre y el Reglamento General de Vehículos, aprobado por Real Decreto 2822/1998, de 23 de diciembre, en materia de medidas urbanas de tráfico]. En particular, el texto de 2020 ha modificado, de una parte, los artículos del 38 al 50 del Reglamento General de Circulación. De otra parte, con respecto al RGV, ha modificado los artículos 3, 22.3, 25.1 y 28.1, además de los Anexos II y XVIII, y ha añadido el artículo 22bis.

Con anterioridad a la reforma de 2020, tanto el Reglamento General de Circulación como el Reglamento General de Vehículos ignoraban la realidad de los VMP.

En cambio, las cuestiones relativas a la regulación de estos VMP estaban recogidas de forma muy limitada en la ordenación transitoria efectuada por la Dirección General de Tráfico (DGT), a través de la Instrucción 2019/S-149 TV-108 (esta Instrucción de 2019 clarificaba y adaptaba algunos aspectos de la anterior Instrucción 16/V-124, de la misma autoridad, que hizo una primera clasificación de los VMP, con efectos sobre todo el territorio estatal). Sin embargo, el carácter transitorio y la insuficiencia de las Instrucciones de la DGT (ya sea la de 2019, o la previa de 2016), han sido consideradas insuficientes por la doctrina jurídica.

Así, la reforma de 2020 sobre el RGV y el RGC ha dado carpetazo (en principio) a la reiterada crítica doctrinal sobre la incertidumbre provocada por la falta de regulación común al territorio nacional (véanse, por todos, Perona Gómez, 2019: 26; Vestri, 2018; y Morell Aldana, 2020).

Como cierre del sistema legal estatal, y aunque no inciden de manera explícita en la regulación de los VMP, sí aluden a la movilidad sostenible otra serie de mandatos del Legislador estatal, que deben ser tenidos en consideración por todos los poderes públicos a la hora de dictar sus propias disposiciones sobre la materia. Así sucede, por ejemplo, con la Ley 37/2003, de 17 de noviembre, del Ruido; la Ley 34/2007, de 15 de noviembre, de Calidad del Aire y Protección de la Atmósfera; o la Ley 2/2011, de 4 de marzo, de Economía Sostenible.

Conviene subrayar, en fin, que la regulación estatal mencionada hasta ahora puede verse reforzada y actualizada de manera notable si prospera el (por ahora) Anteproyecto de Ley de Movilidad Sostenible y Financiación del Transporte.

Esta iniciativa legislativa del Gobierno incluye, entre otros aspectos novedosos, la creación de un Sistema Nacional de Movilidad.

3.2.2. Los tres tiempos de la reforma reglamentaria de 2020

La reforma de 2020 sobre el RGV y el RGC significa, de hecho y en la actualidad, que los municipios cuentan con una menor discrecionalidad para regular el uso de los VMP en su territorio a partir de la vigencia de las primeras de sus disposiciones aplicables. Sin embargo, la entrada en vigor de las propias previsiones de esta reforma opera en tres tiempos distintos: uno ya pasado, otro inminente, y un tercero aún indeterminado.

Una parte fundamental de las reformas de 2020 ha entrado en vigor, a los efectos que interesan en este estudio, el 2 de enero de 2021 (las definiciones conceptuales o las relativas a la prohibición de circulación de los VMP por determinadas vías, entre otras). No obstante, la reforma contempla dos medidas específicas cuya vigencia es pospuesta.

La primera obedece a la previsión explícita de la Disposición final única, que retrasa el cambio de los límites de velocidad en vías urbanas y travesías (artículo 50 del Reglamento General de Circulación) hasta los seis meses desde la publicación de la reforma (es decir, el 11 de mayo de 2021).

La segunda vigencia pospuesta remite a una fecha no concretada en el momento de la publicación de la reforma, a propósito de la adición de los párrafos j) y k) en el artículo 3 del Reglamento General de Vehículos, sobre un nuevo régimen de certificación de los VMP. Esta regla se refiere a la obligación de los usuarios de VMP de disponer de un “certificado para la circulación” recabado por los fabricantes para la “identificación” del tipo de vehículo, de acuerdo con un “Manual de características de los vehículos de movilidad personal” que debe elaborar la Dirección General de Tráfico (aún pendiente). En consecuencia, esta exigencia de certificado queda pospuesta hasta el transcurso de veinticuatro meses desde que el Boletín Oficial del Estado publique dicho Manual (podría ser efectivo, por tanto, a mediados de 2023, como pronto).

3.2.3. El nuevo concepto estricto de VMP en el Reglamento General de Vehículos

Desde el 2 de enero de 2021, el Anexo II del RGV (rubricado como "Definiciones y categorías de los vehículos") recoge una serie de definiciones fundamentales que permitirán dar mejor certeza y seguridad jurídica a la ordenación estatal, autonómica y local. La definición anticipada de los VMP es el resultado de dos operaciones normativas. En primer lugar, el RGV define ya un VMP en los siguientes términos:

> "(V)ehículo de una o más ruedas dotado de una única plaza y propulsado exclusivamente por motores eléctricos que pueden proporcionar al vehículo una velocidad máxima por diseño comprendida entre 6 y 25 km/h. Solo pueden estar equipados con un asiento o sillín si están dotados de sistema de autoequilibrado".

Esta definición, utilizada como delimitadora material del objeto de este estudio, refleja las siguientes cualidades que deben ser debidamente apreciadas: a) el número de ruedas, superior a uno, es irrelevante, lo cual flexibiliza el concepto, incluso hacia ámbitos de desarrollo industrial aún desconocidos; b) los aparatos con velocidad máxima inferior a los 6 km/h son considerados juguetes u artilugios no aptos para ser calificados de VMP (posiblemente, porque se asemejen al denominado "paso de persona", y sean susceptibles de uso peatonal); c) la alteración de los productos, o la comercialización formal de ellos, con velocidad máxima superior a los 25 km/h, convierte a estos aparatos en otro tipo distinto de vehículo, ajenos a los VMP, y a los que se aplican otras normas jurídicas o, directamente, sanciones; d) la condicionalidad del sillín al sistema de autoequilibrado parece obedecer a criterios técnicos sobre el riesgo producido por las superficies de impacto, en casos de colisión; e) la propulsión exclusiva a motor va a permitir diferencias en características y en exigencias normativas a los VMP de otros aparatos de propulsión híbrida, como las bicicletas a pedales con pedaleo asistido, que serán asemejadas (en ciertas condiciones) a las tradicionales bicicletas sin motor eléctrico que asista el pedaleo (de hecho todo ello va acompañado de otras adaptaciones conceptuales: en el mismo Anexo II, relativas a las "bicicletas de pedales con pedaleo asistido" –antiguas "bicicletas con pedaleo asistido"–, así como la supresión de los "cuatricilos" y su sustitución por los "cuatriciclos ligeros", "cuatriciclos pesados" y "ciclos de motor") , y f) al ser concebidos como monoplazas, el uso de los VMP por más de una persona de forma simultánea (un conductor y un pasajero, por ejemplo) incurrirá en una infracción administrativa debidamente tipificada.

En segundo lugar, la definición anterior es clarificada mediante tres exclusiones conceptuales explícitas. La primera, al excepcionar los VMP de la categoría estricta de "vehículo a motor". La segunda, al diferenciarlos por sus características técnicas objetivas (no serán VMP aquellos con sillín sin sistema de autoequilibrado, o "con una tensión de trabajo mayor a 100 CV o 240 VAC") o funcionales (los "concebidos para competición" o "para personas con movilidad reducida"). La tercera exclusión opera por la delimitación efectuada en la normativa europea ya mencionada, al no considerar como VMP todo aquel vehículo que encaje en la definición del Reglamento (UE) nº 168/2013 del Parlamento Europeo y del Consejo, de 15 de enero de 2013.

3.2.4. Los efectos directos sobre el uso y la circulación de los VMP a partir del concepto del Reglamento General de Vehículos

Las interpretaciones previas a la reforma de 2020 sugerían sujeciones tales como el eventual sometimiento a pruebas de alcohol y drogas (Perona Gómez, 2019), o la más que razonable toma obligatoria de seguros, aun cuando el sector de las aseguradoras no pareciera preparado para ello (Vestri, 2018: 25). La primera entra ya dentro de la consecuencia indubitada de la regulación vigente. No así la segunda: la explícita exclusión de los VMP como "vehículos a motor" parece debilitar el argumento de Vestri (2018), que presumía la obligatoriedad de los seguros a partir de la consideración de los VMP como vehículos dotados de motor, y dentro, por tanto, del ámbito de aplicación del Real Decreto 1507/2008, de 12 de septiembre, por el que se aprueba el Reglamento del seguro obligatorio de responsabilidad civil en la circulación de vehículos a motor. Sin embargo, expulsados de tal categoría, nada dice al respecto la reforma de los RGC y RGV de 2020, por lo que parece quedar solo en manos de los municipios la exigencia de este tipo de seguros para la circulación en sus respectivos ámbitos. La toma de estos, en fin, parece recomendable en municipios como el de Barcelona, y obligatoria en otros, como Cáceres (Rometo *et al.*, 2019).

La modificación del RGV de 2020 trae consigo, además, una aclaración de sus regímenes de certificación del vehículo y autorizaciones de sus usuarios (que son necesariamente sus conductores, al ser vehículos monoplazas).

De una parte, el RGV incorpora en su artículo 3.j) la exigencia de un nuevo "certificado para la circulación" de los VMP. Es un documento expedido por la Jefatura Central de Tráfico, para acreditar el cumplimiento de los requisitos técnicos de la normativa aplicable, nacional y supranacional. La obtención del mismo es responsabilidad de los fabricantes, importadores o representantes de estos en España.

De otra parte, el artículo 3.k) RGV prevé la implantación de un "Manual de características técnicas" de los VMP. De tal documento, aún no aplicable, el RGV señala: 1º) el órgano competente para aprobarlo (mediante Resolución del Director General de Tráfico –art. 22 bis, apartado 3–); 2º) su contenido mínimo (requisitos técnicos de los VMP que permitan su puesta en circulación, la clasificación de los mismos, los procesos de ensayo para la certificación y una serie de mecanismos empleados para su fácil identificación); y 3º) la necesidad de que sea publicado en el Boletín Oficial del Estado y en la página web de la Dirección General de Tráfico para su plena validez normativa.

Finalmente, el RGV incluye a los VMP (art. 22 bis) junto a los ciclos y la bicicletas a pedales con pedaleo asistido (art. 22.3) en la excepción de la obligatoriedad de obtener una autorización administrativa del artículo 1.1 del RGV, es decir, aquel “permiso de circulación” común, con carácter general, a todos los vehículos objeto de regulación, “dirigida a verificar que estén en perfecto estado de funcionamiento y se ajusten en sus características, equipos, repuestos y accesorios a las prescripciones técnicas que se fijan” en el RGV. Por tanto, los VMP no parecen sujetos a inspecciones periódicas, como el común de los vehículos a motor (salvo que la normativa autonómica o municipal disponga otra cosa, en el ámbito de sus respectivas competencias).

3.2.5. Los nuevos límites derivados de la reforma del Reglamento General de Circulación

Definidos con claridad los VMP en la normativa correspondiente (RGV), la misma reforma de 2020 incorpora dos medidas principales en relación con, por un lado, la circulación general de estos, y, por otro lado, la de todos los vehículos.

La primera de las medidas se introduce mediante la reforma del artículo 38 RGC, incorporando un nuevo apartado 4 con dos prohibiciones. Así, impide a los VMP tanto “circular por travesías, vías interurbanas y autopistas y autovías que transcurren dentro de poblado” como hacerlo “en túneles urbanos”.

La segunda medida supone la reescritura del artículo 50 RGC, alterando los límites genéricos de velocidad en vías urbanas. No es una medida que afecta de forma exclusiva a los VMP, pero sí parece motivada por el interés público de reducir la siniestralidad en el ámbito urbano, al crecer el uso compartido de las vías por otros vehículos distintos de los automóviles (así lo indica el Preámbulo del RD de 2020 que introduce la reforma). Es notorio el esfuerzo en la parte expositiva de esta reforma por subrayar la correlación causal entre la velocidad de los vehículos a motor y la siniestralidad y las probabilidades de sobrevivir en los atropellos. Por ello, el Ejecutivo introduce a partir del 11 de mayo de 2021 (Disposición final única del RD 970/2020) los siguientes límites genéricos: a) hasta 20 km/h para vías de plataforma única (en franca expansión en el diseño urbano); b) hasta 30 km/h en vías de un único carril por sentido de circulación; y c) hasta 50 km/h en las vías de dos o más carriles por sentido. Es relevante señalar, no obstante, que el RGC confiere a las autoridades municipales la potestad de excepcionar al alza el tercer supuesto o rebajar la velocidad en cualquiera de ellos (potestades condicionadas a la correcta señalización, en todo caso).

Al incluir a los VMP en las reglas generales aplicables a los vehículos, sus conductores están sujetos al régimen disciplinario por el incumplimiento también de estos límites, aun considerando que la velocidad máxima absoluta del VMP deba ser, para su homologación, los 25 km/h. Los incumplimientos de los límites de velocidad son considerados infracciones graves o muy graves –el art. 50.8 RGC remite, para su precisión, a los arts. 76.a) y 77.a) de la Ley de Tráfico–.

3.3. La regulación de las comunidades autónomas

Las comunidades autónomas han ejercido una competencia desigual en el ámbito de la movilidad sostenible, o con incidencia directa en la ordenación de los VMP.

De las comunidades autónomas de particular interés para este estudio, solo tres (Asturias, Castilla y León y Cataluña) disponen de normas legales vigentes que aluden, de forma al menos tangencial, al papel de los VMP en la promoción de la movilidad sostenible.

En síntesis, en el caso de Asturias, la regulación está condensada y protagonizada por la Ley 12/2018, de 23 de noviembre, de Transportes y Movilidad Sostenible. Cataluña cuenta con dos normas con rango de Ley que inciden en esta cuestión, a juzgar por el criterio técnico en el que se apoya su Ejecutivo: la Ley 9/2003, de 13 de junio, de movilidad; y el Decreto Legislativo 1/2019, de 3 de agosto, por el que se aprueba el Texto refundido de la Ley de urbanismo. Finalmente, a pesar de una denominación algo confusa, el legislador castellanoleonés incluye disposiciones relativas a la movilidad urbana sostenible y al fomento de un transporte que podría conectar, de forma implícita, con la ordenación de los VMP, a través de la Ley 9/2018, de 20 de diciembre, de transporte público de viajeros por carretera de Castilla y León.

Por otro lado, el Gobierno del País Vasco se encuentra tramitando, desde 2019, un Proyecto de Ley de Movilidad Sostenible de Euskadi (remitido al Parlamento el 17 de enero de 2020). Esta propuesta normativa, en la versión disponible para este estudio, adolece de cualquier alusión a los VMP, de manera directa o implícita. Solo menciona a las bicicletas o el desplazamiento a pie, como únicas alternativas de movilidad individual frente a los estrictos "vehículos a motor". Por su parte, Galicia ha rechazado hasta el momento, de forma explícita, la posibilidad de dotarse de un instrumento jurídico de rango legal sobre la movilidad sostenible en su territorio (su Parlamento se opuso a una iniciativa en tal sentido el 27 de marzo de 2019).

Conviene apuntar que Perona Gómez (2019: 24) ya advirtió de, al menos, dos formas de afrontar la regulación autonómica sobre la movilidad sostenible, bien con leyes específicas (como es el caso, según este autor, del Principado de Asturias, Cataluña y la Comunidad Valenciana), o bien mediante la incorporación de principios jurídicos en otras normas sectoriales distintas, alusivos al valor de la sostenibilidad en la movilidad (como serían las leyes de transporte de la Comunidad de Madrid o la Ley de accesibilidad de Castilla y León, según este autor).

A continuación, detendremos el análisis en dos de las tres comunidades que disponen de una regulación al menos tangencial sobre esta materia, entre sus normas legales. Esta selección se debe, por un lado, a la promulgación reciente (han transcurrido apenas tres años) de las normas asturiana y castellanoleonesa. Por otro lado, también parece pertinente una sucinta exposición que facilite la comparativa entre ambas, dada la proximidad cronológica y geográfica de las leyes y sus territorios de aplicación, respectivamente, y ante la falta de vigencia, aún, de la normativa vasca proyectada.

3.3.1. El silencio de la legislación de Castilla y León con respecto a los VMP como principal debilidad de su normativa sobre movilidad sostenible

Como anticipábamos *ad supra*, la Ley castellanoleonesa del transporte público de viajeros (Ley 9/2018, de 20 de diciembre) va más allá del ámbito objetivo explícito que la norma declara en sus primeros artículos o en su título. En efecto, regula aspectos de movilidad personal (como el deber público de incentivar los desplazamientos peatonales y en bicicleta), que solo conectan con el transporte público de forma tangencial y circunstancial.

Sin embargo, la Ley omite cualquier referencia explícita, o alusión directa implícita, relativa al uso de los VMP, a pesar de ser una norma reciente (de 2018). Así, por ejemplo, el artículo 15.4 de la Ley insta a las Administraciones públicas (autonómica y otras competentes, como podrían ser las municipales) “al fomento y desarrollo de estrategias públicas de uso” de la bicicleta “en combinación con el servicio público de transporte de viajeros”, mediante la creación de una Oficina de la Bicicleta. En esta misma idea incide el artículo 19.2 de la Ley (mediante la difusión en internet de la posibilidad de viajar con bicicletas en los transportes ofrecidos por las administraciones públicas castellanoleonesas). También el artículo 56.2.b).8º incluye, entre las actuaciones mínimas de los planes de movilidad sostenible de competencia municipal, el fomento “de la movilidad a pie y en bicicleta a través de la construcción de espacios para el peatón y el ciclista”. No parece que esta previsión organizativa y de fomento incida de forma explícita en materia de VMP, a pesar de las evidentes conexiones conceptuales con el fin público perseguido para la movilidad personal sostenible entre unas y otras formas de desplazamiento.

No obstante lo anterior, el artículo 8.1.d) contempla como un derechos de los viajeros del transporte público que estos puedan llevar determinados equipajes, incluyendo bicicletas, sin que “suponga un coste adicional para las personas usuarias”. Partiendo de la indeterminación de la cláusula, y de la realidad fáctica de que los VMP suelen ocupar un volumen inferior al de la mayoría de bicicletas convencionales (si tomáramos esta alusión expresa como ejemplo de máximos permitido por el precepto), parece razonable que la legislación autonómica ampare, por analogía, el derecho de los usuarios del transporte público (urbano e interurbano) a hacer uso del mismo cargando con sus posibles VMP.

Esta previsión podría operar como incentivo en el ámbito de influencia metropolitana de Valladolid, en los casos de desplazamientos que puedan combinar transporte público con el uso de VMP, o cuando cambios meteorológicos a lo largo de una jornada puedan hacer aconsejable el uso del VMP durante un tiempo determinado, y el acceso al transporte público en otro horario.

Sea como fuere, el silencio del legislador castellanoleonés sobre los VMP es, tal vez, una de las debilidades más notorias puestas de manifiesto, y con mayor rapidez, en la Ley de 2018. Carece del tratamiento de una obvia realidad de hecho emergente.

En este sentido, sería más que recomendable una revisión puntual de la norma, que incorpore estos nuevos elementos en un plano similar y equiparable al del fomento de la movilidad a pie y en bicicleta, pero atendiendo a las peculiaridades de los VMP que los hacen constituir una categoría diferenciada del resto de vehículos propulsados a motor (esto es, en consonancia con la ordenación estatal mencionada).

3.3.2. La previsión limitada en la legislación sobre movilidad del Principado de Asturias

La principal norma asturiana que aquí interesa es la Ley 12/2018, de 23 de noviembre, de Transportes y Movilidad Sostenible. El artículo 2.1.a) de esta Ley prevé, de forma explícita, la aplicación de sus disposiciones a los desplazamientos personales mediante “transportes activos realizados a pie, en bicicleta, patines u otros de similares características”. No deja de ser extraño el empleo de la expresión “transportes a pie” (en términos de racionalidad lingüística, parece más apropiado haber empleado la expresión “desplazamientos” o “movilidad”), pero es evidente que, aun sin la denominación que se ha generalizado con posterioridad a esta disposición normativa de 2018, el legislador quiso incluir en su ámbito de ordenación el uso de los hoy conocidos como VMP.

A lo largo del texto, la Ley es profusa en alusiones y referencias a estos modelos de transporte llamados “de bajo” o “nulo” impacto, ajenos al uso de combustibles fósiles y equiparables a la movilidad peatonal o en bicicletas.

Las bicicletas son el vehículo alternativo configurado en la Ley como protagonista indiscutible de la movilidad sostenible. Son aludidas de forma explícita en más de cincuenta ocasiones a lo largo de los 153 artículos y múltiples disposiciones de otro tipo, y el legislador dedica, incluso, un Capítulo propio a la “movilidad ciclista” (arts. 132 a 136) dentro del Título X (rubricado “La movilidad ciclista y peatonal”). En definitiva, la norma es exhaustiva en previsiones de toda índole, con el objeto de promover el uso de esta forma de movilidad.

Frente a la movilidad ciclista y peatonal, solo existe una segunda referencia explícita a la terminología alusiva en 2018 a los VMP –“patines a motor, segway y similares”, y aparte de la referida al ámbito de aplicación de la Ley, del artículo 2–. Tal referencia se encuentra en el artículo 18.2.m) de la Ley. En todo caso, este precepto reviste especial valor, ya que obliga a los Planes de Movilidad Sostenible de los municipios a incluir, al menos, la "planificación de una adecuada red de carriles mixtos y para tráfico segregado de vehículos como bicicletas, bicicletas eléctricas" y los VMP. Resulta digno de mención que ya esta Ley autonómica de 2018 recogiera el sentido que sería luego incorporado en la regulación estatal, confirmando la condición de vehículos de estos VMP (posiblemente, en consonancia con la previa Instrucción 16/V-124, de 3 de noviembre de 2016, de la Dirección General de Tráfico).

Por su valor comparativo con la normativa castellanoleonesa, cabe mencionar la distinción nominal de las referencias de la norma asturiana que modifica los preceptos de otra Ley (Ley 1/2002, de 11 de marzo, del Consorcio de Transportes de Asturias), en relación con la Oficina de la Bicicleta y Movilidad Activa, cuya mera denominación ya amplía el ámbito de intervención sustantiva respecto de su homóloga en Castilla y León. Además, esta reforma de la Ley del Consorcio de Transportes hace constar, de forma explícita, aquello que apuntábamos en el caso castellanoleonés de forma implícita: la promoción del uso intermodal entre medios de transporte público y vehículos como la bicicleta con o sin motor (y similares, sobre los que la normativa insta, por ejemplo, a "estudiar, promocionar y estimular la implantación de soluciones de micrologística" –art. 12 *ter*.1.i) de la Ley del Consorcio de Transportes, reformada por el apartado Tres de la Disposición final primera de la Ley de Transportes y Movilidad Sostenible, de 2018–.

4. REGULACIÓN MUNICIPAL COMPARADA

Hemos apuntado ya la competencia de las autoridades municipales para regular un amplio abanico de condicionantes y de elementos de gran relevancia sobre el uso ordinario de estos VMP. Algunos autores, incluso, han llegado a sostener la posible existencia de responsabilidad administrativa municipal en los supuestos de accidentes que involucren a tales vehículos (Perona Gómez, 2019).

La Memoria de la Fiscalía General del Estado 2018 aludía ya entonces a la necesidad de que los Ayuntamientos regularan mediante ordenanzas el uso de los VMP en sus respectivos ámbitos, habida cuenta del creciente riesgo que el crecimiento de su uso estaba produciendo, materializado en accidentes (cfr. Perona Gómez, 2019: 26-27). Sobre la persecución penal a propósito del uso del uso ilícito de estos vehículos se ha pronunciado, también, Morell Aldana (2020), quien cita las instrucciones internas e interpretativas de distintas instancias del Ministerio Fiscal, tratando de ordenar la persecución de los delitos cometidos con ellos.

Las ciudades inicialmente elegidas para la comparativa de su regulación fueron Gijón, Valladolid, Vigo, Hospitalet de Llobregat y Vitoria-Gasteiz. La principal razón de la elección era la similitud de población residente. Sin embargo, la búsqueda (heurística) de sus fuentes normativas, especialmente de sus eventuales ordenanzas sobre VMP, arrojó como resultado la inexistencia de reglamentaciones específicas, adaptadas a estos nuevos vehículos, en tres de las cinco ciudades (carecían de regulación específica vigente, en 2020, Gijón, Valladolid y Vigo, aunque la primera de ellas se ha dotado de una reforma aprobada en marzo de 2021, a la que nos referiremos por su complitud). No obstante, incluso en las ciudades que no cuentan con referencias normativas alusivas al uso de estos vehículos (directa o indirectamente), una sencilla búsqueda de las hemerotecas recientes de la prensa digital local en cada caso evidencia que existen iniciativas municipales tendentes a la regulación.

Las orientaciones de unas y otras encuentran puntos de sinergia, otros de discrepancia, pero todos evidencian algunas innovaciones normativas tratando de adaptarse a nuevas realidades y a situaciones complejas. Sus respuestas pueden servir de inspiración a otras normativas municipales, o para reflejar mejor las zonas más o menos oscuras que aún persisten en otros regímenes jurídicos.

4.1. La implantación de los Planes de Movilidad Urbana Sostenible

Aunque las cinco ciudades objeto de comparación en este estudio disponen de sus propios y vigentes Planes de Movilidad Urbana Sostenible (con esta u otra denominación específica), ninguno de ellos recoge de manera explícita, en sus versiones aplicables a principios de 2021, expectativas de ordenación del uso de los VMP, con esta u otra denominación. Por orden cronológico, el Plan aún vigente más antiguo es el de Valladolid (2004, publicado en BOP-Valladolid el 1 de marzo de 2005), que parece que será sustituido a lo largo de 2021 por uno nuevo. Al vallisoletano le siguió el “Plan de movilidad sostenible y espacio público de Vitoria” (2007), aunque desde 2019 parece haberse iniciado el proceso de reforma, contemplando (esta vez sí) una especial atención tanto a los VMP como a las bicicletas a pedales con pedaleo asistido. Vigo y Hospitalet de Llobregat cuentan con Planes de movilidad sostenible desde 2014, sin que haya evidencias conocidas de su reforma, y sin que hagan mención alguna a los VMP. No obstante, Hospitalet de Llobregat dispone de un específico “Plan director de la bicicleta”, de 2006. Finalmente, Gijón adoptó su vigente “Plan Integral de Movilidad Sostenible y Segura” en 2018, sin mencionar de forma explícita a los VMP, aun cuando una de las propuestas de actuación del mismo sí es una nueva ordenanza municipal de movilidad sostenible (empezada a tramitar formalmente en octubre de 2020 y aprobada en marzo de 2021, aunque no publicada en su versión definitiva al cierre de este artículo), la cual sí contempla la ordenación del uso de los VMP en su espacio urbano.

4.2. Las ordenanzas municipales alusivas a la movilidad y la aplicación de sus normas a los VMP

La promulgación de las normas estatales de 2020, y su vigencia a partir de 2021, marcan una pauta de regulación mínima, confiriendo la potestad a los municipios para excepcionar algunos aspectos (como los límites de velocidad genéricos aludidos), o dictando normas más restrictivas y adaptativas sobre el uso de los VMP, pero no más permisivas de lo que ha previsto el Real Decreto 970/2020.

Gracias a una valiosa labor compiladora de organizaciones de la sociedad civil, resulta fácil constatar la existencia de ordenanzas de movilidad que contemplan el uso específico de los VMP en más de una veintena de municipios de diversa envergadura: A Coruña, Almuñécar, Benidorm, Alicante, Denia, Palma, Burgos, Ciudad Real, Cáceres, San Sebastián, Granada, Logroño, León, Lleida, Alcalá de Henares, Colmenar Viejo, Madrid, Tres Cantos, Pamplona, Valencia, Sevilla, Pozuelo de Alarcón o Aravaca de la Cruz –cfr. AVPE (2021), Romero *et al.* (2019) o la compilación divulgativa de Norauto (2020)–.

La comparación plena de todas estas disposiciones excede, con creces, del tiempo y espacio disponibles para este análisis. Por ello haremos alusiones circunstanciales e ilustrativas a algunas de las normas de estas otras localidades, pero centrando la atención en los modelos vigentes y proyectados de las cinco ciudades elegidas.

En el caso de los municipios seleccionados para un análisis comparativo singular en este estudio, cabe hacer las siguientes precisiones preliminares.

En primer lugar, Gijón dispone de una Ordenanza de Circulación y Transportes, de 2002, que contiene alusiones al uso de las bicicletas pero no de otros vehículos que pudieran interpretarse extensivamente como VMP, pero se ha dotado recientemente de una nueva regulación, a través de la Ordenanza de Movilidad Sostenible del Concejo de Gijón, de 2021, que sí los contempla de forma pormenorizada. Esta Ordenanza no figura publicada al cierre de este artículo, por lo que las referencias se hacen con respecto al texto del proyecto disponible en la web del Excmo. Ayuntamiento de Gijón.

En segundo lugar, Valladolid cuenta con su normativa general de circulación de 2005 (Reglamento general de tráfico, aparcamiento y seguridad, de 2005), otra previa de Movilidad Urbana de 2004, y otra específica sobre el uso de bicicletas, de 2015 (BOP-Valladolid, núm. 67, de 21 de marzo de 2015), pero todas estas normas contienen pocas disposiciones directamente aplicables a los VMP. Además de escasa, la regulación vallisoletana sobre el uso de los VMP es de dudosa validez a partir de la entrada en vigor de la reglamentación estatal de 2021. Esto se debe a que presupone, en parte, una definición ya incompatible con el nuevo marco regulador, porque la Ordenanza municipal de 2015 califica a quienes utilizan patines, monopatines o patinetes como "peatones" (al definir así a los "patinadores" en el anexo de definiciones de aquella normativa). Dado que los objetos que usan pueden abarcar tanto a VMP como a elementos similares, pero sin motor eléctrico, la definición subjetiva puede ser válida para estos últimos sin propulsión motorizada, pero ya no para los VMP, que son conducidos necesariamente por sujetos considerados conductores.

En tercer lugar, Hospitalet de Llobregat reformó su Ordenanza de Circulación (BOP-Barcelona, de 21 de septiembre de 2015), mencionando los VMP mediante la fórmula de "*patins eléctrics i anàles, degudament homologats, i autorizats conforme a la normativa* *vigent*” (art. 19). Esta ordenanza hospitalense de 2015 prevé la aplicación de las reglas dadas para la circulación de bicicletas también a los patines eléctricos y vehículos análogos (en clara alusión a lo que, después, ha sido definido como VMP), haciendo una remisión mínimamente excepcionada desde el artículo 19 (específico de estos vehículos calificados como pre-VMP) al artículo 18. Por tanto, la aplicación debe hacerse matizada por las reglas singulares de las características objetivas de los VMP.

En cuarto lugar, Vitoria adoptó una Ordenanza municipal reguladora de los usos, tráfico, circulación y seguridad en las vías públicas de carácter urbano en 2013 (cfr. BOTHA (Boletín Oficial del Territorio Histórico de Álava) núm. 1, de 3 de enero de 2014), que ha recogido una aparente regulación de los VMP, denominándolos “patines y similares” (en el Capítulo III del Título I de aquella ordenanza). Sin embargo, la mayoría de estas cláusulas, que diferencian el uso de los vehículos de motor de otros vehículos (bicicletas, monopatines, etc.) lo hacen excluyendo expresamente a los VMP, al circunscribir las reglas, en general, a los “patines no motorizados”. En consecuencia, solo podemos deducir algunas normas excepcionales con ciertos ejercicios analógicos, remitiendo el resto a la regulación supletoria que el art. 10.9 de aquella norma prevé (es decir, aplicando la regulación general de los vehículos a motor, aun cuando no lo son en sentido estricto).

En quinto y último lugar, la Ordenanza de Circulación de Vigo data de 1993 (cfr. Boletín Oficial de Pontevedra, núm. 123, de 30 de junio de 1993). No recoge ninguna mención indirecta o directa a los VMP. No obstante, la corporación municipal ha anunciado su intención de reformar tal régimen e incorporar a su ordenamiento local una normativa explícita para estos vehículos (abriendo trámite de consulta pública por acuerdo de la Junta de Gobierno de 25 de marzo de 2021). El interés principal que hoy ofrece el análisis de la situación de Vigo radica en esta programación normativa, que contempla su adopción en el verano de 2021. De la información que es accesible en la actualidad, a través de las comunicaciones de prensa del consistorio y de la apertura del trámite de audiencia pública sobre la norma, extraeremos algunos elementos significativos sobre la previsión de ordenación modal.

Finalmente, conviene anotar un rasgo común: incluso en las propuestas normativas más exhaustivas (como la nueva Ordenanza de Gijón de 2021), el régimen sancionador aplicable a los VMP no difiere de manera significativa de las reglas generales dadas para las infracciones y sanciones en materia de conducción general de vehículos, o en todo caso a las especialidades previstas para las bicicletas y ciclos de transporte.

4.3. Previsiones subjetivas y objetivas para el manejo de vehículos de movilidad personal en las disposiciones normativas municipales

Con independencia de las denominaciones de las ordenanzas, y de la complitud de sus previsiones, el análisis comparado que ya han abordado diversos autores, como Vestri (2018; 2019) o Romero *et al*. (2019), hace evidente una serie de elementos que están dentro de la esfera de competencias de los municipios, y que facilitan apreciar de manera ordenada las sinergias y divergencias de las distintas regulaciones municipales. Esta visión sistematizada de las reglas dadas y de los ámbitos susceptibles de ordenación municipal podría facilitar el ejercicio racional de esta potestad normativa de los Ayuntamientos.

A grandes rasgos, las previsiones del sistema jurídico adoptado en la mayor parte de municipios españoles analizados, hasta el momento, parecen poder reducirse a tres grandes categorías de disposiciones: a) aquellas subjetivas, que regulan las condiciones de los sujetos usuarios-conductores de los VMP, sobre su capacidad para conducirlos y las responsabilidades derivadas; b) las de tipo objetivo, referidas a las características materiales del vehículo, en tanto que objeto; y c) las propiamente modales, o que determinan el modo de uso del objeto, por los sujetos mencionados, en el específico contexto urbano. Estas últimas centrarán la atención del epígrafe siguiente.

4.3.1. Las previsiones sobre las circunstancias de los sujetos: la edad y la diversidad funcional

Con anterioridad a la reforma de 2020, la literatura académica había advertido (fundada en la jurisprudencia disponible y en las instrucciones interpretativas de la Fiscalía, como acredita Perona Gómez, 2019) la sujeción de los conductores de los VMP a las reglas generales de la conducción de vehículos, previstas en la Ley de Tráfico y en su desarrollo reglamentario (RGV y RGC).

Hoy, como nota diferenciadora entre los VMP y los vehículos a motor en sentido estricto, los conductores de los primeros están exentos de contar con una licencia o permiso personal de circulación para su manejo. Así lo prevé la normativa estatal ya mencionada (además, de forma consistente desde la primera Instrucción 16/V-124 hasta el RD 970/2020). Pero ello no impediría, en principio, que los municipios exigieran alguna autorización subjetiva para su uso en las vías de su competencia.

La principal característica subjetiva que ha sido omitida en la regulación estatal es la edad de los potenciales conductores de VMP. Esto da lugar a una actual disparidad notable de previsiones entre unos y otros municipios. Es cierto que el rango no es muy amplio –Pamplona serviría de ejemplo del más bajo, a los catorce años, y Barcelona, Burgos o Cáceres del más alto, a los dieciséis (Norauto, 2020: 7-9; Romero *et al.*, 2019)–. De las ciudades que nos interesan, la edad sirve de criterio no solo para establecer prohibiciones concretas a usuarios por razón de su edad, sino también habilitaciones explícitas u obligaciones circunstanciales.

Las habilitaciones especiales por razón de la edad han sido recogidas, primero, por las ordenanzas de Hospitalet de Llobregat y de Gijón con efectos sobre cualquier tipo de actividad, y, segundo, por la normativa de Vitoria circunscribiendo la restricción etaria al ejercicio de actividades económicas. Las normas e iniciativas normativas de Valladolid y de Vigo guardan silencio en este sentido, por el momento, y sus previsiones sobre la edad para el uso de bicicletas u otros análogos no son extrapolables a los VMP.

La norma hospitalense indica que no existe un claro límite de edad que impida su uso. No obstante, parece que, como excepción, los menores de 12 años (art. 18.16) podrían circular con bicicletas o VMP por las aceras, siempre que respeten el paso de peatón y estén acompañados de adultos (peatones). Reglas similares prevé la ordenanza de Vitoria (de 2013) para el uso de bicicletas, pero sin regla explícita de analogía extensible a los VMP, como es el caso de la ordenanza de Hospitalet de Llobregat (art. 19). Por otro lado, los menores de 16 años están obligados a llevar casco protector, sea cual sea la vía por la que circulen, siendo solo recomendable para el resto de usuarios (igual sucede en Madrid, por ejemplo, o en municipios más pequeños, como Almuñécar –*víd.* Romero *et al.*, 2019–).

La regulación de la edad por la que se ha inclinado el proyecto de ordenanza de Gijón parece un intento de optar por un método avanzado de regulación de los aspectos etarios, y basado en una doble técnica: a) crea un primer rango jurídico que reconoce la capacidad indubitada a los ciudadanos a partir de los quince años para la conducción de los VMP; y b) añade una cláusula de habilitación a los menores de esta edad, basada en circunstancias de su capacidad natural aplicada al caso (esto es, basada en las características aptitudinales propias del sujeto en relación al objeto, como la altura o el peso del menor de quince años).

Sin embargo, aunque esta doble reglamentación debiera favorecer el realismo de la norma, añade también varias condiciones que ya han sido criticadas en normativas vigentes precedentes, por su imprecisión. Resulta que la habilitación a los menores de 15 años exige que deban "ir acompañados de un adulto y bajo la responsabilidad de sus progenitores y/o tutores". Siendo vehículos monoplazas, no resulta del todo claro qué significa el acompañamiento, o cómo opera la asignación de la responsabilidad en exclusiva a unos progenitores/tutores que no parecen ser los únicos adultos habilitados para actuar de acompañantes (pensemos, por ejemplo, en el desplazamiento en grupo con un responsable adulto usando estos vehículos hacia los centros escolares, o en colectivos realizando actividades de tiempo libre educativo). Como cláusula de cierre, los menores 15 años solo podrán conducirlos, además de cumpliendo las condiciones antedichas, "fuera de las zonas de circulación, en espacios cerrados al tráfico" de vehículos a motor.

Entre las ciudades objeto de nuestro análisis, las prohibiciones etarias vinculadas al uso para ciertos fines son expresamente contempladas solo en la norma de Vitoria (en su ordenanza de 2013). Esta norma parece indicar que el uso de VMP para actividades económicas de carga (entendiendo que es viable en el formato de mochila adaptada de algunas marcas de reparto) está limitado a las personas mayores de edad, de acuerdo a lo que indica su artículo 24. Este, aun cuando no alude expresamente a los VMP, establece tal limitación refiriéndose a los vehículos de propulsión eléctrica semejantes pero distintos de las bicicletas.

Finalmente, el elemento de la diversidad funcional, en relación con la discapacidad de cualquier índole, es motivo de especial regulación en varias disposiciones, aunque con previsiones distintas. El proyecto de ordenanza de Gijón prevé, en concreto, la prioridad de las personas con movilidad reducida sobre el resto de peatones, también cuando estas circulen sobre VMP (sin confundirlos con sillas motorizadas u otros vehículos) en vías ciclistas del tipo acera-bici (art. 35.3). Vitoria, en el artículo 21 de su ordenanza de 2013, también alude a la prioridad de las personas con diversidad funcional respecto del resto de usuarios de las vías, con independencia de la forma de desplazarse que tengan.

4.3.3. Los requisitos materiales y otros factores objetivos condicionantes

Las normas de las ciudades objeto de estudio contemplan reglas bastante dispares sobre las exigencias que deben reunir los VMP para circular en su ámbito.

Sobresalen dos conjuntos de previsiones dignas de mención. En primer término, encontraremos las exigencias relativas a elementos que no han sido determinados por la normativa estatal (nótese que el requisito frecuente de sistemas de frenado adecuados para los VMP es de alusión innecesaria en la actualidad, dadas las exigencias de homologación de estos vehículos en el ámbito estatal). En segundo término, identificamos la especificación de condiciones objetivas que justificarían la retirada de estos vehículos por las autoridades municipales, al considerar que están en condiciones de abandono.

Por un lado, la normativa de Hospitalet y de Gijón contempla unos requisitos detallados, equiparables a las exigencias de ciudades como Madrid, Valencia o Pamplona (Norauto, 2020). Este grado máximo de previsión (para Hospitalet de Llobregat y Gijón) es el que prevé la exigencia expresa de sistema de frenado adecuado, timbre, iluminación frontal y trasera, y elementos reflectantes o catadióptricos homologados traseros y laterales (art. 18.11 de la ordenanza hospitalense de 2015, y art. 50.6 del proyecto de Gijón aprobado en 2021). La regulación hospitalense hace especial mención al uso de los elementos de iluminación y reflectantes como requisitos indispensables para circular en ciertas condiciones de visibilidad reducida, sea cual sea la causa –tipo de vía, condición meteorológica u horario nocturno, por ejemplo–.

Por otro lado, Valladolid solo dispone de una cláusula residual, a lo sumo de aplicación por analogía, procedente de la regulación de las bicicletas, acerca del “timbre que los conductores harán sonar siempre que haya viandantes o vehículos a los que puedan alcanzar” –art. 43.f) del Reglamento de circulación de 2005–. El timbre ha sido concebido como elemento recomendable, no obligatorio, por las normativas de otras ciudades aplicables a algunos de los tipos de VMP, ni siquiera a todos ellos (Norauto, 2020).

Finalmente, la actual normativa conocida y proyectada de Vigo y Vitoria no prevén ningún elemento exigible más allá de los mínimos impuestos por la aplicación directa de la normativa estatal. La ordenanza hospitalense es la que recoge una definición más precisa de “estado de abandono” de uno de estos vehículos: cuando, encontrándose en la vía pública, carezca de dos o más elementos indispensables para su funcionamiento. Los arts. 155 al 158 del proyecto gijonés regulan de forma exhaustiva las condiciones de la retidada de los VMP, pero solo anota que el abandono pueda ser presumido “racionalmente” por las autoridades municipales competentes.

En Vigo, por último, es hoy de aplicación a los VMP las mismas reglas sobre consideración del abandono que para el resto de vehículos, según se desprende del artículo 23 de su ordenanza de 1993.

4.4. Las condiciones modales

La insuficiencia de la regulación estatal motivó que no pocas de las ordenanzas que contemplaban la circulación de los VMP antes de 2020 contuvieran aspectos hoy reiterativos, como la prohibición de usar dispositivos móviles o auriculares durante su conducción (Romero *et al.*, 2019), o incluso parcialmente contradictorios, como la prohibición de circular por la calzada. Nos interesan aquellas que suscitan distinciones entre los municipios elegidos.

Algunas reglas municipales sobre la conducción de estos VMP son genéricas e independientes de cualquier factor exógeno. No son muy numerosas, y en ocasiones se aplican por analogía (por indicación explícita o implícita). Pero, por ejemplo, la normativa vallisoletana incluye cláusulas de este tipo, como el deber de los conductores de controlar “en todo momento” el propio vehículo, y “adoptar las precauciones necesarias para la seguridad” del resto de usuarios de las vías (art. 5.2 del Reglamento de 2005), o la obligación de mantener “el campo necesario de visión y la atención permanente a la conducción, que garanticen la propia seguridad (…) y la de los demás usuarios de la vía” (art. 6.1). Por otro lado, algunas reglas son de aplicación discutible a los VMP, o al menos no tan evidente, como las del artículo 43 del mismo Reglamento, que exige a los conductores de bicicletas (quizá teleológicamente extensible a los de VMP) “circular lo más cerca posible de los bordillos de aceras y paseos”, y no pueden circular “sujetos a cualquier otra clase de vehículos” (art. 48.2), algo que también prevé prohibir el consistorio de Vigo, según Melchor (2021). La incipiente propuesta regulatoria de esta última ciudad añade otros dos aspectos generales: la prohibición de la circulación en paralelo de varios VMP (como varias ciudades prevén ya para las bicicletas), y el transporte de animales por parte del conductor.

En todo caso, la mayoría de las normas se aplican en función del uso de los espacios y las condiciones del contexto. En síntesis, sobresalen cuatro conjuntos de regulaciones sobre el modo de uso de los vehículos que nos ocupan, que dependen de factores exógenos. En primer lugar, la materia que es objeto principal de la atención de las normas municipales es la regulación de formas de circulación de los VMP condicionadas a los tipos de vías que existen en cada localidad y a otros factores externos (meteorología, ocupación síncrona del espacio, etc.). En segundo lugar, merecen mención aparte, aunque está estrechamente vinculado con lo anterior, las reglamentaciones alusivas al uso del espacio para el estacionamiento de estos vehículos. En tercer lugar, son frecuentes las previsiones sobre el uso de elementos de protección y visibilización por parte de los conductores, en función de diversas circunstancias del contexto. En cuarto y último lugar, no es extraño encontrar algunas reglas aplicables al uso específico de los VMP para diversas actividades económicas.

4.4.1. Las condiciones de circulación en función de los tipos de vías

El tipo de vías por las que se puede circular aparecen reguladas con tres técnicas: una de preferencia de estos vehículos frente al resto, otra de habilitación del uso de las vías y espacios, y una tercera de prohibición expresa de circulación por otras vías.

En relación el uso preferente de algunas vías por parte de los VMP está asentado en la mayoría de ordenaciones que los contemplan de forma explícita, pero también en aquellas que pueden ser de aplicación por analogía implícita. Este último caso es el de la regulación hospitalense, por ejemplo, donde (si la analogía es válida) ciclistas y conductores de VMP tendrían preferencia frente a los demás vehículos cuando circulen por vías reservadas a bicicletas o en caminos vecinales. Previsión similar recoge el artículo 43 del mismo Reglamento de Valladolid de 2005. Como es habitual, el artículo 32 de esta norma vallisoletana aclara que las bicicletas tienen una prioridad sobre el resto de vehículos en las áreas residenciales, pero no la tienen sobre los peatones. Por su parte, Gijón (en su proyecto) contempla como plataformas especialmente reservadas a los VMP (junto a otros, como bicicletas y ciclos) tres tipos concretos de vías: los carriles-bici, las aceras-bici, y las sendas ciclables (art. 26 del proyecto). También habilita a estos vehículos (VMP, bicis y ciclos) el acceso a áreas de prioridad residencial, excepcionando la restricción horaria prevista con carácter general para el resto de vehículos. Igualmente, y por razones obvias, el artículo 34.5 del proyecto prevé la eventual exclusión de los VMP (entre otros muchos tipos de vehículos) de la aplicación de medidas restrictivas de tráfico o de la prohibición de estacionamiento en los supuestos de ordenaciones temporales por motivos medioambientales.

El grueso de las previsiones normativas se centra en el establecimiento de condiciones específicas para la circulación en función de la vía. El artículo 51.1 del proyecto de Gijón precisa las únicas vías por las que podrán circular los VMP. Esta previsión consta de dos reglas generales, aplicables a todos los VMP, dos reglas particulares condicionadas (que excluyen a los VMP de una sola rueda), y una cláusula de aplicación supletoria de las reglas previstas para las bicicletas y otros ciclos –art. 51.1.e)–. Las dos primeras reglas, aplicables a todos los VMP, suponen que estos pueden circular por: a) carriles bici segregados, sin rebasar la velocidad máxima de 15 km/h también prevista para las bicicletas; y b) por acera bici, a una velocidad no superior a 10 km/h.

Las dos reglas particulares, que excluyen a los VMP de una sola rueda, permiten a los demás circular por otras vías, siempre que “no se haga a una velocidad anormalmente reducida”, y con esta condición pueden circular por: a) las calzadas que tengan la velocidad limitada a 30 km/h; y b) por el carril limitado a 30 km/h, si existe, en aquellas calzadas de varios carriles. En sintonía con este mecanismo, la propuesta normativa de Vigo parece apuntar en la misma dirección. De aprobarse la inicial propuesta del gobierno municipal, parece que el uso de los VMP estaría condicionado a distintos límites de velocidad en función de la vía por la que circulen: a) por las zonas residenciales –de prioridad peatonal– a un máximo de 10 km/h, reduciéndose o desmontando si la falta de espacio lo aconseja; b) por carriles bici y sendas ciclables, a un máximo de 20 km/h; y c) por carriles-bus y por las vías ordinarias con velocidad máxima a 30 km/h, al máximo de su capacidad legal, es decir, a 25 km/h. Distanciándose parcialmente de la pretensión de la DGT, de impedir la circulación de los VMP por las zonas peatonales, con carácter general, la reglamentación de Vitoria permite interpretar un uso autorizado de los VMP de forma excepcional en zonas peatonales, siempre que adapten su conducción a un especial cuidado hacia los peatones (art. 10.9), dada la forma abierta de referirse a vehículos entre los que podrían encontrarse los que nos interesan en este estudio.

Un último factor exógeno que habilita el uso de ciertas vías en determinados momentos, dependiendo del estado específico en el que estas se encuentren, es la reglamentación de la circulación en función de la existencia de aglomeraciones. La regulación de Hospitalet de Llobregat define esta circunstancia como la imposibilidad de guardar un metro de distancia entre vehículos –bicis o VMP– y peatones, o la imposibilidad de circular 5 metros seguidos en línea recta, preferentemente por el centro de la vía. Tal situación permite deducir para los VMP, con las cautelas expuestas, la posibilidad de ser utilizados en dos grandes conjuntos de espacios o vías. Las aglomeraciones no son relevantes para la circulación de los VMP en Hospitalet por vías no peatonales: a) expresamente en pasos reservados exclusivamente a bicicletas (art. 18.5); b) calzadas, pero por la zona más próxima a las aceras (art. 18.4); y c) carriles-acera, aunque con la velocidad limitada a 10 km/h (art. 18.9). *Sensu contrario*, las aglomeraciones impiden la circulación, por lo demás permitida, en: a) parques y áreas peatonales; b) caminos vecinales de plataforma única de preferencia peatonal (siempre que guarden el sentido de circulación de los vehículos); y c) calles vecinales de uso exclusivo de peatones, en ambos sentidos de circulación.

Finalmente, las prohibiciones completan la técnica de reglas que condicionan la circulación de los VMP en las distintas reglas municipales. Una primera prohibición llamativa de las regulaciones analizadas es la relativa a la circulación por las calzadas. Tanto la normativa de Hospitalet de Llobregat expresamente dictada para los VMP (art. 19 de la Ordenanza de 2015), como las disposiciones susceptibles de aplicación teórica a los “patines” y “patinetes” en la reglamentación vallisoletana (art. 48 del Reglamento de 2005), impiden, aparentemente, la circulación de estos vehículos por la calzada, como regla general.

Tal regla contradice la previsión estatal. Esta singularidad, interpretada de forma restrictiva, podría conducir a la práctica imposibilidad de circular por ambas ciudades con VMP, al concurrir las restricciones generales estatales con esta del municipio, sin exista una contradicción invalidante de una sobre otra, en sentido estricto. Por el contrario, si en Valladolid aplicaran las reglas de las bicicletas a los VMP, el artículo 34 de su Reglamento de 2005 prohíbe expresamente "la circulación sobre las zonas destinadas a peatones" (algo ya insistentemente recomendado por la DGT desde 2016, y que el proyecto de Vigo parece contemplar de forma expresa para los VMP).

La interpretación más coherente con el espíritu de la norma vallisoletana de 2005 es, por tanto, que la aplicación de las reglas a los VMP está condicionada a su redefinición como "vehículos" ciertamente conducidos, y no como instrumentos de desplazamiento de "peatones", lo que hace que solo las reglas que sean compatibles con tal conceptualización serán aplicables a estos (la prohibición de circular por la calzada no lo sería).

4.4.2. Las reglas sobre el estacionamiento

En cuanto al estacionamiento de VMP, la tendencia emergente en las regulaciones es reflejo de las normas ya contempladas para las bicicletas, mediante el establecimiento de una regla general de estacionamiento preferente, otra regla subsidiaria y una prohibición explícita. Este es el caso de la Ordenanza de Hospitalet de 2015 (art. 18.14), actualizada en el proyecto de Gijón (art. 110).

La regla de estacionamiento preferente es que se produzca en lugares expresamente habilitados. El artículo 128 de la regulación gijonesa prevé, además, reservas especiales de aparcamiento para bicicletas, ciclos y VMP. Solo cuando estos no existan (regla subsidiaria), "podrán estacionar en las bandas de estacionamiento, en forma oblicua a la línea de acera y ocupando un máximo de 2 metros, de forma que no se impida el acceso a otros vehículos o el paso desde la acera a la calzada".

El mismo precepto hospitalense antedicho impide el estacionamiento donde no puedan hacerlo tampoco los vehículos a motor ordinarios (zonas de carga y descarga, estacionamientos para personas con movilidad reducida, etc.), así como anclándolos al mobiliario urbano, elementos adosados a las fachadas o en los estacionamientos del servicio público de bicicletas. Se distancia de este planteamiento el proyecto de Gijón. Es cierto que la normativa proyectada prohíbe, con carácter general, el anclaje de los VMP (y del resto de vehículos equivalentes mencionados) a "elementos de señalización, elementos vegetales, bancos, marquesinas" u "otros elementos de mobiliario urbano" (art. 110.5).

Pero, "excepcionalmente" ("cuando no existan aparcamientos disponibles en un entorno de 200m"), los VMP y las bicicletas podrán ser ancladas a "callas o elementos del mobiliario urbano" cumpliendo cuatro requisitos: "a) no altere la funcionalidad del elemento del mobiliario urbano; b) no ocasione ningún daño ni implique deterioro del patrimonio público; c) no se entorpezca el tránsito peatonal, la accesibilidad ni la circulación de vehículos; d) no dificulte ni impida la realización por los servicios municipales de tareas de mantenimiento o reparación de tales elementos delimitadores y de mobiliario urbano" (art. 110.6).

La regulación es exhaustiva, más allá de estas previsiones, y añade un régimen de prohibición general de estacionamiento: "a) en el ámbito peatonal de las paradas de transporte público; b) en el ámbito peatonal de las reservas de personas con movilidad reducida; c) en el ámbito peatonal de las paradas de taxi; [y] d) sobre tapas de registro o de servicios". Prueba de la exhaustividad de esta es la cláusula que contempla que los usuarios de VMP están obligados, además, a desmontar del vehículo en aceras y zonas peatonales, hasta llegar al "elemento de anclaje" si este se encuentra en tales espacios (art. 110.4 del proyecto de Gijón).

A diferencia de las previsiones recientes, las normas anteriores a 2010 conservan una equivalencia de regulación del estacionamiento entre los VMP y los vehículos a motor. Este es el caso de la ordenanza de Vigo de 1993, que ordena de forma indistinta el uso que puede dar lugar a la retirada por estacionamiento incorrecto (arts. 20 a 22) o por su abandono (art. 23). Nada distinto significativo aportan las normas de Valladolid o Vitoria.

4.4.3. Los elementos de protección y señalización para la conducción de los VMP

Sobre el uso de elementos de protección, y al margen de las exigencias a ciertos sujetos por razón de su edad, ya mencionadas, el casco es considerado con cada vez más frecuencia como obligatorio (véase, por ejemplo, el artículo 18.19 de la ordenanza hospitalense). El texto de Gijón de 2021, en su artículo 50.5, aboga por una exigencia generalizada de la utilización de casco de protección a las personas conductoras de VMP cuando circulen por la calzada. Además, el apartado 6 del mismo precepto contempla la exigencia, también a los conductores, de portar "alguna prenda o elemento reflectante" cuando "sea obligatorio el uso del alumbrado" (es decir, en función de la visibilidad). La mayoría de estas reglas aplicables a los conductores de los VMP son una trasposición o extensión por analogía de las normas dadas para los ciclistas. Estos, en Valladolid (según el Reglamento de 2005) "deberán ir provistos de un sistema de señalización luminosa delantero y trasero que permita su visibilidad por otros conductores". En el mismo sentido se pronuncia la normativa de Vitoria de 2013, aunque no es fácil determinar la obligatoriedad estricta para los conductores de VMP.

4.4.4. Las exigencias especiales en función del uso económico de los VMP

A juicio de la mayoría de autoridades locales, el uso de los VMP con fines distintos del desplazamiento privado de personas hace aconsejable el establecimiento de reglas diferenciadas, que ordenen un el uso de los mismos para determinadas actividades económicas.

En la normativa de Vitoria de 2013, aun sin mencionarlos expresamente, una cierta apertura expresiva invita a aplicar las reglas sobre el uso de los VMP como vehículo de reparto a las normas generales de horarios y limitación de zonas para estas operaciones de carga y descarga, como prevé el artículo 12.1.2 para las bicicletas y otros vehículos de tracciones eléctricas no convencionales. Esta idea ha sido expresamente incorporada por el proyecto de Gijón (art. 85), reconociendo el papel que ya desempeñan en el abastecimiento de comida a domicilio, o servicios de mensajería, cuando los conductores portan mochilas aptas para tal carga. El Ayuntamiento de Vigo anunciaba su propuesta en similares términos. Este último, sin embargo, contemplaba la posibilidad de exigir la tramitación de una autorización específica para otros usos económicos, como las actividades de ocio o turismo. Sin diferenciar el sector de actividad, Gijón opta por exigir solo la suscripción de un seguro de responsabilidad civil obligatorio, que responda de daños a terceros (art. 50.7), para poder destinar el VMP a cualquier actividad económica. Pero en la línea de la exhaustividad de la que esta normativa hace gala, también ordena de forma pormenorizada el uso de los VMP destinados al arrendamiento, entre los artículos 77 al 79 y 82. Exige a las empresas la existencia de estaciones fijas para su estacionamiento, debidamente reservadas en el suelo público, o el sometimiento periódico a controles y especiales actividades de mantenimiento preventivo, entre otros aspectos. También impone, para su uso turístico, que los titulares de la explotación se responsabilicen de que no accedan al uso del VMP personas que carezcan de la “habilidad mínima” que garantice su seguridad y la de terceras personas, y el apartado 5 del mismo precepto limita a 15 personas el máximo de los desplazamientos organizados por empresas de turismo (art. 82).

5. CONCLUSIONES

La investigación realizada ha permitido esclarecer la maraña jurídica que envuelve a la movilidad urbana sostenible y en particular a los VMP. Así, se ha determinado el esquema básico normativo relacionado con ambos conceptos, desde los artículos de la CE que tocan aspectos relacionados con la movilidad a la situación de la legislación estatal y autonómica en vigor, y concluyendo con la comparativa entre la regulación municipal (Tabla 1).

<table>
<tr><th>Ciudad</th><th>Principal normativa estatal</th><th>Principal normativa autonómica que puede afectar a los VMP</th><th>Ordenanzas que afectan especialmente a los VMP</th><th>Planes de movilidad</th></tr>
<tr><td>Gijón</td><td rowspan="5">∗Ley 6/2015, de tráfico
-Reglamento General de Circulación
-Reglamento General de Vehículos

∗Otra normativa en materia de movilidad:
-Ley 37/2003, del Ruido
-Ley 34/2007, de Calidad del Aire y Protección de la Atmósfera
-Ley 2/2011, de Economía Sostenible</td><td>Ley 12/2018, de Transportes y Movilidad de Asturias</td><td>2021</td><td>2018</td></tr>
<tr><td>Hospitalet de Llobregat</td><td>Ley 9/2003, de Movilidad de Cataluña
DL 1/2009, Ley de Urbanismo de Cataluña</td><td>2015</td><td>2014</td></tr>
<tr><td>Valladolid</td><td>Ley 9/2018, de Transportes Públicos de Viajeros de Castilla y León</td><td>2005 y 2015</td><td>2004</td></tr>
<tr><td>Vigo</td><td>-</td><td>2013</td><td>2014</td></tr>
<tr><td>Vitoria</td><td>-</td><td>1993</td><td>2007</td></tr>
</table>

Tabla 1. Esquema normativo actual de las ciudades estudiadas. Ninguno de los planes de movilidad en vigor alude de forma directa a los vehículos de movilidad personal.

El análisis de la evolución del corpus normativo permite afirmar que la regulación de ámbito estatal en materia de VMP ha llegado tarde, solo precedida por orientaciones y disposiciones administrativas de alcance controvertido y sin aclarar de manera suficiente aspectos esenciales que han provocado confusión a diversas autoridades municipales. No obstante, la reforma del Reglamento General de Vehículos y del Reglamento General de Circulación, mediante el Real Decreto 970/2020, de 10 de noviembre, ha supuesto una importante actualización de alcance estatal, que condiciona la normativa autonómica y municipal. Este punto de inflexión aún no se ha completado, a la espera de la adopción, por la Dirección General de Tráfico, de un importantísimo "Manual de características de los vehículos de movilidad personal", que condicionará la implantación de certificaciones de estos vehículos (por tanto, la plena eficacia de las disposiciones de 2020 es muy probable que se demore hasta 2023, al menos).

En paralelo a este retraso, y en virtud de sus competencias expresamente reconocidas por la legislación aplicable, los municipios se han dotado de normas para hacer frente a los riesgos de la circulación de los VMP o el fomento de formas de movilidad sostenible de manera heterogénea, ya con anterioridad a la promulgación de la reforma reglamentaria estatal. Pero el tamaño de los municipios no parece ser determinante en la diligencia con la que las autoridades locales han abordado la cuestión, ni en las soluciones que han adoptado. Con independencia del tamaño de los municipios, existen casos en los que las reglas específicas sobre los VMP son aún inexistentes o muy limitadas, cuando no directamente incompatibles o incongruentes con la ordenación estatal de 2020, frente a otros que han abordado la cuestión de forma exhaustiva y pormenorizada.

En ese sentido, y de manera no explícita, las regulaciones municipales parecen obedecer a una sistemática de tres ejes: en qué condiciones un individuo puede conducir un VMP (previsiones subjetivas); qué requisitos adicionales a los previstos ya de forma genérica para su comercialización en todo el país deben reunir estos vehículos, materialmente, para poder ser utilizados (previsiones objetivas); y qué reglas rigen para su uso en los distintos espacios públicos urbanos y en qué circunstancias (previsiones modales).

Entre las condiciones subjetivas para el uso de los VMP sobresale la opción mayoritaria por no exigir permisos específicos de circulación a los conductores, aunque la edad puede condicionar su manejo. Tampoco existe un criterio unificado ni coherente sobre tal edad de los sujetos que pueden conducirlos, o en qué condiciones especiales en función de su edad.

Además, de las previsiones técnicas objetivas que estos VMP deben reunir, que no sean obligatorias de forma generalizada por indicación de la normativa estatal, destacan las previsiones relacionadas con la seguridad del vehículo (elementos lumínicos y reflectantes, sistemas de alerta sonora como timbres, etc.).

Por otra parte, las disposiciones que regulan su circulación son las más detalladas en el ámbito de las normas municipales, posiblemente porque los aspectos técnicos de los vehículos son ya considerados de forma detallada por las reglas de certificación europeas y las exigencias estatales reglamentarias, que dejan deliberadamente a las autoridades municipales la regulación de las formas de uso que sean acordes los tipos de vías y condiciones específicas de cada localidad.

El estudio detallado de la normativa municipal analizada ha permitido comprobar que las disposiciones sobre los modos de circular en las ciudades abordan, con carácter general, cuatro conjuntos de previsiones:

a) sobre las condiciones en distintos tipos de vías, adaptando las reglas de seguridad, impidiendo el acceso a algunas de ellas o exigiendo requisitos subjetivos u objetivos especiales según el espacio y o el contexto (visibilidad, aglomeraciones, etc.).
b) sobre el estacionamiento de estos vehículos en la vía pública, tratando de preservar –en las reglas más detalladas– la integridad del mobiliario urbano y la prioridad del uso de las aceras por los peatones.
c) sobre los concretos elementos de protección y señalización para la conducción de los VMP, adaptados al tipo de uso, del usuario y del espacio en el que se use.
d) sobre diversas exigencias específicas en función de la finalidad con la que sean utilizados los VMP, destacando reglas de revisión y control adicionales para usos

económicos, normas de prevención y similares. Conviene apuntar que, en las regulaciones que más atención prestan a estos vehículos, se acude de forma creciente a la técnica autorizatoria para su uso con fines de lucro, en el contexto de actividades económicas tanto de reparto como de turismo o alquiler de corta duración.

En relación a las ciudades analizadas, Gijón se ha dotado (hasta el momento) de la normativa más detallada sobre estos vehículos, y con numerosas previsiones que flexibilizan su uso a diversas circunstancias de los sujetos, de los vehículos y del espacio en el que circulan. Aún pendientes de las evidencias que arroje su aplicación en los próximos años, el grado de detalle y precisión técnica de la normativa gijonesa puede convertirla en un referente para otras ciudades españolas. Tras ella, Hospitalet de Llobregat dispone de la siguiente regulación con más normas directamente aplicables a los VMP, al menos por una regla de analogía explícita, pero con algunas cláusulas ya no plenamente coherentes con la ordenación estatal de 2020. Vitoria, Vigo y Valladolid no cuentan con un régimen jurídico claro para la ordenación eficiente de estos vehículos, y sería más que recomendable la revisión de sus normas de circulación.

Una de las cuestiones llamativas de la regulación estatal es la escasa exigencia hacia los municipios para que se doten de redes especialmente diseñadas para los VMP. Así como hay legislación en materia de accesibilidad universal, y así como hay determinadas exigencias en materia de urbanismo para considerar que un espacio determinado puede ser considerado un solar -por ejemplo, el acceso rodado-, también podrían determinarse una serie de condiciones para garantizar la existencia de redes.

En este sentido sorprende la prohibición de que los VMP no circulen por túneles urbanos, cuando sería más lógico determinar qué requisitos deben cumplir los túneles urbanos para poder ser usados por los VMP, y exigir dichos requisitos a los túneles urbanos futuros. Lo mismo sucede con la prohibición de que puedan circular por travesías, cuando la realidad de muchas poblaciones de pequeño tamaño es que la travesía es de facto la calle principal del municipio -si no la única-. Consideramos, por ello, que la irrupción de los VMP podría ser aprovechada para subsanar el histórico retraso de España en materia de construcción de redes ciclistas (Plasencia Lozano, 2021), impulsando desde los distintos poderes legisladores determinadas reformas de las leyes urbanísticas, de movilidad o accesibilidad que condujeran a la creación de una auténtica tercera malla urbana y regional segregada de las otras dos existentes (peatonal y de tráfico rodado).

Finalmente, la cronología de la normativa de los VMP ha puesto de manifiesto la brecha temporal existente entre el desarrollo tecnológico de estos vehículos y su regulación. Esta cuestión deja el campo abierto a investigar si ese retraso entre la difusión masiva de determinados vehículos y la generación del corpus normativo relativo a su uso también se produjo con otros vehículos (automóviles, autobuses, motocicletas) o si sucede lo mismo en otros modos de transporte (aviones, ferrocarriles), y caso de ser así, qué plazos existieron entre la difusión amplia de la nueva tecnología asociada al transporte y su regulación. Al respecto, podemos recordar que el Plan de Innovación para el transporte y las infraestructuras 2017-2020 sí incluía una sección completa sobre el Hyperloop como nuevo paradigma del transporte, pese a que dicha tecnología estaba dando sus primeros pasos cuando dicho plan fue redactado, y, sin embargo, nada decía de los VMP (aunque sí de las bicicletas).

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MEDICIÓN DE $PM_{2,5}$ SEGÚN LAS CONDICIONES DEL TRÁFICO EN EL CENTRO DE MADRID MEDIANTE UN DISPOSITIVO MÓVIL

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RESUMEN

El control de la calidad del aire en las ciudades es uno de los grandes retos en los próximos años. La ciudad de Madrid, como muchas otras ciudades del mundo, cuenta con un sistema de monitorización de la calidad del aire mediante estaciones fijas de medición. Distintos estudios defienden la idea de que los modelos de este tipo presentan ciertas carencias en cuanto a representatividad de la información generada. En este trabajo, se ha evaluado la calidad del aire en ciertas calles de Madrid mediante el uso de sensores móviles. Para ello, se ha diseñado una ruta, analizando las concentraciones de $PM_{2,5}$ agrupadas en los tramos de la ruta. La recopilación de datos mediante un sensor móvil permite una cobertura homogénea de datos en la ruta, gracias a la cual se han mapeado las zonas con mayor riesgo de presentar concentraciones elevadas. Así mismo, se han comparado los resultados dentro y fuera de Madrid Central y se ha estudiado la relación entre las concentraciones de $PM_{2,5}$ con factores meteorológicos y condiciones del tráfico. A pesar del bajo coste de esta tecnología, se han obtenido mediciones de calidad aceptable que pueden ser complementarias a las realizadas con las estaciones fijas del Sistema de vigilancia de la Calidad del Aire del Ayuntamiento de Madrid.

1. INTRODUCCIÓN

1.1 La contaminación en las ciudades

La contaminación se considera uno de los problemas más acuciante en las grandes ciudades, debido a las grandes concentraciones de población expuesta..

Estudios científicos señalan a la contaminación ambiental como causante de la muerte de 6,4 millones de personas en el mundo en 2015 (Landrigan, 2017). Por otro lado, el Banco Mundial estimó unas pérdidas relacionadas con la contaminación de 225.000 millones de dólares en 2016 y la Agencia de Protección Ambiental del Gobierno de los EE.UU. (EPA), la considera un factor de intensificación de las consecuencias del cambio climático.

El tráfico en sí, los atascos y la presencia de bloques continuos de edificios y construcciones altas provocan los llamados *street canyons*, que bloquean la dispersión de las emisiones y dan lugar a altas concentraciones de contaminación (Wu et al., 2017). Esta contaminación atmosférica engloba la presencia de distintos elementos potencialmente peligrosos para los seres vivos que habitan en las ciudades. Estos elementos se presentan en dos estados, gaseoso y sólido (partículas). Los contaminantes gaseosos en los que se centra la OMS en sus Directrices de calidad del aire (OMS, 2005) son el dióxido de nitrógeno (NO_2), el ozono (O_3) y el dióxido de azufre (SO_2). El NO_2 es un gas emitido principalmente en procesos de combustión y fertilizantes y es particularmente peligroso en condiciones de humedad debido a que, en combinación con el agua, genera ácido nítrico, el causante de la lluvia ácida. Por su parte, el O_3 es un fuerte oxidante que se presenta de forma natural en la estratosfera en concentraciones variables, pero su presencia en la troposfera está directamente relacionada con las actividades humanas (Godish et al., 2018) y se considera uno de los contaminantes secundarios más problemáticos de cara al futuro, por sus daños, tanto para el hombre, como para la vegetación (Calderón-Guerrero et al., 2013). Por último, el SO_2 es un gas cuyas principales fuentes de origen son la quema de combustibles fósiles ricos en sulfuro para calefacción doméstica, generación de energía y en vehículos motorizados.

Además, existen otros contaminantes gaseosos que generan preocupación a expertos de todo el mundo, como los compuestos orgánicos volátiles (COVs), importantes precursores del ozono troposférico (Camargo et al., 2015). Todos ellos provocan afecciones al ser humano, relacionadas con problemas respiratorios principalmente.

Las partículas en suspensión que se estudian en materia de contaminación ambiental son las que tienen un tamaño menor a 10 micras (PM_{10}). Según se estima, en Madrid el tráfico rodado constituye la fuente principal de emisiones de partículas. Estas provienen tanto de los tubos de escape de los vehículos a motor, como del levantamiento de capas acumuladas en el firme de rodadura por abrasión mecánica, frenos, obras de construcción y demolición, etc. Así mismo, se considera en Madrid la intrusión de aire africano como fuente probable de episodios de elevadas concentraciones (Ayuntamiento de Madrid, 2004). De ellas, las menores de 2,5 micras ($PM_{2,5}$) son capaces de llegar hasta los bronquios y en el caso de las PM_1 serían transportadas a la sangre a través de los alveolos. Recientemente, un estudio (Soldevilla et al., 2020) ha demostrado que la presencia de partículas ultrafinas está altamente relacionada con el aumento de la presión arterial. También se las relaciona con enfermedades neurodegenerativas, como consecuencia del aumento generalizado de las partículas en suspensión en los ambientes urbanos (Maher et al., 2016).

1.2 Redes de monitorización ambiental

En España, los criterios de medición y evaluación de la calidad del aire quedan dictados por el Real Decreto 39/2017 del 27 de enero, que modifica al RD 102/2011. En las grandes ciudades, de cara a solventar el problema de la contaminación atmosférica se han planteado redes de medición o Air Quality Monitoring Networks (AQMN). Las principales ventajas derivadas de una red efectiva de medición se resumen: (i) poder comparar los niveles monitorizados con los estándares establecidos por el organismo competente; (ii) prevenir el riesgo de exposición a los contaminantes monitorizados; y (iii) mitigar y controlar las emisiones de fuentes conocidas (Afshar-Mohajer et al., 2018). Generalmente, estas redes están compuestas por puestos fijos y suelen contar con mediciones históricas de largos períodos de tiempo. Sin embargo, algunos expertos (Castell et al., 2017; Munir et al., 2019) apuntan que las AQMN generalmente no son suficientemente densas. Además, según Nagendra et al. (2019) las redes de muestreo fijo no proveen variaciones espaciales de las concentraciones de los contaminantes y tienden a subestimar la exposición de los humanos.

Las concentraciones de los contaminantes pueden variar enormemente en el espacio y en el tiempo (Afshar-Mohajer et al., 2018). Consecuentemente, es importante registrar estos picos de polución. Recientes estudios (Nagendra et al, 2019) establecen que los dispositivos de medición basados en sensores *low-cost* pueden ser efectivos para capturar variaciones espaciales y temporales de los contaminantes y constituir un suplemento a las mediciones actuales. En la actualidad, existe una serie de acciones de ciencia ciudadana mediante el empleo de estos sensores *low-cost* dentro de la comunidad escolar (Calderón-Guerrero et al., 2021), que pretenden concienciar a los jóvenes de los niveles de contaminación a nivel local y ser miembros activos en la toma de datos mediante el diseño y empleo de sensores móviles.

2. LA CALIDAD DEL AIRE EN MADRID

2.1 Actuaciones recientes

En los últimos años, la preocupación social y política por la contaminación del aire, ha provocado la puesta en marcha de diversas medidas recogidas en el Plan de Calidad del Aire y Cambio Climático en la ciudad de Madrid de 2017, conocido como Plan A y reestructurado posteriormente y denominado MADRID 360 (Ayuntamiento de Madrid, 2019a). El transporte por carretera es la causa principal de 3 de los 5 contaminantes más relevantes (Ayuntamiento de Madrid, 2019b). En el Plan de 2017, en torno a un 30% del presupuesto se destinaba a las medidas dirigidas a reducir la intensidad del tráfico (154 M€), y un 60% a actuaciones sobre el parque móvil y la ordenación de sectores clave con alto impacto en la movilidad urbana (330 M€) (Ayuntamiento de Madrid, 2017). Plan A de Calidad del Aire y Cambio Climático, 2016).

MADRID 360 pretende cumplir los límites de calidad del aire establecidos en la Directiva 2008/50/CE del Parlamento Europeo y del Consejo, de 21 de mayo de 2008.

Entre otras medidas, se actúa principalmente en la movilidad. Se pretende llevar a cabo nuevas peatonalizaciones; favorecer el transporte público, con líneas cero emisiones y renovación de flotas de autobuses, el uso de la bicicleta y la moto; construir más aparcamientos disuasorios; limitar la entrada de los vehículos más contaminantes en toda la ciudad; y establecer restricciones al tráfico en la zona de emisiones bajas, atendiendo al distintivo ambiental de vehículos.

2.2 Sistema de vigilancia de la Calidad del Aire del Ayuntamiento de Madrid

Sistema de vigilancia forma parte del Sistema Integral de la Calidad del Aire del Ayuntamiento de Madrid (Ayuntamiento de Madrid, 2021). Está compuesto por 24 estaciones de monitorización que miden de forma precisa los niveles de gases y partículas contaminantes. No todas las estaciones miden los mismos contaminantes, lo que repercute en la representatividad de la información. El Sistema de Vigilancia cuenta además con captadores manuales para la determinación de contaminantes específicos y de unidades móviles de vigilancia para la realización de campañas de medición específicas.

3. OBJETIVO

Como se ha visto, la contaminación en las ciudades es uno de los grandes problemas a los que se enfrenta la ciudad de Madrid. El Sistema Integral de la Calidad del Aire está diseñado para permitir al Ayuntamiento una toma de decisiones basada en la información que aportan 24 estaciones de medición. Sin embargo, aunque la calidad de dichas mediciones en cuanto a precisión es indudable, es muy posible que se presenten deficiencias en cuanto a cantidad de puntos de muestreo y representatividad de los datos.

Por tanto, el objetivo general de este trabajo es conocer la concentración de $PM_{2,5}$ en un conjunto de calles de Madrid mediante el uso de sensores móviles. Para ello, se ha diseñado una ruta por la ciudad de Madrid y para conocer el estado de las distintas partes del recorrido, se llevará a cabo un análisis de las concentraciones agrupadas en los tramos de la ruta. Además, se caracterizarán los puntos más controvertidos dentro de los tramos mediante una malla poligonal, algo totalmente imposible mediante los métodos de información de contaminación convencionales. Del mismo modo, la recopilación de datos mediante un sensor móvil permitirá una cobertura homogénea de datos en la ruta, gracias a la cual se mapearán las zonas con mayor riesgo de presentar concentraciones elevadas. En cuanto a Madrid Central, se compararán los niveles medios observados dentro y fuera de sus límites, con el fin de conocer la efectividad de las medidas de regulación del tráfico.

Por último, se tratará de evaluar la relación entre las concentraciones de $PM_{2,5}$ observadas y las variables externas, tales como la meteorología y la velocidad del tráfico.

4. METODOLOGÍA

La metodología seguida consta de 4 fases: (i) una primera fase de selección de componentes y montaje del sensor móvil; (ii) calibración del sensor; (iii) selección del caso de estudio y de las rutas de medición, que recorren distintas calles de la ciudad, tanto dentro como fuera del área de tráfico restringido; (iv) toma de datos; (v) análisis de los datos.

4.1 Selección de componentes y montaje del sensor móvil

Se ha escogido un procesador *ARDUINO UNO*, en el que se ha montado un sensor de PM *BJHIKE HK-A5*. Se trata de un sensor láser que mide partículas desde 0.3 hasta 10 micras y se ha escogido por la sensibilidad que presenta. Además, el sensor debe contar con un GPS que registra en todo momento la latitud, longitud, hora, altitud (m) y velocidad (km/h). El dispositivo escogido ha sido un *Ublox Neo-6M*. Por último, el sensor registra datos de humedad (%) y temperatura (ºC), suministrados por un sensor DHT22 de *Adafruit Industries LCC*. Una vez conectados los diversos componentes a la placa, el sensor *CAELUS*, que es como se ha llamado, se ha montado sobre una carcasa específicamente diseñada para ello.

4.2 Calibración del sensor

Se ha realizado una calibración en campo de los datos registrados por el sensor, comparándolos con a los datos oficiales publicados por el Ayuntamiento de Madrid. Se ha realizado un circuito de tal modo que la ruta coincide con la situación de 2 estaciones con medidores de PM del Sistema de Vigilancia del Ayuntamiento de Madrid (Castellana y Escuelas Aguirre). El dispositivo lleva a cabo mediciones que coinciden en un 75% con los datos oficiales, atendiendo exclusivamente a la clase ICA a la que pertenecen. Las diferencias se deben en parte a que el dato de la estación oficial corresponde a un valor interpolado entre medias horarias. En este proceso se han constatado la capacidad del sensor para captar concentraciones pico frente al sistema de datos promedio del Sistema de Información del Ayuntamiento.

4.3 Selección del caso de estudio y de la ruta de medición

Se ha seleccionado un conjunto de calles de Madrid para realizar las mediciones que se encuentran dentro y fuera de Madrid Central. Por tanto, la ruta de medición planteada alterna salidas y entradas al recinto restringido, así como por su perímetro. Del mismo modo, se considera fundamental el paso por las estaciones del Sistema de Vigilancia del Ayuntamiento, ya que servirán para mantener una calibración de campo y asegurar en todo momento la fiabilidad de nuestras mediciones. De este modo, la ruta diseñada es la que puede observarse en la Figura 1, con un recorrido total de 17,2 km.

4.4 Toma de datos

El sensor se ha colocado en el techo de un *Mitsubishi Outlander Phev* híbrido enchufable y se han tomado datos durante 19 días.

Por otro lado, ya que se trata de factores determinantes en la calidad del aire, es necesario disponer de datos de los factores meteorológicos y el estado del tráfico correspondientes a cada uno de los días de toma de datos. Para los factores meteorológicos (velocidad del viento, temperatura, radiación solar, HR y presión atmosférica) se cuenta con los datos de las estaciones más cercanas a la ruta de medición la red de control meteorológico del Ayuntamiento de Madrid. Los datos de intensidad de tráfico media diaria (IMD) se han obtenido de la Web del Portal de Datos Abiertos del Ayto. de Madrid. En este repositorio se obtienen datos del número de vehículos que pasan por cada estación de medición, en períodos de 15 minutos.

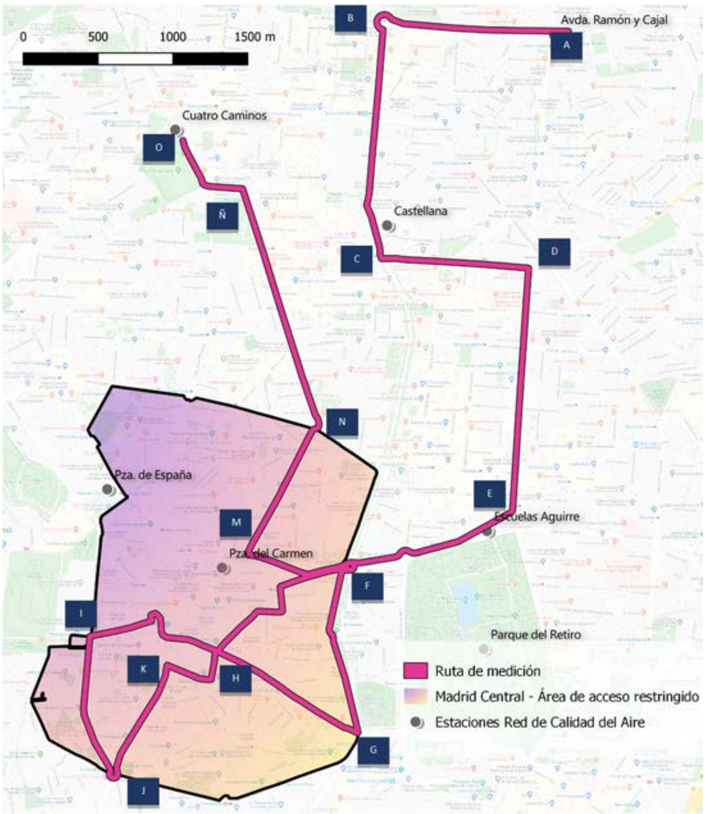

Fig. 1 – Ruta de medición

4.5 Análisis de los datos

Se han realizado varios análisis de las mediciones realizadas: (i) por tramos (Figura 2 izquierda); (ii) mediante malla hexagonal de 50 metros de apotema que contienen puntos de medición (Figura 2 derecha). De este modo, se pretende observar el comportamiento de las diversas concentraciones de contaminantes en puntos más concretos del recorrido; (iii) de altas concentraciones, mediante la generación de mapas de calor que identifiquen las zonas de mayores concentraciones en la ruta de medición; (iv) en Madrid Central, comparando los niveles medios de las concentraciones de $PM_{2,5}$ que aparecen en los tramos interiores del área de bajas emisiones (dentro de Madrid Central) frente a las medias de los tramos externos; y (v) de las variables meteorológicas externas, que pueden condicionar la aparición de patrones de aumento o descenso de las concentraciones de $PM_{2,5}$ en la ciudad.

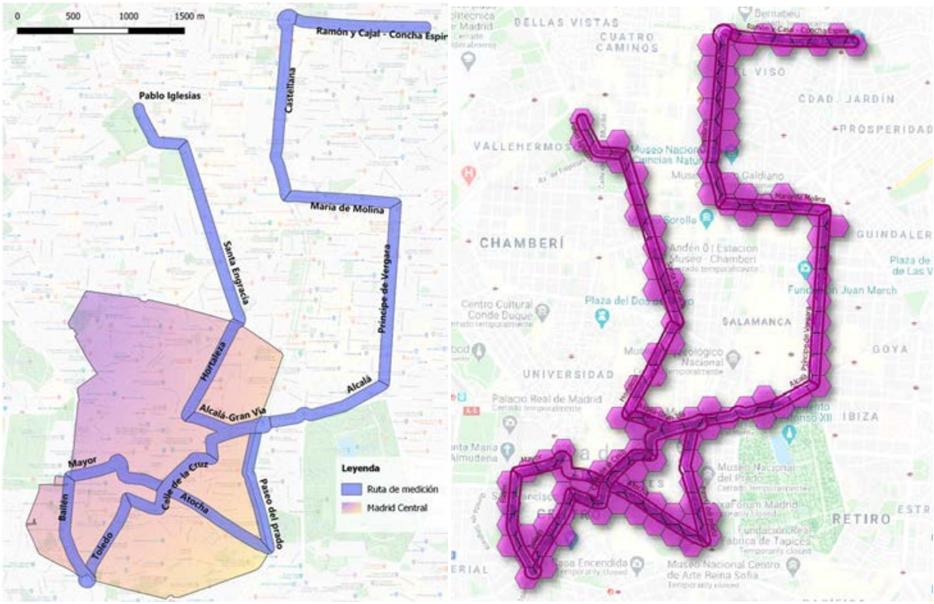

Fig. 2 – izquierda: división de la ruta en tramos; derecha: malla hexagonal

5. RESULTADOS

Atendiendo al estudio de medias por calles, las cuatro calles se superan los promedios globales en un mayor número de ocasiones son: la calle de la Cruz, el Paseo del Prado, la calle Hortaleza y la calle Mayor. Al final de la calle de la Cruz se encuentra la plaza de Canalejas, cuyo acceso está regulado por un semáforo que condiciona plenamente la circulación del único carril de esta calle. Prácticamente todos los días de medición se han encontrado dificultades de acceso a dicha Plaza de Canalejas, con retenciones continuas en la calle de la Cruz en sus 300 metros de recorrido. Este punto concreto, además, supone la sección más estrecha de la ruta, contando con un único carril y apenas cinco metros entre los edificios, lo que puede condicionar la aireación de la zona y el estancamiento de los contaminantes. La suma de los mencionados factores condiciona notablemente la movilidad y la calidad del aire en la calle de la Cruz. Casos similares con los de la calle Hortaleza (supera las concentraciones promedio en 12 ocasiones) y calle Mayor (supera en 8 ocasiones las concentraciones promedio de la ruta), presentando una mayor media global de concentración de $PM_{2,5}$ durante el período de estudio. En ella se producen frecuentes retenciones y la anchura entre edificios es de las menores de la ruta seguida.

En la Figura 3 se muestran los resultados del análisis por malla hexagonal, divididos en mapa de concentraciones medias y mapa de niveles máximos. En los valores promedio del trabajo global de medición se obtienen valores de clase “Buena” (de acuerdo a los valores del índice de calidad del aire (ICA)) de forma predominante, excepto en ciertos puntos de la ruta en los que encontramos promedios de concentraciones superiores, con la clase “Regular” e incluso “Mala”. Cabe destacar que la mayor parte de las concentraciones de tipo “Regular”, posicionadas entre 20 y 25 µg/m3, se encuentran en el interior del área de acceso restringido (Madrid Central). Respecto a los promedios correspondientes a la clase “Mala”, entre 25 y 50 µg/m^3, los principales problemas los encontramos en la calle Príncipe de Vergara, calle de la Cruz y Santa Engracia. El mapa de máximos corrobora dónde se encuentran los principales focos causantes de las altas concentraciones que puedan haberse observado en las distintas calles en el análisis por tramos. Podemos hallar picos máximos puntuales en plaza de Lima, Príncipe de Vergara, calle Atocha, la calle Mayor y la calle de la Cruz.

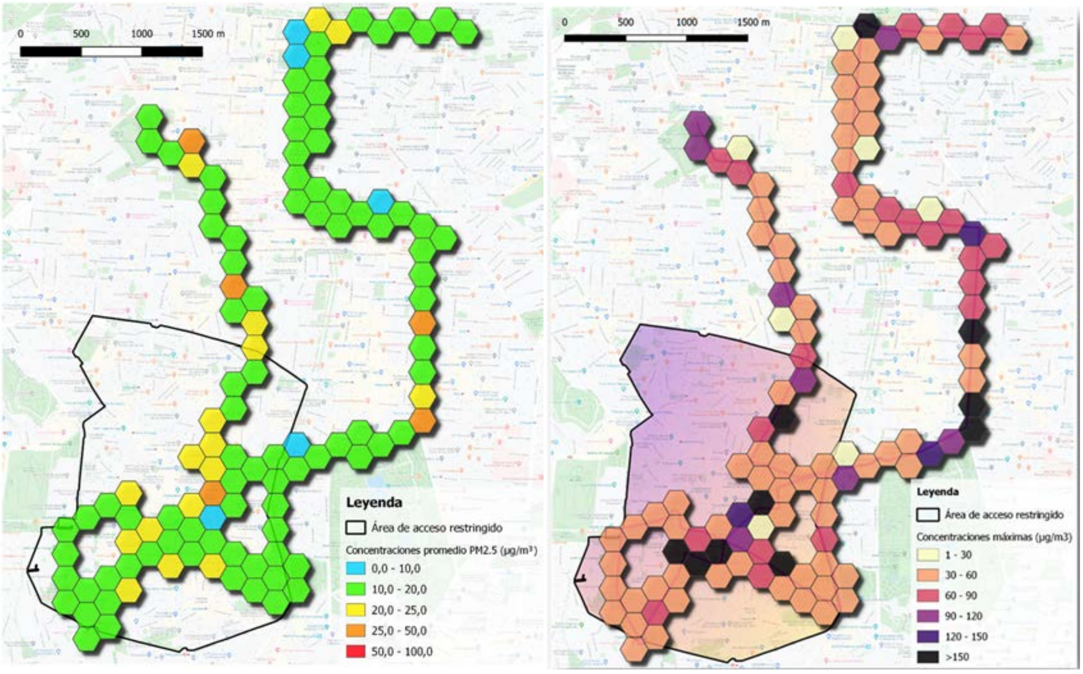

Fig. 3 – Mapas de medias globales y máximos de las concentraciones de PM2,5 sobre malla hexagonal

La Figura 4 representa el histograma de distribución de las concentraciones de PM2,5 durante el recorrido. Esta figura revela que el 30% de todos los valores recogidos se encuentra por encima de 20 µg/m3, es decir, categorías peores que “Buena”. De todos los valores de altas concentraciones, encontramos la máxima frecuencia en la franja entre 20 y 25 µg/m^3, la cual concentra un 7% de todos los valores recogidos. Mientras tanto, la clase “Mala” (entre 25 y 50 µg/m^3) recoge el 18% de las mediciones y la “Muy mala” (de 50 µg/m3 en adelante) tan sólo un 5%. Es reseñable que prácticamente un tercio de todos los datos medidos presentan una concentración entre 0 y 5 µg/m^3, es decir, con niveles de partículas extremadamente bajos.

Los focos principales de las presencias de la clase "Muy Mala" se encuentran en la Plaza de la Lima, la esquina de Príncipe de Vergara con calle Alcalá, la calle de la Cruz, la conexión entre Hortaleza y Santa Engracia (plaza de Alonso Martínez) y en la propia calle Santa Engracia. Con respecto a la situación en Príncipe de Vergara, este análisis pone de manifiesto que este se trata de uno de los puntos más problemáticos de la ruta, corroborando así las conclusiones que pueden obtenerse al analizar los promedios tanto por calle como por la malla hexagonal.

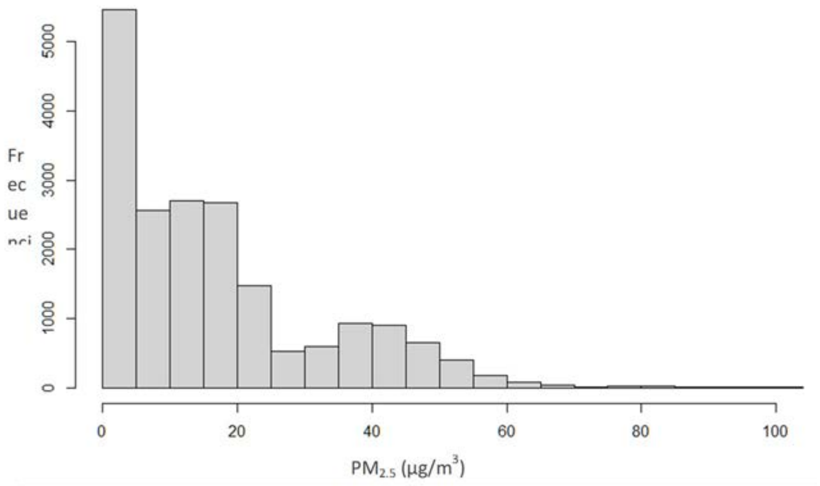

Fig. 4 – Histograma de distribución de las concentraciones de $PM_{2,5}$ durante los trabajos de medición

En cuanto a la comparación entre las medias diarias de los tramos del interior del área de tráfico restringido (Madrid Central) y los tramos externos, no se observan diferencias en los promedios entre ambos. Los datos obtenidos no respaldan una menor concentración de $PM_{2,5}$ en el interior frente al exterior. La Figura 5 muestra una comparativa de los diagramas de cajas y bigotes de las concentraciones de $PM_{2,5}$ para cada uno de los días de estudio.

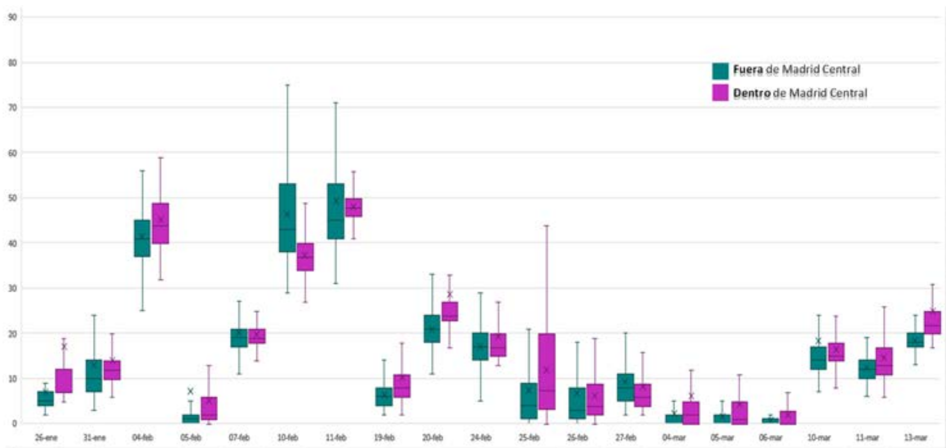

Fig. 5 – Diagramas de distribución de las concentraciones de PM2,5 durante los trabajos de medición

Con respecto a las variables externas evaluadas, el principal resultado obtenido es que únicamente la velocidad del viento muestra una tendencia clara a hacer disminuir las concentraciones de PM, al menos en los rangos de velocidades registrados. Estos resultados coinciden con algunos expertos (Wang y Ogawa, 2015). La temperatura y radiación solar no parecen estar relacionados con el aumento o descenso global de la concentración de $PM_{2,5}$. En el caso de las temperaturas, de hecho, estudios previos obtienen resultados contrarios, ya que mientras que unos aprecian una correlación positiva (Tai et al., 2010), otros defienden la hipótesis contraria (Dawson et al., 2007). La HR y la presión atmosférica deben ser analizadas con mayor profundidad. Aunque también muestran cierta tendencia a ser influyentes en los ascensos y disminuciones de los niveles de PM, la HR afecta a la sensibilidad del sensor de $PM_{2,5}$ y la presión barométrica no describe un abanico suficientemente amplio de valores para sacar conclusiones.

En la comparativa con los valores de IMD, se comprueba de nuevo que las calles con mayor nivel promedio de contaminación por $PM_{2,5}$ no se corresponden con aquellas con menores niveles de IMD. De este modo, encontramos valores promedio de IMD máximos en el Paseo del Prado y Castellana (2200 y 1700, respectivamente) mientras que los mínimos se dan en la calle de la Cruz y la calle Mayor (260 y 290). En cambio, tanto la calle de la Cruz y la calle Mayor como el Paseo del prado han sido evaluadas como algunas de las más problemáticas del recorrido en cuanto a niveles de $PM_{2,5}$. Por tanto, estos aumentos de $PM_{2,5}$ en calles con bajos niveles de IMD deben ser explicados por otros factores, tales como la propia fisionomía de las calles (que en este caso coinciden con las más estrechas de la ruta) y la presencia de elementos perturbadores tales como retenciones constantes en la calle de la Cruz o el túnel de la calle Mayor.

Al comparar los niveles medios de $PM_{2,5}$ con las velocidades de tráfico medias recogidas por el sensor, se puede decir que, al menos a nivel cualitativo, las concentraciones promedio de partículas en el ambiente tienden a verse influidas de forma inversa por la velocidad del tráfico. Es decir, en calles con una elevada tendencia a atascos y retenciones se dan unos promedios generalmente más altos de concentraciones de $PM_{2,5}$. No obstante, mientras que los análisis descriptivos, que comparan las $PM_{2,5}$ con los valores promedio de los factores externos agrupados en días o calles sugieren una alta afinidad de la velocidad del tráfico promedio en cada calle, el análisis de correlación de Pearson no defiende esta aparente tendencia. Esto quiere decir que no se aprecia una correlación lineal entre los aumentos y descensos de $PM_{2,5}$ y los valores de velocidad de tráfico. Esta tendencia podría darse, en parte, por un descenso real de las concentraciones en calles más amplias, con mayor circulación del aire, o por la menor densidad de tráfico presente en el tramo. No obstante, este enfoque también puede estar alterado por una reducción del número de puntos de muestreo debido al menor tiempo de presencia en estas calles.

6. CONCLUSIONES

En este trabajo se ha analizado la concentración de $PM_{2,5}$ en un conjunto de calles de Madrid mediante el uso de sensores móviles. A pesar del bajo coste de esta tecnología, se han obtenido mediciones de calidad aceptable que pueden ser complementarias a las realizadas con las estaciones fijas del Sistema de vigilancia de la Calidad del Aire del Ayuntamiento de Madrid.

Se ha podido comprobar que ciertas calles presentan concentraciones mayores que la media con asiduidad. También cómo la velocidad media del tráfico en cada calle parece afectar a las medias globales de dicho tramo. El método permite caracterizar los puntos problemáticos de la ciudad con un enfoque mucho más minucioso que los sistemas de medición estándar, tal y como se muestra en los resultados por malla y de altas concentraciones. Uno de los factores que más parecen afectar a la aparición de altas concentraciones es la existencia de tramos estrechos de un solo carril, tales como la calle de la Cruz o la calle Hortaleza, donde no circula una gran cantidad de vehículos, pero estos suelen verse sometidos a fuertes retenciones.

De hecho, se han encontrado evidencias de mayores concentraciones de $PM_{2,5}$ promedio en las calles con menor intensidad de tráfico media diaria (IMD), dado que coinciden con los tramos menos amplios, con menos carriles y, en definitiva, mayores dificultades de aireación. Esta valoración del estado de cada una de las calles por las que discurre el recorrido no habría sido posible mediante la recopilación de la información suministrada por estaciones fijas. De hecho, los expertos (Qiu et al., 2017) critican que este es el gran problema de la ciencia de los datos de calidad del aire. Hasta ahora la mayoría de los estudios han recopilado información de estaciones fijas, dejando de lado variables estructurales, tales como el trazado de las carreteras, su anchura, etc.

Hay constancia de otros estudios en la ciudad de Madrid, donde sí se ha considerado otros factores, como la presencia y características del arbolado de las zonas verdes, y la IMD de las calles próximas a los puntos de medición, así como la distancia entre las vías de tránsito y arbolado, y el efecto de los factores meteorológicos sobre estos valores (Calderón-Guerrero, 2014), confirmando la variación de los niveles de contaminación atmosférica en función de la presencia de estas zonas verdes, la distancia y la IMD. De igual modo, en estudios posteriores (Sánchez Martín, 2017), se corroboran estas variaciones de los niveles de partículas (PM_1, $PM_{2.5}$, PM_{10}) en diferentes zonas de la Casa de Campo de Madrid, mediante la adaptación de unos sensores low-cost, similares a los de este estudio, en una aeronave pilotada de forma remota (*DRON*) en las proximidades de las autopistas A-5 y A-6, lo cual avala los resultados de este estudio, y realza la utilidad de estos sensores móviles a la hora de identificar las variaciones de los niveles de contaminantes atmosféricos por otros factores.

En cuanto a Madrid Central, los resultados de este estudio no han identificado una diferencia entre ambas zonas, por lo cual podría establecerse que las restricciones al tráfico no están resultando en un impacto positivo para el interior de dicha área.Se recomienda continuar con investigaciones de esta línea durante los futuros años, para observar posibles cambios con el endurecimiento de las restricciones previstas en la Estrategia MADRID 360.

En la comparativa con los valores de IMD, los resultados indican que las calles con mayor nivel promedio de contaminación por $PM_{2,5}$ no se corresponden con aquellas con menores niveles de IMD. De igual forma, a nivel cualitativo, las concentraciones promedio de partículas en el ambiente tienden a verse influidas de forma inversa por la velocidad del tráfico. Por otra parte, parece claro que las variables meteorológicas como la velocidad del viento y su dirección, la humedad relativa y la presión barométrica tienen un mayor peso que otras variables externas que puedan aplicarse a modelos predictivos en un futuro. Con una mejora futura de los trabajos de medición podrían construirse experimentos con resultados más robustos en este sentido.

Las mayores limitaciones encontradas en el proyecto residen en el diseño del sensor móvil. Por ejemplo, el acabado del prototipo impide su viabilidad de uso en días de lluvia. También se debería incorporar otros sensores como el de O_3 y NO_2, de gran importancia para una ciudad como Madrid.

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CAMPAÑA DE ENCUESTAS PARA LOS PLANES DE MOVILIDAD UNIVERSITARIA SOSTENIBLE (PMUNIVS) DE LA COMUNIDAD DE MADRID. ESTRATEGIAS DE SEGUIMIENTO PARA ANIMAR A LA PARTICIPACIÓN EN TIEMPOS DE LA PANDEMIA DE LA COVID-19

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RESUMEN

La Comunidad de Madrid y sus seis universidades públicas presenciales comenzaron la elaboración del primer Plan de Movilidad Universitaria Sostenible (PMUnivS) general a finales de 2019. El plan de trabajo incluye, como parte fundamental de los trabajos a realizar, la toma de datos sobre como la comunidad universitaria madrileña se desplaza hacia los campus y entre campus, y la calidad urbanística de éstos. Esta encuesta, realizada del 22 de febrero al 26 de marzo de 2021, tenía una población objetivo que se estimaba en más de 200.000 personas, entre estudiantes, personal docente e investigador, personal de administración y servicios, y personal de servicios externalizados.

Desafortunadamente, la pandemia de la COVID-19 y las restricciones adoptadas para contenerla, especialmente en materia de movilidad, tuvo un impacto significativo en el objeto de la encuesta, la movilidad a los campus universitarios, y que limitó la estrategia de comunicación. En general, la presencialidad en las universidades presenciales disminuyó en un más del 50%: gran parte de las clases se imparten on-line, muchos servicios están cerrados y el teletrabajo se ha implementado de manera general. Además, cualquier actividad presencial para animar a la participación no se consideraba adecuada. En consecuencia, la campaña de las encuestas debía realizarse, casi por completo, mediante el uso de las vías de comunicación virtual de cada universidad y en el uso de redes sociales, tales como Twitter o Instagram.

En esta comunicación se detalla la estrategia ha sido usada durante la campaña de encuestas, qué decisiones se tomaron desde el punto de comunicación y cuáles fueron sus efectos sobre las tasas de respuestas obtenidas.

El objetivo científico es intentar encontrar una relación causal entre las diferentes actuaciones de comunicación online con cada colectivo de la comunidad universitaria y posibles patrones anormales de participación. Esta experiencia puede ser de utilidad para otras instituciones con la misma problemática.

1. INTRODUCCIÓN

Los campus de las universidades, lugares en los que se concentran varios centros de enseñanzas superiores y centros de investigación, atraen a un gran número de personas a lo largo del día, entre estudiantes (el colectivo generalmente más numeroso), profesores, investigadores y personal de administración y servicios, de diferentes orígenes, estilos de vidas, rentas y actitudes (Balsas 2003). Los campus universitarios, por sí mismos, constituyen espacios urbanísticos propios, con un diseño que tiene a ser diferente al de su entorno, que acoge una gran variedad de actividades a lo largo del día. Además, suelen disponer de infraestructuras y servicios de transporte especialmente diseñadas para su excepcionalidad. En consecuencia, la movilidad a los campus universitarias suele presentar unas pautas propias y muy marcadas por los ritmos de la actividad académica, que deben ser conocidas para realizar una planificación y gestión integral de estos lugares.

La movilidad a los campus universitarios es un tema que ha sido abordado desde diferentes puntos de vista y con diferentes objetivos. Por mencionar algunos de ellos están los estudios que cuyo objetivo era el conocimiento de la movilidad universitaria en general (Albertos et al. 2008), la patrones espaciotemporales de la movilidad universitaria (Delmelle y Delmelle 2012), predisposición a actuaciones con estrategias TDM en los campus (Cherry et al. 2018), la estimación de la utilidad de los modos activos (Lundberg y Weber 2014), la selección modal (Shannon et al. 2006; Hasnine et al. 2018; Etminani-Ghasrodashti, Paydar y Hamidi 2018), cambios de movilidad por cambio de residencia (Haggar, Whitmarsh y Skippon 2019), influencia de la localización del campus y de las características socioeconómicas y comportamiento social para la movilidad em coche (Soria-Lara, Marquet y Miralles-Guasch 2017) o las diferencias entre la movilidad de la universidad y la movilidad en el resto de la ciudad (Danaf, Abou-Zeid y Kaysi 2014).

Generalmente, estos estudios capturaron parte de los datos mediante campañas de encuestas online, salvo Albertos et al. (2008). Algunas de estas campañas fueron propias del estudio y otras fueron realizadas con propósitos generales. La mayoría de dichas encuestas siguieron un muestreo no-probabilístico por cuotas y autoselectivo (Galloway 2005) que incluía, como mínimo, la participación del colectivo de estudiantes, pudiendo estar seleccionados por su vinculación esperada con el campus debido a tipo de estudios y curso. En los casos de Shannon et al. (2006) y de Albertos et al. (2008) la muestra fue aleatoria estratificada al seleccionar previamente a qué personas o grupos académicos se les invitaría a participar en la encuesta. La participación en dichas encuestas se situó en torno al 10%, pudiendo llegar en algunos casos a más del 17%.

Las campañas de encuestas de casi todos los estudios mencionados se dieron a conocer mediante los medios digitales propios de cada universidad, tales como el correo electrónico institucional o los servicios de intranet, salvo los caso de Haggar, Whitmarsh y Skippon (2019), que usaron anuncios de Facebook, y de Shannon et al. (2006) que enviaron correos convencionales. En general, los documentos mencionados previamente no aportan apenas detalles sobre las acciones de comunicación para dar a conocer las respectivas encuestas de movilidad universitaria y animar a su participación. Del mismo modo ninguno de estos documentos realiza valoraciones sobre éxitos y fracasos de dichas acciones y no se especifican si hubo estrategias de seguimiento de la participación para focalizarse en aquellos colectivos con menor número de respuestas de las esperadas a lo largo de la campaña. Estos aspectos que, generalmente, pueden considerarse cuestiones menores para la literatura de las encuestas de movilidad, pueden ser de interés de cara a planificar nuevas campañas de encuestas, sobre todo en aquellas cuya gran parte de población objetivo parece tener unos comportamientos diferenciados en los medios que usan para participar en encuestas online (Bosch, Revilla y Paura 2019).

El objeto de esta comunicación es presentar los efectos observados en la participación en la campaña de encuestas para los grandes colectivos de la comunidad universitaria del Plan de Movilidad Universitaria Sostenible (PMUnivS) de la Comunidad de Madrid que tuvieron las acciones de comunicación usadas y el uso de dichos indicadores relacionados con la participación para la detección de patrones anómalos. Esta encuesta se ha realizado de manera conjuntamente en las seis universidades públicas presenciales de la Comunidad de Madrid durante las primeras semanas del segundo semestre académico del curso 2020/2021. Esta campaña se realizó durante el segundo estado de alarma por la pandemia de la COVID-19 y mientras estaban vigentes una serie de medidas y restricciones para contenerla.

El resto de la comunicación se estructura de la siguiente manera: en la sección 2 se presenta el objeto de la encuesta y las principales características de ésta; en la sección 3 se presentan las características de los campus universitarios en los que se realizó la encuesta y su cuota de presencialidad en tiempos de la COVID-19; en la sección 4 se presenta la campaña de comunicación; en la sección 5 se presentan los indicadores usados para entender el impacto de las acciones de la campaña de comunicación en la participación; la sección 6 se muestran los efectos de las acciones de comunicación sobre la participación; finalmente, la sección 7 presenta las conclusiones y se realizada la discusión.

2. EL PMUNIVS Y LA CAMPAÑA DE ENCUESTAS

El Plan de Movilidad Universitaria Sostenible (PMUnivS) para las seis universidades públicas presenciales de Madrid empezó sus trabajos a finales del año 2019, promovido por las consejerías de Transportes, Movilidad e Infraestructuras, y de Ciencia, Universidades e Innovación de la Comunidad de Madrid y por el Consorcio Regional de Transportes de Madrid (CRTM). Este plan contempla la realización de una serie de encuestas a los diferentes colectivos de la comunidad universitaria para conocer cómo se mueven a los diferentes campus universitarios. La campaña de encuestas se dividió en dos: una primera etapa para las empresas proveedoras de materiales y consumibles y otra etapa en la que se pregunta la movilidad a los grandes colectivos de la comunidad universitaria: estudiantes, personal docente e investigador (PDI), personal de administración y servicios (PAS), y personal de servicios externalizados. Esta comunicación solo hace referencia a las acciones de comunicación y seguimiento de la participación de la segunda etapa.

Estas encuestas debían haberse realizado a lo largo del año 2020 pero la pandemia de la COVID-19 y las diferentes restricciones que se decretaron para contenerla supuso la necesidad de posponer dicha campaña hasta volver a una situación de cierta normalidad. Finalmente se decidió que entre el lunes 22 de febrero y el viernes 26 de marzo de 2021 (antes de las vacaciones de Semana Santa del curso 2020/21) se abriese la campaña de encuestas a los grandes colectivos de la comunidad universitaria de la Comunidad de Madrid. Esta encuesta sería online, mediante SurveyMonkey, previendo inicialmente unos 15 minutos para completarla totalmente. El muestro de esta encuesta responde, por el diseño de las acciones de comunicación para animar a su participación, a un muestreo no-probabilístico con cuotas, por campus y colectivo, y autoselectivo.

La encuesta tenía una parte común y una parte adaptada a la realidad urbanísticas y de la oferta de transporte propia de cada uno de los campus. Además, las preguntas relacionadas con la movilidad no hacían sólo referencia a la movilidad en las circunstancias de la COVID-19 sino también en cómo se movía anteriormente (si tenía desplazamientos al campus) y como estimaba hacerlo en próximos cursos (bajo el supuesto de no necesitar ninguna medida de contención de la pandemia actualmente vigente).

Para animar a la participación se sorteaba, entre las encuestas finalizadas que indicasen un correo electrónico válido de contacto, abonos mensuales para transporte público, cajas de experiencias y diferentes regalos institucionales de cada una de las universidades.

Para conocer más sobre la encuesta, consulte la comunicación (Balsero Martínez, Lamarty Belica y Monzón de Cáceres (2021), presentada en este congreso.

3. LAS UNIVERSIDADES PÚBLICAS PRESENCIALES DE LA COMUNIDAD DE MADRID Y SUS CAMPUS. LA PRESENCIALIDAD EN TIEMPOS DE LA COVID-19

La Comunidad de Madrid tiene seis universidades públicas presenciales: la Universidad de Alcalá (UAH), la Universidad Autónoma de Madrid (UAM), la Universidad Carlos III de Madrid (UC3M), la Universidad Complutense de Madrid (UCM), la Universidad Politécnica de Madrid (UPM), y la Universidad Rey Juan Carlos (URJC).

En total, se estima que el número de personas asociadas a estas universidades es de más de 200.000 personas para el curso 2020/2021, la cual está formada por los estudiantes casi del 90%, el PDI, alrededor del 8,5%, y el PAS, entorno al 4%. A esta comunidad hay que sumarle el personal de servicios externalizados, como son el personal de cafeterías, de seguridad o de limpieza, entre otros, cuyo valor relativo a la población no pudo ser obtenido con precisión.

La gran mayoría de los centros académicos y de investigación de las universidades públicas presenciales están ubicados en alguno de los 14 campus principales de la Comunidad de Madrid (Figura 1), entendiendo campus como áreas en las que se ubican más de un centro académico o de investigación de una misma universidad. Salvo el campus de Ciudad Universitaria, en Madrid y en el que se encuentran centros de la UCM y de la UPM, el resto de los campus son propios de una única universidad. Por tamaño, el que acoge mayor número de personas de la comunidad universitaria es el campus de Ciudad Universitaria, con más del 36% sobre el total. Cabe destacar que, pese a que existen otros centros aislados que se encuentran en Madrid y Aranjuez que no han sido incluidos en esta comunicación.

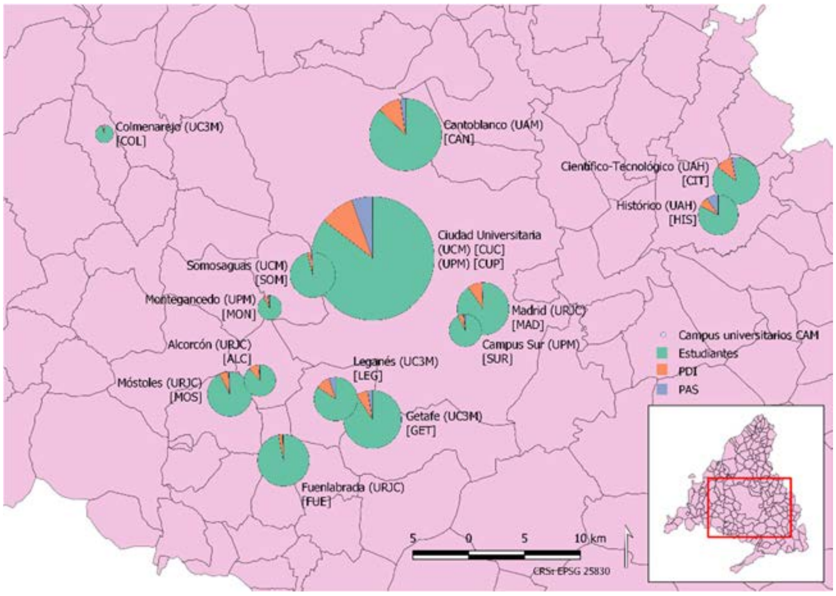

Figura 1. Distribución de los campus universitarios de la Comunidad de Madrid y el porcentaje de estudiantes, PAS, y PDI. A mayor área del diagrama circular, mayor población total de la comunidad universitaria. Entre corchetes está el código asignado en esta comunicación a cada campus.

3.1. La presencialidad durante el segundo semestre del curso 2020/2021

La presencialidad de la comunidad universitaria durante el periodo de la encuesta aún estaba afectada por los planes de contención de la COVID-19 y las restricciones de movilidad. Cada universidad, e incluso cada campus y centro, establecieron sus propias medidas con relación a la presencialidad de cada colectivo.

En general, todos los campus mostraban una importante reducción de los requerimientos de presencialidad, especialmente para los estudiantes. Gran parte de las clases se impartían en formato no presencial o con la posibilidad de seguimiento online, salvo las prácticas y los exámenes; además se diseñaron calendarios y horarios pensados para evitar aglomeraciones y coincidencia de flujos de personas en sentidos opuestos. Esta estrategia hizo que gran parte de la comunidad universitaria tuviese, individualmente, unas pautas de presencialidad relativamente irregulares. De la misma manera, muchos servicios se prestaban de manera telemática, requerían el concertar cita previa o, como en el caso de las cafeterías, estaban cerrados, con horarios reducidos o prestando servicios mínimos, con menor número de personal del que es habitual en situaciones normales.

En la Tabla 1 se muestra la estimación de presencialidad informada por los diferentes responsables de cada universidad o campus.

Universidad	Campus	Código	Presencialidad
UAH	Científico-Tecnológico	CIT	Presencialidad limitada. Grados: sólo prácticas en grupos reducidos (12 personas), Máster depende del máster.
	Histórico	HIS	
UAM	Cantoblanco	CAN	Poca presencialidad.
UC3M	Colmenarejo	COL	Estimada en un 50%
	Getafe	GET	
	Leganés	LEG	
UCM	Ciudad Universitaria	CUC	Depende del centro. Se estima máximo en un 50%.
	Somosaguas	SOM	Estimada entre el 25% al 50%.
UPM	Campus Sur	SUR	Estimada entre el 20% al 30%.
	Ciudad Universitaria	CUP	Depende del centro. Se estima máximo en un 50%
	Montegancedo	MON	Estudiantes: 1º de grado al 100%, el resto sólo prácticas y exámenes. Presencialidad limitada para en el resto de los colectivos.
URJC	Alcorcón	ALC	Estudiantes: Facultad de Odontología al 100% y Facultad de Farmacia sólo prácticas. Presencialidad limitada en los otros colectivos.
	Fuenlabrada	FUE	Estimada en un 25%.
	Madrid	MAD	
	Móstoles	MOS	Estimada entre el 5% y el 10%.

Tabla 1. Resumen de la presencialidad estimada por los responsables de cada campus y universidad durante el segundo semestre del curso 2020/2021.

4. LA CAMPAÑA DE ENCUESTAS DEL PMUNIVS. EL RETO DE LAS RESTRICCIONES POR LA COVID-19

La situación de la COVID-19 afectó a las acciones de comunicación relacionadas con el cómo se podía dar a conocer la campaña de encuesta del PMUS, el porqué de ésta, para qué iban a servir sus respuestas, cómo estas respuestas ayudarían a entender mejor la movilidad a los campus universitarios y ayudar a diseñar propuestas de mejoras. Además, estas acciones de comunicación tendrían también como objetivo fundamental el intentar animar a participar a la mayor parte de la población objetivo.

En situaciones normales, algunas de estas actuaciones pueden ser presenciales tales como la entrega de tarjetones en puntos clave o la instalación de puntos de información temporales que pueden disponer de dispositivos electrónicos, como tabletas digitales u ordenadores portátiles, para que las personas que deseasen contestar la encuesta la pudiesen rellenar en ese mismo lugar. Sin embargo, y debido a las restricciones por la COVID-19, ninguna de estas actuaciones fue considerada como adecuada, tanto por la previsible menor e irregular afluencia de personas a los campus, como para evitar la exposición de las personas encargadas de dichas actividades al virus, por incremento de interacciones de varios minutos con personas ajenas a su círculo de convivencia habitual. En consecuencia, gran parte de las acciones de comunicación de la campaña de encuesta debían basarse con medios no presenciales, sin renunciar al refuerzo puntual con material en soporte físico que no requiriese interacción física.

Se prepararon los siguientes materiales promocionales, siguiendo las recomendaciones del (Instituto para la Diversificación y Ahorro de la Energía 2006) y adaptándolas a las oportunidades que ofrecen las nuevas tecnologías:

1. Nota de prensa: En la cual se anunciaba el inicio de la campaña de encuestas y se comunicaba detalles referentes al porqué de estos trabajos, cuál era la población objetivo y se animaba a participar.
2. Carta: Un documento genérico que se envió a todos los miembros de la comunidad universitaria mediante correo electrónico en la que se daba a conocer la campaña de encuestas, se describía brevemente la motivación de ésta, se anunciaban los premios que a los cuales podía optar al completar la encuesta y se indicaban el enlace propio de su universidad por el cuál podía acceder a la encuesta, el correo electrónico de contacto para dudas y los perfiles en redes sociales. Esta carta podía ser adaptada por cada universidad según considerase conveniente.
3. Póster (Figura 2): Una imagen muy sencilla en la que se anunciaba la campaña de encuestas, la fecha de inicio, los promotores, las universidades participantes y un correo electrónico de contacto para dudas. Este poster fue enviado en formato digital, tanto vertical como horizontal, para presentarlo en pantallas informativas de los campus.
   El póster también fue impreso en tamaño DIN A-1 para ser colocado en diferentes puntos acordados entre el equipo de coordinación de los trabajos y los diferentes responsables de campus durante las visitas de campo para presentar la campaña y la captación de datos necesaria para otros trabajos del PMUnivS. El póster no tenía referencia a ningún enlace de la encuesta, por ser diferente para cada universidad ni a las redes sociales puesto a que se decidió su uso posteriormente a su impresión.

Figura 2. Póster de la campaña de encuestas

4. Tarjetones: Los tarjetones contenía la imagen usada del póster y un texto breve animando a participar. Los tarjetones estaban personalizados para cada una de las universidades, usando sus colores instituciones y presentando el enlace a sus respectivas encuestas mediante un código QR con el logotipo y colores de cada universidad.
5. Correo electrónico: El equipo de coordinación de los trabajos disponía de un correo electrónico que fue referenciado en todos los materiales de promoción usados, para que cualquier miembro de la comunidad universitaria pudiese enviar comentarios, preguntas o sugerencias con relación a la encuesta y al PMUnivS.
6. Redes sociales: Se crearon un perfil de Twitter y otro perfil en Instagram con el mismo nombre (@movunicam) Con estos medios se abría otro medio de comunicación directo entre el equipo coordinador y la comunidad universitaria. La utilización de estos perfiles se fue concebida como una medida adicional a pocos días de iniciar la campaña de encuestas. Sin embargo, estas cuentas sólo alcanzaron unos 23 seguidores y, por lo tanto, tenían poco poder de difusión de la campaña de encuestas.

Las acciones de comunicación de la campaña de encuestas tenían dos objetivos principales.

El primer objetivo era el informar a toda la población, tanto si eran miembros de la comunidad universitaria como si no lo eran, del inicio, los motivos y la evolución de la encuesta. El segundo objetivo consistía en animar a la participación del mayor número de miembros de la comunidad universitaria

Las tareas del primer objetivo fueron desarrolladas principalmente por los equipos de comunicación de las consejerías implicadas y del CRTM, con el apoyo del equipo coordinador de los trabajos. Este equipo fue quien diseño la imagen del póster y el encargado de la rueda de prensa de presentación de las encuestas que se realizó el viernes 19 de febrero de 2021. Parte de estas acciones aún no han empezado a poderse hacer al finalizar los trabajos de redacción del PMUnivS.

El segundo objetivo dependió, principalmente, de cada una de las universidades participantes, y tuvo el apoyo del equipo de coordinación de los trabajos. Se establecieron una serie de reuniones para coordinar las acciones de comunicación que debían asumir cada una de las personas responsables de las universidad y campus, en las cuales se definieron los calendarios de comunicación, los mensajes a transmitir, los medios mínimos y medios deseados que debían usarse. El equipo coordinador fue el encargado de preparar los materiales base comunes y de hacer llegar dicho material a cada universidad para que pudiesen adaptarlo a su realidad. El objetivo de la coordinación de estas acciones era intentar que toda la comunidad universitaria pudiese estar informada al mismo tiempo y, de esta manera, permitir que miembros de la comunidad de diferentes universidades pudiesen estar informados de la campaña de encuestas por cualquier medio abierto de cualquiera de las universidades participantes o por conocidos de otras universidades.

La estrategia principal para cumplir el segundo objetivo se basó, en gran medida en el envío de la carta en varios mensajes a los correos electrónicos institucionales de los miembros de la comunidad universitaria. Cabe señalar que esta acción también pudo requerir la necesidad de coordinación interna de diferentes departamentos de cada universidad y campus puesto que, algunas universidades, no disponían de un listado único de correos: la organización más habitual dichos listados era el disponer del correo de los estudiantes en una lista diferente a la de los correos del PDI y PAS los cuales, a su vez, podían estar en listas centralizados o que dependían de cada centro o campus. A parte, se solicitó que cada universidad comunicase a todas las empresas contratadas para la gestión de los servicios externalizados para que hiciesen llegar el enlace a sus empleados. Ninguna de las actividades de esta acción se podía centralizar a un único punto de envío en el cumplimiento de los Ley Orgánica de Protección de Datos Personales (LOPD).

Las universidades, desde perfiles comunes generales y desde perfiles de centros y delegaciones de estudiantes, complementaron su acción de difusión usando sus redes sociales. Esta acción fue complementada con el uso de los perfiles de Twitter e Instagram (@movunicam) con el que se anunciaban los principales avances de participación, se ponían curiosidades de la movilidad universitaria de las diferentes universidades y se respondían a las dudas y preguntas relacionadas con la encuesta.

En esta comunicación, se entiende perfil general de la universidad las cuentas vinculadas a la propia universidad, a servicios comunes como son la red de bibliotecas (que suelen tener un perfil común) o a vicerrectorados u oficinas relacionadas con la campaña de encuestas, como oficinas verdes o programas relacionados con los ODS.

Se establecieron tres olas principales de comunicación durante todo el periodo de la campaña de encuestas (Tabla 2):

- La primera ola se debía realizar a lo largo de los primeros días de la primera semana de la encuesta (a partir del lunes 22 de febrero de 2021). Esta ola era la que mayor esfuerzo conllevaba puesto a que, además, implicaba la colocación de la cartelería en los puntos acordados durante las visitas de campo realizadas con anterioridad y la programación de las pantallas disponibles para que también mostrasen el póster. En esta ola, todas las universidades optaron por el envío masivo de la carta a los correos electrónicos. Además, tres de ellas también publicaron noticia referente a la campaña de encuestas, con el enlace a sus respectivas encuestas y todas enviaron algún mensaje desde algún perfil general oficial de Twitter.
- La segunda ola se realizó durante la segunda semana de marzo (a partir del lunes 8 de marzo de 2021), cuando ya habían transcurrido más de 15 días desde el inicio de la campaña de encuestas. Esta ola volvió a consistir en el envío de un correo electrónico recordatorio a todos los miembros de la comunidad universitaria. Además, se empezaron a repartir tarjetones todos los campus de la UAM y UCM, y en el campus de Ciudad Universitaria de la UPM para llegar a la parte del colectivo que no pudo ser alcanzada por medios digitales y que acudían a la universidad, en especial, el colectivo de personal de servicios externalizados.
- La tercera ola se llevó a cabo durante la última semana de la campaña de encuestas (a partir del 22 de marzo de 2021). Esta semana era, a su vez, la semana última semana completa de marzo y que coincida con la última semana lectiva antes de las vacaciones de Semana Santa. En esta tercera ola, las universidades debían haber repartido los tarjetones, especialmente en los puntos habituales del personal de servicios externalizados. Además, y de manera opcional, podían volver a enviar correo electrónico recordatorio o enviar mensaje de último aviso en redes sociales.

No se consideró adecuado más olas de comunicación para no generar un rechazo a participar por exceso de recordatorios a todo aquel posible participante que no había participado aún.

		feb-21										mar-21																									
		V	S	D	L	M	X	J	V	S	D	L	M	X	J	V	S	D	L	M	X	J	V	S	D	L	M	X	J	V	S	D	L	M	X	J	V
		19	20	21	22	23	24	25	26	27	28	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
UAH	E-mail					M															M												M				
	RRSS						R									R														R							R
	Noticias																																				
	Tarjetones																																				
UAM	E-mail				M																M																
	RRSS							R													R																
	Noticias																																				
	Tarjetones																			T	T	T	T			T	T	T	T				T	T	T	T	T
UC3M	E-mail				M																	M															
	RRSS				R	R	R								R							R				R							R			R	
	Noticias				N																																
	Tarjetones																																	T	T	T	T
UCM	E-mail						M														M															M	
	RRSS						R																														
	Noticias																																				
	Tarjetones																			T	T	T	T			T	T	T	T				T	T	T	T	T
UPM	E-mail				M																M																
	RRSS				R	R	R	R	R		R	R		R	R	R					R	R					R	R									
	Noticias	N																																			
	Tarjetones																					T	T			T	T	T	T				T	T	T	T	T
URJC	E-mail				M											M																					
	RRSS				R		R					R	R			R					R												R				
	Noticias																																				
	Tarjetones												N																				T	T	T	T	T
Coor.	RRSS				R		R	R	R				R		R											R											
	Noticias	N																					N														

Tabla 2. Calendario de actuaciones realizadas en materia de comunicación, de acuerdo con los diferentes responsables de cada universidad y por el seguimiento de su actividad en Twitter.

4.1. Consideraciones que se tuvieron en cuenta en el diseño de las acciones de comunicación

Debido a que la encuesta y las acciones de comunicación se realizaron íntegramente online, existía el riesgo a que se pudiese sufrir un “ataque” cibernético. Una de las principales preocupaciones era que se recibiesen una cantidad elevadas de cuestionarios con respuestas falsas que, en el peor de los casos, pudiese parecer que fuesen respuestas coherentes y, por lo tanto, difícil de filtrar.

Las medidas para reducir la posibilidad de ataque, sin que ello significase que las redujese completamente, fueron:

- Disponer de un enlace propio de cada universidad para acceder al cuestionario. De esta manera se esperaba limitar el alcance de un posible ataque. Sin embargo, pese a que no se publicó ningún material promocional con los seis enlaces, algunos buscadores ofrecían estos enlaces.
  Esta característica de la encuesta fue inicialmente pensada por motivos de diseño y particularización del cuestionario a cada universidad y campus.
- Evitar la publicación del enlace en redes sociales abiertas (tipo Twitter o Instagram) para evitar el rastreo de enlaces por parte de bots.
- Limitar el número de cuestionarios admitidos por dirección IP.

En el período por el cual la encuesta estuvo activa, se realizó un seguimiento de posibles comportamientos anómalos sin haber detectado ningún patrón que indicase un posible ataque masivo y que pudiese invalidar, a priori, la totalidad de la campaña de encuestas

5. MÉTODOS PARA ENTENDER EL EFECTO DE LAS ACCIONES DE COMUNICACIÓN EN LA PARTICIPACIÓN.

Con el fin de comprobar el efecto que han tenido las diferentes acciones de comunicación sobre la participación, se ha realizado el seguimiento día a día, por campus y colectivo, de los siguientes indicadores:

- Número total de encuestas iniciadas, diferenciando entre las encuestas finalizadas y las no finalizadas.
- Horas de inicio de la encuesta por colectivo.
- Tiempo requerido desde que se inicia a responder la encuesta hasta que la finaliza o la abandona.

La evolución de estos indicadores también permitía tener datos de cara a la adopción de nuevas medidas de comunicación orientadas a aquellos colectivos y campus con menor número de respuestas de las esperadas, a la vez que permitía detectar la presencia de comportamientos anómalos.

Los valores de estos indicadores se obtienen de la explotación de los datos de la encuesta.

Debido a que la encuesta tenía preguntas diferentes según lo que contestaba el participante, lo que en SurveyMonkey se llama *Logic Features* (SurveyMonkey [sin fecha]), los ficheros originales contenían varios campos cuyo nombre estaba repetido. En este caso, las primeras preguntas del cuestionario, las relativas sobre cuál es el campus de la actividad del participante y a qué colectivo pertenecía, creaban estos campos repetidos, sin que eso no signifique que hubiesen más de este tipo de campos generados a medida que se respondían otras preguntas. Es por ello por lo que, previamente a analizar los cuestionarios, se tuvo que realizar una tarea de compactación de datos, por la cual se fusionaban todos los campos con el mismo nombre en un mismo campo eligiendo, en caso de discrepancia por error de almacenamiento, el valor del campo moda de registros no nulos para el campus y colectivo de dicho participante. Esta tarea se realizó usando un script de Python 3.7.6 que usa el paquete *pandas* específico para esta comunicación.

Estos indicadores se representan, en el apartado 6.2., en gráficos de barras o de líneas y áreas, cuyo eje abscisas representa cada uno de los días en los que estaba abierta la campaña de encuestas. Además, se han añadido líneas verticales indicando el tipo de acción de comunicación que se ha realizado para poder ver en el gráfico cuál fue el efecto de cada acción sobre la participación (envío de correos electrónicos en negro y con línea discontinua y envío de tweets en azul y con línea punteada) y la duración de dichos efectos. Estos gráficos han sido generados con el paquete *ggplot* de R, versión 4.0.2.

Finalmente, para conocer el detalle de todos los tweets enviados desde las cuentas de interés de las universidades se usó la API de Twitter, versión *Academic Research product track* que permite el acceso a todos los tweets publicados desde el inicio de dicha red social. Para esta comunicación, sólo se preguntó por los tweets twiteados y retwiteados desde el viernes 19 de febrero de 2021 hasta el sábado 27 de marzo de 2021. La captura de los tweets se realizó mediante un script de Python 3.7.6 que usa el paquete *requests* para almacenarlo en un base de datos MongoDB mediante el paquete *pymongo*. Para detectar qué tweets podían hacer referencia a la encuesta, se filtraron aquellos tweets que en el texto tuviesen las palabras “movilidad”, “encuesta”, o “plan”. Estos tweets serían posteriormente leídos por personal del equipo de coordinación para acabar de decidir si eran o no tweets de interés para la presente comunicación.

6. LAS ACCIONES DE COMUNICACIÓN Y LA EVOLUCIÓN DE LA PARTICIPACIÓN

Los resultados mostrados en esta sección son los resultados obtenidos de los primeros análisis preliminares. Dichos resultados podrían variar con respecto a la versión definitiva de los trabajos de redacción del PMUnivS por correcciones que se realicen a medida que se analicen cada encuesta con mayor detenimiento.

6.1. Participación en la campaña de encuestas

Durante la campaña de encuestas del PMUnivS se recibieron un total de 35.538 encuestas en los campus objeto de esta comunicación, lo que representa una participación total entorno al 17,58%, considerando solamente estudiantes, PAS y PDI). Del total de encuestas, el 83,13% estaban completas y, por lo tanto, podían participar en el sorteo de diferentes premios. Este porcentaje de encuestas completadas es similar en todos colectivos de la universidad siendo algo superior para los PDI y siendo algo inferior para el personal del servicio externo. Solamente el 8,29% de las personas que completaron la encuesta rechazaron participar en el sorteo al no facilitar ningún correo electrónico válido de contacto. De los cuestionarios que sí decidieron participar, casi el 85% indicaron usaron el correo institucional de la universidad a la que pertenecían. Hay que señalar que se encontraron 117 participantes usaron exactamente el mismo correo electrónico de contacto en, a lo sumo, 2 encuestas diferentes.

Como se puede ver en la Figura 3, la participación no fue uniforme ni por colectivo ni por universidades ni campus. El colectivo más participativo fue el PAS con más del 40%, seguido del PDI con más del 30% y finalmente los estudiantes con una participación próxima al 15%. En cuanto a universidades, destaca la UCM por ser la que movilizó más participantes de su comunidad y cuyo primer correo fue enviado y firmado por el Rector de la universidad. Por campus, se puede destacar el campus de Colmenarejo (UC3M) destaca por una elevada participación tanto de PAS como de PDI, mientras que los campus de Montegancedo (UPM) y Fuenlabrada (URJC) tuvieron participaciones cercanas al 60% por parte del PDI, y el campus de Ciudad Universitaria (UCM) tuvo una participación de más del 25% del colectivo estudiante. No se ha podido determinar el grado de participación del personal de servicios externalizados debido a que se conoce la población total. Se han excluido de la Figura 3 los campus de Somosaguas (UCM) y Móstoles (URJC) debido a la detección de valores atípicos pendientes de corregir.

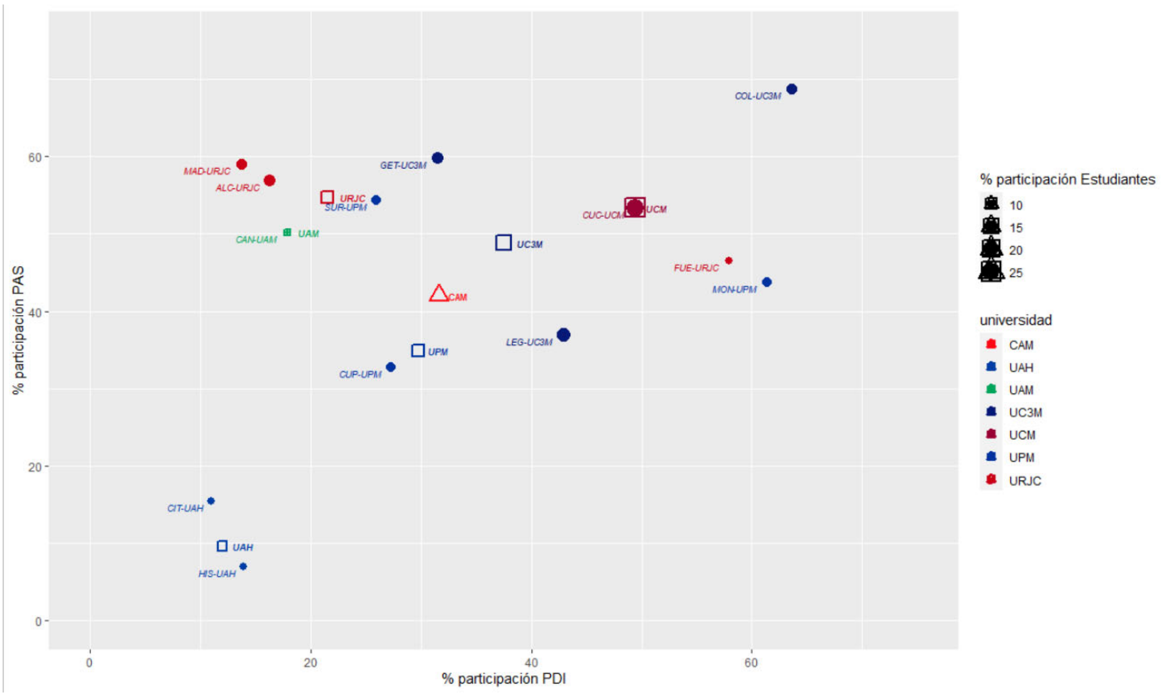

Figura 3. Diagrama del porcentaje de participación de los Estudiantes, PAS y PDI, por campus y por universidad

6.2. Evolución de indicadores de participación, ¿efectos de las acciones de comunicación?

En relación con los días de mayor participación, se puede apreciar en la Figura 4 como estos incrementos son, en general, más prominentes en aquellos días en los que se enviaba algún mensaje mediante correo electrónico de cada una de las olas principales de comunicación y durante el día inmediatamente posterior. El correo electrónico solía enviarse durante el turno de mañana.

Hay que mencionar que, como era de esperar, el incremento de participación es muy destacado en los primeros días de la campaña de encuestas, cuando toda la población objetivo aún no había participado. En estos días no solo se consiguió la más de la mitad de la participación en prácticamente todas las universidades, sino que también se superaron las cuotas mínimas previstas para casi todos los colectivos y campus, no requiriendo tomar casi ninguna medida adicional para dar a conocer la encuesta a segmentos que tuviesen menor participación. También cabe señalar que los primeros días fueron los días que más encuestas no finalizadas se recibieron, en relación con las encuestas finalizadas.

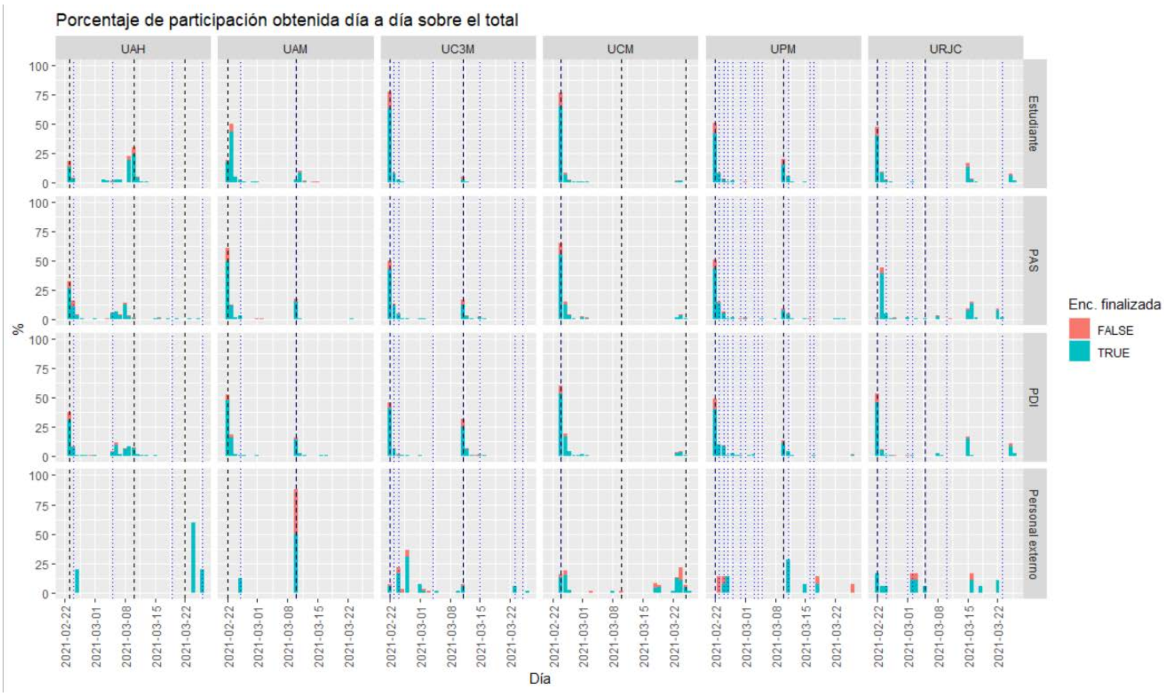

Figura 4. Porcentaje de participación obtenida día a día sobre el total por universidad y colectivo.

Se puede observar cómo los colectivos a los que se les pudo enviar mensaje directamente desde las universidades, es decir todos los colectivos salvo el personal de servicios externos, siguen una pauta similar. Sin embargo, mientras las llamadas de participación tienen un efecto muy puntual y concentrado en el día del envío del mensaje sobre el colectivo de estudiantes, el mismo efecto se prolonga, en cierta manera, a uno o dos días más en los colectivos PAS y PDI.

En relación con el efecto de redes sociales (Twitter) parece ser que estas acciones no han tenido efecto sobre la participación. Las cuentas de interés de las universidades generaron un total de 55 tweets y retweets, de los cuales, el 40% fueron emitidos durante la primera semana de la campaña. Estos mensajes apenas recibieron interacciones que aumentasen la difusión de la comunicación de la encuesta. De media, cada tweet era retwiteado menos de 5 veces, obtenía 3 “me gusta” y apenas tenían interacciones en forma de respuestas o citas; además, gran parte de las interacciones se recibieron durante la primera semana.

Un caso de estudio son las cuentas de interés de la UPM, que enviaron un total de 27 tweets y retweets en todo el periodo de la campaña de la encuesta. La cuenta general de la UPM (@La_UPM) tenía unos 44.500 seguidores durante la campaña, mientras que la cuenta de la biblioteca (@biblioUPM) casi 4.000 seguidores. Los mensajes relacionados con la campaña de encuesta tuvieron la misma reacción en ambas cuentas en cuanto a número de veces que estos fueron retwiterados, no así en cuanto al número de “me gusta” en cuyo caso el que solamente la cuenta @La_UPM recibía este tipo de interacción.

En relación con la hora de inicio de las encuestas (Figura 5), la gran mayoría de las encuestas (90%) se iniciaban entre las 10 y 20 horas, para todos los colectivos y universidades, y tanto para encuestas finalizadas como para las no finalizadas. Este comportamiento era el esperado puesto a que son horas en que hay actividad académica.

Los días cuya hora mediana se acercaba a alguno de los extremos del 90% de respuestas suele coincidir precisamente con días con poca participación. Obsérvese que estos resultados tienen una gran variabilidad, debido precisamente a la disparidad de número de encuestas obtenidas pudiéndose considerar un comportamiento casi aleatorio de la hora de inicio en dicho, y sin envío de correo electrónico.

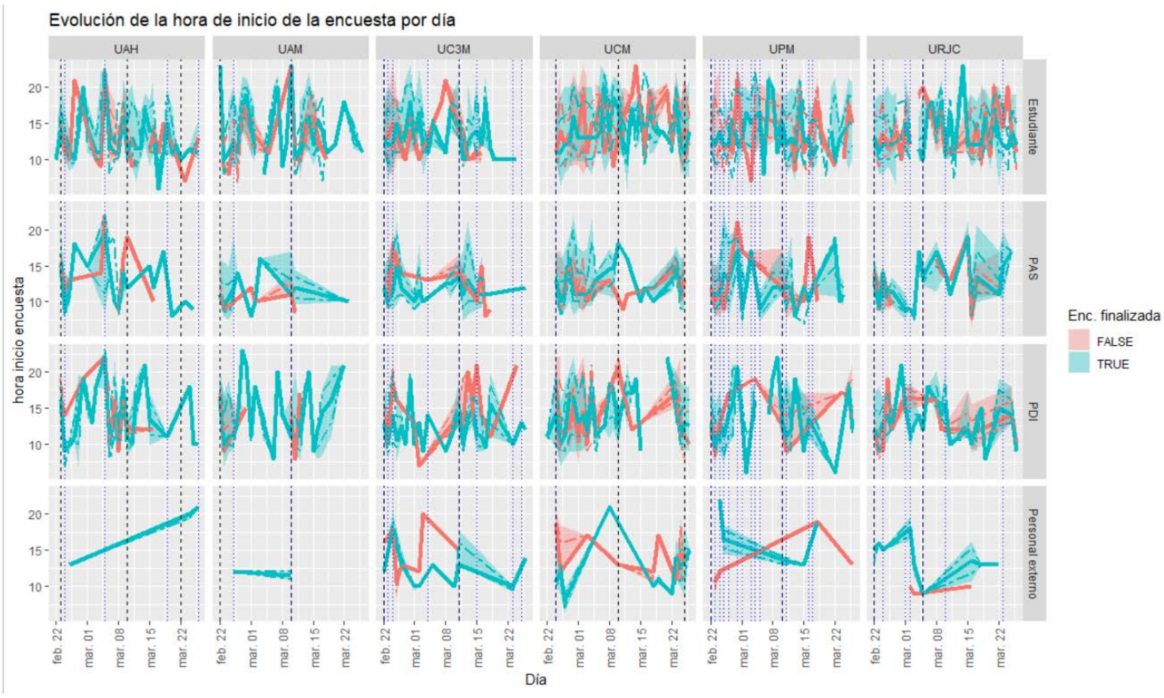

Figura 5. Evolución de la hora de inicio de la encuesta por día, colectivo, universidad y separado entre finalizadas y no finalizadas. La línea gruesa hace referencia a la hora media, las líneas discontinuas hacen referencia al valor del primer cuartil (inferior) y tercer cuartil (superior) y la sombra hace referencia al intervalo de tiempo que contiene el 90% de las respuestas de ese día (P10-P90).

Finalmente, otro indicador de interés era el tiempo que se dedicaba a la encuesta. El 95% de las encuestas necesitaban menos de 60 minutos para completarlas, siendo el 5% restante encuestas no finalizadas hasta que SurveyMonkey cerraba sesión. La evolución del tiempo necesario para las encuestas realizadas en menos de 60 minutos puede verse en la Figura 6.

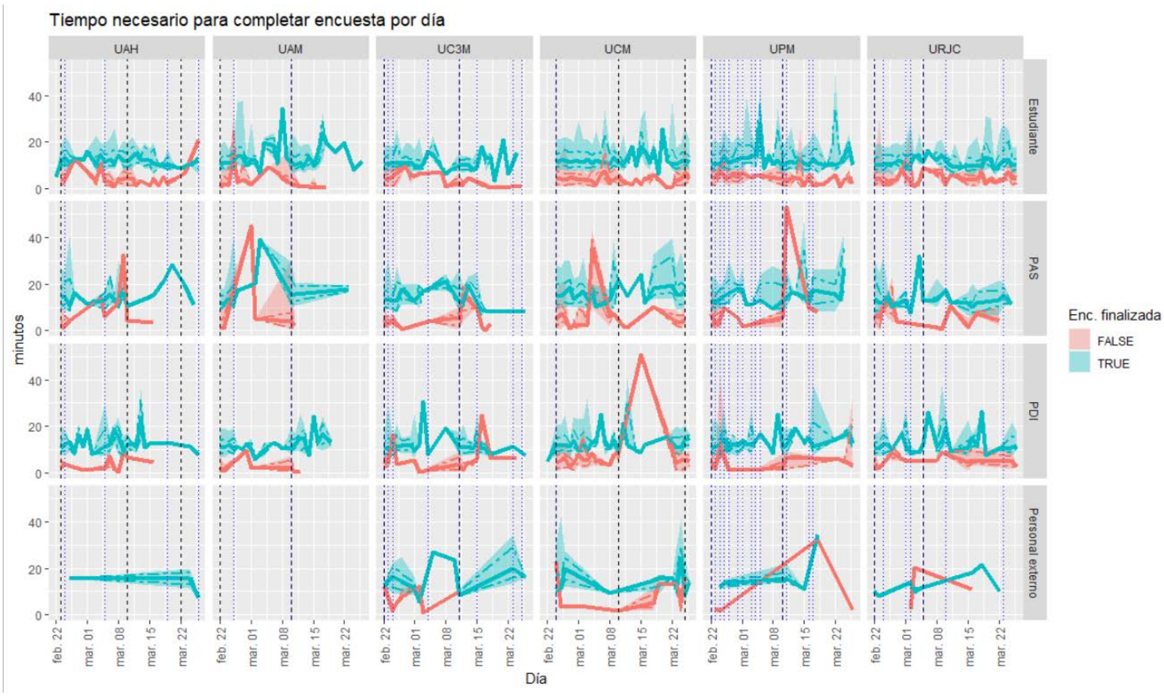

Figura 6. Evolución del tiempo usado en cada encuesta, por día, colectivo, universidad y separado entre encuestas finalizadas y no finalizadas. La línea gruesa hace referencia a valor mediano del tiempo requerido para la encuesta, las líneas discontinuas hacen referencia al valor del primer cuartil (inferior) y tercer cuartil (superior) y la sombra hace referencia al intervalo de tiempo requerido para realizar la encuesta que contiene el 90% de las respuestas de ese día (P10-P90).

Se observa una cierta igualdad en el tiempo de respuestas por colectivo y universidad, no así por si la encuesta se finalizaba o no. El valor medio de las encuestas finalizadas para todos los días rondaba los 15 minutos, que era lo estimado, sin embargo, el colectivo de estudiantes parece que requirieron de un poco menos de tiempo que el resto, salvo en casos muy puntuales en días en los que había poca participación y para los casos en los que se presupone que se cerraba la sesión voluntariamente antes del cierre automático. En el caso de las encuestas no finalizadas solían requerir menos tiempo.

Las campañas de comunicación parecen no tener efecto sobre los tiempos necesarios.

7. DISCUSIÓN Y CONCLUSIONES

La campaña de encuestas del Plan de Movilidad Universitaria Sostenible se realizó en unos tiempos atípicos debido a las restricciones por la pandemia de la COVID-19. Sin embargo, el haber alcanzado más de 35.000 encuestas en los campus presentados en esta comunicación, lo que representa un 17% del total de la comunidad universitaria es un éxito.

En general, parece que el envío masivo de la carta mediante al correo institucional es la acción de comunicación que mayor efecto ha tenido en la participación, especialmente para los grandes colectivos de la comunidad universitaria.

Este hecho puede remarcar la importancia de mostrar públicamente el apoyo a este tipo de encuestas y participar en acciones de comunicación por parte de las máximas autoridades académicas de cada universidad. Por otro lado, se podría considerar que el envío del correo electrónico pudo haber tenido mayor efecto que en otras circunstancias por el hecho de realizar una gran parte de la actividad académica diaria en formato virtual que pudo provocar una mayor atención a dicha vía de comunicación y, en consecuencia, fomentar la participación.

El resto de las acciones de comunicación parecen que no han tenido ningún efecto, tanto por el hecho de no haber visto ningún efecto en los días en los que éstas se aplicaban como por la baja interacción reportada.

La campaña de encuestas del PMUnivS se pueden realizar las siguientes recomendaciones relacionadas con el objeto de esta comunicación de cara a futuras campañas similares:

- En cuanto a las estrategias para animar a la participación, se podría recomendar el implicar a las máximas autoridades de la universidad en las acciones de comunicación puesto a que parece favorecer la participación. De la misma manera, que los perfiles de redes sociales a usar por la campaña de encuesta tengan un elevado número de seguidores antes de comenzar la campaña, esto requeriría ir, poco a poco, generando la red mediante la publicación de tweets que pudiesen convertir a estos perfiles en los referentes de la movilidad universitaria (noticias, avisos y miscelánea relacionada con el objeto de la encuesta). En relación con el material físico de apoyo, éste debería tener tanto el enlace a la encuesta, preferentemente vía código QR, y el nombre de los perfiles de las redes sociales.
- En relación con el seguimiento de las estrategias para animar a la participación y detección de comportamientos anómalos, se podría recomendar el incluir dentro de la encuesta preguntas del tipo para saber cómo ha conocido la encuesta, y si la ha contestado al momento de recibir el enlace o ha esperado, entre otras.
- Finalmente, y en relación con la investigación sobre los efectos de la comunicación, se aconsejaría que en próximas campañas las acciones de comunicación también se diseñasen, desde el principio, incluyendo este tema como objeto propio de la investigación. Especialmente en situaciones de relativa normalidad en la que se pueda comparar el efecto de las acciones físicas con las acciones virtuales.

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THE POTENTIAL IMPACT OF USING TRAVEL APPS AS A TOOL TO REDUCE CAR USE IN CITIES. A LITERATURE REVIEW

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ABSTRACT

64% of total trip-km are made in urban environments and these phenomena threaten urban sustainability (Van Audenhove et al. 2014). In the last decades, cities have been applying different policy measures to reduce car use. But they have notable limitations and usually produced small impacts (Sunio y Schmöcker 2017).

Smartphone has emerged as a promising alternative tool to enhance the effects of the policy interventions, because it can overcome several limitations and improve their efficient adoption of sustainable options. Travel apps can be very useful because they provide accurate and real-time information. In addition, user-created information could greatly reinforce information from operators.

A review of the literature of 98 recent papers was performed. It had two main objectives: which factors influence commuters to use travel apps; and second, what persuasive interventions supported by travel apps produce changes towards a more sustainable mobility behavior.

Some facets offered by apps are effective for changing travel behaviour: individualized advice, feedback on one's own behavior and social comparisons between users. The GoEco! experimental travel app, provided feedback and social comparisons on travel behavior among users (Cellina et al. 2019). It was found to produce a statistically significant change in individual mobility patterns.

Travel apps remain underutilized, especially in suburban travel. Scholars found factors that influence app usage: curiosity, expectations of increased utility, attractive design and performance attributes are influence factor for app usage.

In contrast, environmental motives, privacy (desire not to share information) and age (older people are less likely to adopt apps) do not influence or do so not significantly.

The findings of the literature review show that, moreover, to increase apps usage, app design and implementation requires different strategies for each segment of the population.

There are groups of people who are more likely to use apps (e.g., technophiles and young people).

1. INTRODUCTION AND BACKGROUND

This article consists of a systematic literature review on the potential impact of the use of travel apps as a tool to reduce car use in cities, specifically in the periphery.

While in the core of metropolitan areas there is an increased use of travel applications and the modal share of total sustainable travel modes is often important, this not the case in the outskirts.

Almost 50% of the population of OECD (Organisation for Economic Co-operation and Development) countries live in urban areas (OEDC 2016) due to better economic opportunities and the availability of services. Cities are facing an accelerated sprawling process, increasing travel distances, making public transport systems less competitive, and becoming suburban mobility more car dependent. As a consequence, 64% of total trip-km are made in urban environments and is expected to triple by 2050 (Van Audenhove et al., 2014).

These phenomena threaten urban sustainability (Lyons, 2018) because of their well-known impacts, not only on the environment but also on social and economic issues, such as distributive effects, equity and mobility justice (Pereira, Schwanen, Tim y Banister 2017).

Therefore, there has been a challenge for several decades to persuade commuting through sustainable travel modes. And multimodality is an attribute of travel that increases sustainability.

Measures implemented to pursue that challenge have been generally classified as hard and soft. Soft measures started to conduct by public administrations due to hard measures often requires too high investments.

Soft measures look for to change travel behaviour towards sustainability ways. Soft measures have been implemented through, what is most generally called, Travel Behaviour Change Programs (TBCP). TBCP began to be implemented approximately 20 years ago.

At the same time, urban lifestyles and mobility needs are adapting to the requirements and opportunities of the digital age, characterised by the use Information and Communication Technologies-based activities (Mokhtarian 2009). Smartphone arrival has impacted our daily life. In the transportation field, it has emerged as a promising alternative tool to enhance the effects of the TBCP interventions, due to it can overcome several limitations.

This literature review has two goals:

- Firstly, to review the state of the art and practice regarding the factors of travel apps adoption. Two main groups of elements can be identified: the internal, regarding the app itself, and the external related to the user characteristics. The internal ones include aspects such as simplicity, appearance, performance, integration of modes, ticketing, etc. The external factors are related on the user personal traits, social norms, socio-economic and geographical features, etc.
- Secondly, to conduct an exhaustive analysis of the so called 'persuasive interventions' to foster the modal transition. Recent findings suggest that real time informed decisions tend to be sensitive to sustainability and social impacts. We aim to conduct a literature review to extend their impacts as driver for persuasive interventions for motivating changes towards sustainable metropolitan mobility. Apart from public transport information, there is a growing interest to explore the link between public transport and Park & Ride facilities. This option is not properly connected with travel apps, then users do not take informed decisions when accessing by car to city centres.

This article is framed within the U-MOVE research project, funded by the Ministry of Science and Innovation (PID2019-104273RB-100). "U-MOVE" is the acronym for "Intelligent strategies for sustainable urban mobility: the role of travel apps".

2. METHODOLOGY

A systematic literature review was carried out with the aim of working with the most complete sample of available scientific publications. For this purpose, the Scopus database was chosen due to its high scientific impact, the diversity of databases that comprise it and the versatility of the subject matter and formats or types of documents it supports (De las Heras et al. 2021). The literature selection scheme is shown in Figure 1.

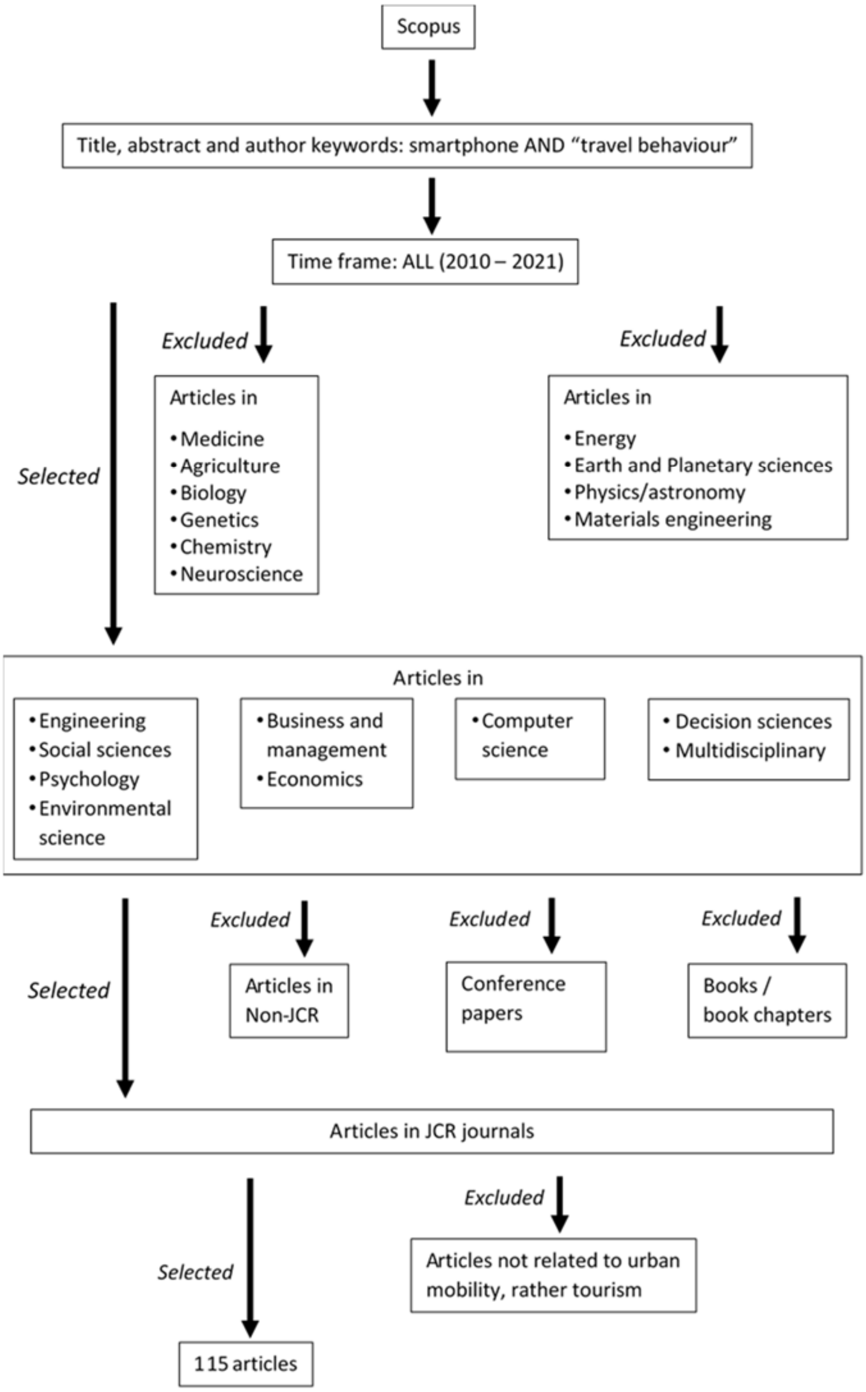

Figure 1 – Process of selection and exclusion of papers indexed in Scopus.

The keywords used in Scopus had to be related to the influence of the use of travel apps on the reduction of car use. The keywords were: 'smartphone', 'travel behaviour'. The query string used was: smartphone AND “travel behaviour”.

Author title, abstract and keywords were used as search fields. Otherwise, articles in which "smartphone" and "travel behavior" are not a key part of their content could have been considered. Further filters were used to select the most relevant articles for this research.

Regarding the subject matter of the articles, those that were considered unrelated to the research were excluded. As for the type of document, only articles published in JCR journals were considered. Finally, an important part of the papers related to 'tourism' and not to mobility were not considered. For this purpose, 'NOT tourism' was added to the query string. Finally, 115 scientific articles were selected for the literature review.

VOSviewer is a bibliometric and network analysis software (van Eck y Waltman 2013). It is a very valuable tool for a literature review and has been widely used for this work.

From the list of 115 papers, the VOSviewer software was used to find out the most relevant keywords. The software has different utilities and, in this case, attention was paid only to the keywords. It was obtained: a) a graph of co-occurrences with the keywords and, b) a list of the keywords and the number of papers (from the list of 115) in which they appear.

In order to ensure that the literature review includes the most studied concepts in the discipline, the keywords with the highest number of occurrences were selected. Finally, of the 115 papers, only those in which one of these keywords appeared (in title or abstract or author keywords) were studied in depth.

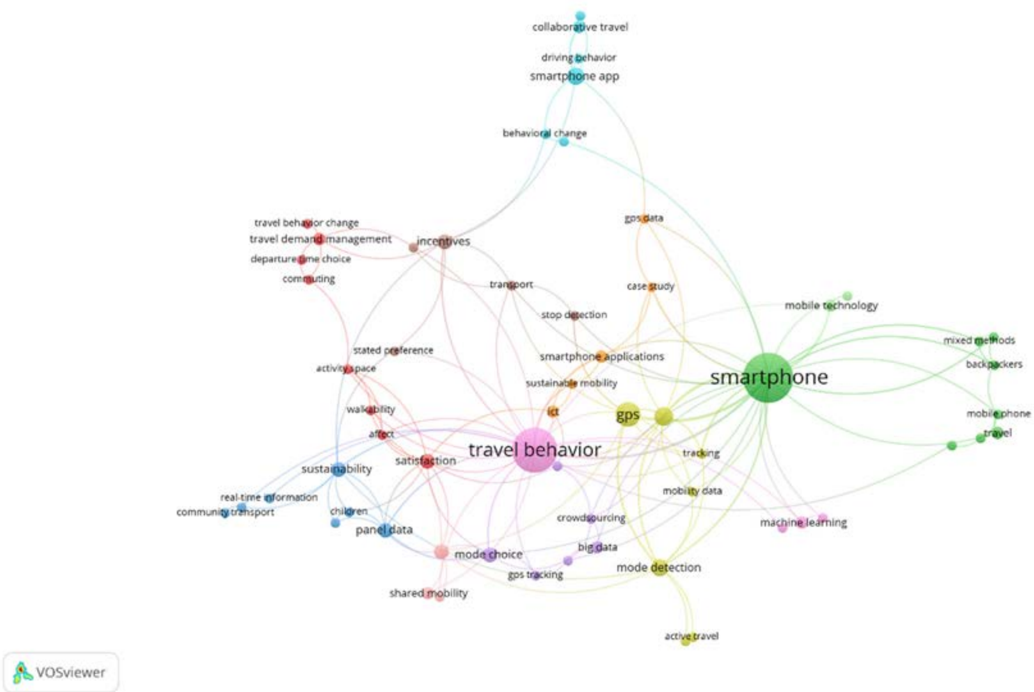

Figure 2 – Map of co-occurrences of keywords (from the title, abstract and author's keywords). Source: VOSviewer.

Figure 2 shows shows the co-occurrence map obtained through VOSviewer. The coloured balls “smartphone”, “travel behavior” and “GPS” are the largest, so these keywords have the highest number of occurrences in the list of 115 papers.

Position	Keyword	Occurrences	Total link strength
1	Smartphone	29	19
2	Travel behavior	24	17
3	GPS	9	13
4	Travel survey	6	11
5	Mode detection	5	9
6	Smartphone app	5	1
7	Incentives	4	4
8	Mode choice	4	7
9	Panel data	4	7
10	Public transportation	4	5
11	Satisfaction	4	4
12	Sustainability	4	5

Table 6. Classification of the occurrence of keywords (in the title, abstract and author keys). Source: own elaboration.

Table 6 shows the number of occurrences of the keywords. "Smartphone", "travel behaviour" and "GPS" have the highest number of occurrences: 29, 24 and 9, respectively.

The keywords "smartphone", "travel behaviour" and "GPS" were selected. 98 of the 115 articles included at least one of these three keywords. These 98 articles were analysed in depth.

3. RESULTS

This section presents the relevant results of the review of the 98 selected documents that have been analysed in depth.

Cities has been planned for a massive use of the car and a lot of resources are needed to revert the situation. Due to changing the urbanization is highly cost, public administrations has been trying to look for other kind of measures to reduce the car usage. Interventions to modify the commuter travel behaviour, as TBCP, has been implemented commonly last decades.

TBCP programs help to reduce the car usage (Arroyo et al. 2018), but only produce small derived effects (Sunio y Schmöcker 2017). Smartphone arrival may dramatically help to change the travel patterns through mobile apps adoption.

Recently some TBCP programs are starting to carry out through smartphones. They are habitually called technology-based interventions.

They consist of persuasive strategies and are carried out through smartphone travel apps.

3.1 Persuasive interventions to foster sustainable mobility

At the same time, the MaaS approach is a new tool to promote smart mobility with a promising perspective (Jittrapirom et al. 2017). Comparing to interventions programs, like TBCP, MaaS projects do not exactly include explicit persuasion strategies. MaaS concept is still under development, but they are commonly developed through an app that integrates the services of multiple travel modes (public and private) with their related information and generally tries to work through packages subscriptions (Arias-Molinares y García-Palomares 2020). These attributes seem to be useful for the commuters but there is still a lack of pilot evidences.

Cost savings is an important factor influencing the decision to switch to public transportation (Abou-Zeid y Ben-Akiva 2012; De Witte, Macharis y Mairesse 2008). Some people were interested to use UbiGo mobility app (MaaS) because expected to reduce costs comparing to the car (Sochor, Strömberg y Karlsson 2015).

Another important factor to switch from car to public transportation is to have a precise and reliable information about travel modes. There are some studies that affirm a notable misperception with public transport (Abou-Zeid y Ben-Akiva 2011; 2012). One study even stated that 50% of citizens have a significant lack of information about transit alternatives (Brög, Erl y Mense 2002). The quality of public transportation service logically has increased along time (Sukor y Basri 2019).

Travel apps can easily offer multimodal, real-time and reliable information. An experiment was proposed to participants to use an existing travel app called Metropia (Li, Chen y Tian 2021). Metropia provides to user real-time traffic information, travel feedback and distributing monetary rewards. It was found that helped users save 5% - 10% of their travel time, due to avoiding traffic peak hours.

On the other hand, Park and Ride facilities are an appropriate measure to reduce car use (Duncan y Cook 2014). Regarding multimodal travel apps, pilots conducted by academics do not typically include P&R in the multimodal travel system.

Also, existing travel apps typically do not include them. Nevertheless, P&R information included in multimodal information affects travel choices (Gan y Ye 2018). Therefore, travel applications should include P&R information to encourage the modal shift from car to public transportation.

Regarding the MaaS implementation, more than a few MaaS pilot projects have been carried out. UbiGo was the first MaaS experience and consisted of a experiment mobility app. It provided an integrated mobility service (public transport, taxi, carsharing, bikesharing, rental cars) and works through a monthly subscription service. 97% of the participants wanted to continue using UbiGo at the end of the test (Sochor, Strömberg y Karlsson 2015).

Two MaaS projects that have started recently in Asia have been assessed (Chang, Chen y Chen 2019). UMAJI is a mobile platform for trip planning and payment services. The app integrates Metro, bus and public bike services in the Taipei-Yilan corridor of 40 kilometers. There is a monthly pass for using the three services. Public transportation has increased 3,2% in the first 6 months (80% of the increased trips are from the existing users). MenGo is an app of MaaS in Kaohsiung metropolitan, and integrates mass transit (city buses, inter-city buses, MRT, light rail, ferries) and shared transportation (public bicycles). There are four types of monthly service packages. Users of motorized vehicles contribute 21% of MaaS MenGo members.

Due to the positive impacts of travel applications, scholars are studying persuasion features, within travel applications, to switch to sustainable modes. For example, a prototype app with motivational features was developed for inducing sustainable travel choices: goal setting (inviting users to set weekly goals), self-monitoring, encouragement (personalized messages according the user profile and travel behavior) and social-sharing features (leaderboard of participants eco-scores weekly provided). An improvement in the use of sustainable modes of 14% was found (Gabrielli y Maimone 2013).

Social comparison is one of the strongest motivational features. Favorable comparisons to others (e.g. shorter commute time than others) enhance commute satisfaction (Abou-Zeid y Ben-Akiva 2012). It has also been featured by a persuasive travel app called GoEco! that exploits information feedback elements and promotes a social comparison of their performance, within a gamified framework. It was found to bring about a statistically significant change in systematic individual mobility patterns, reducing both energy consumption and CO2 emissions in Ticino, where car-dependency is deeply rooted. In Zurich, where individual mobility patterns are already optimized and car-dependency is lower, no significant effects were found (Cellina et al. 2019).

Some authors concluded that including feedback information to the participants in persuasive smartphone applications is a successful factor for promoting a sustainable travel behaviour (Andersson, Winslott Hiselius y Adell 2018; Li, Chen y Tian 2021). Feedback on one's travel history can affect one's awareness of their impact on the environment, intentions to change behavior, and actual behavior change" (Jariyasunant et al. 2012)). Feedback information may include a behaviour comparison among travel app users.

The registered information of the travel application can be processed according to the characteristics of the user and provide personalized/individualized advice. It would be a step beyond simple feedback information. It is known that individualised advice is an effective persuasive technique (Cellina et al. 2019; Fujii y Taniguchi 2006). The reasons behind each person chooses to commute in a specific mode of transport are different from those of the others. (Cellina et al. 2019) experimented the use of GoEco! app that provided "bicycle and walking-friendly suggestions for alternatives and weather-aware personalized recommendations, challenges and badges". (Gabrielli y Maimone 2013) developed a prototype mobile app that sent personalized messages encouraging sustainable travel choices according to his profile and travel behavior. An improvement in the use of sustainable means of transport was observed. (Ahmed et al. 2020) developed an algorithm that determined realistic walking, cycling and public transport potential in an activity-travel routine of an individual by considering constraints related to personal, household, mobility and urban environment.

Individualised advice may be mixed with social comparison techniques. (Jariyasunant et al. 2012) carried out an experiment developing an app which unobstrusively tracked users location and with that collected data participants received feedback (in a website) with trends and comparisons with various peer groups. They observed a significant shift from driving to walking.

Some scholars have assessed planning trips as a proper alternative towards reducing car dependency. Planning a trip consists of basically to evaluate which is the best alternative to arrive to a specific destination. If a Travel Feedback Program (TFP) required participants to create a behavioural plan for their travel behaviour, it resulted in a dramatic increase in TFP effectiveness in terms of behaviour change (Fujii y Taniguchi 2006).

Recorded travel information of the commuter may be a great tool to create and suggest personalized behavioural plans. Based on the recorded travel diary of the individuals, a website was developed with pro-environmental personalized travel plans that were suggested along with pro-environmental and pro-health impacts (Ahmed et al., 2020). It was found a decreasing in car dependency and increasing in physical activity.

Experts agree that market targeting is key to effective persuasion interventions. Persuading interventions to foster public transport may be more effective for non-riders than for frequent riders (Fujii & Taniguchi, 2006). An experiment was carried out encouraging MIT university pupils with free public transportation tickets and was found that free public transportation tickets worked better for commuters more inclined to switch (Abou-Zeid & Ben-Akiva, 2012). Related to this, an study affirmed "it is not fruitful to convince Devoted Drivers to change transport mode with marketing since they oppose messages that promote sustainable transport" (Andersson et al., 2020).

Travel Feedback Programs may be more effective for new residents (Fujii y Taniguchi 2006). Though that statement could be valid for all the persuading interventions. Logically, new residents have not yet developed habits to commute, and habits strongly influence travel patterns (Pronello, Simão y Rappazzo 2017).

In addition, personal health plays an important role over some commuters and they have preference of active travel. Trips with high walking or bicycling rates have priority over public transit. The experimental web with pro-environmental and pro-healthy travel plans suggested (Ahmed et al. 2020) led to the conclusion that public transport options failed to significantly persuade individuals to shift from car to public transport, but active modes did (walking and cycling).

Regarding the sample limitations of the classical intervention programs (TFPs, TBCPs, etc.), a study explored if programs who consists of providing travel feedback information to the participant (Travel Feedback Programs, TFPs) can be replicated without a travel counselor (Jariyasunant et al. 2015). It was developed “a computational system in the mobile cloud” surrogating the travel counselor and the model showed that “the more frequent the interaction with the website, the greater is the increase in the amount of walking/biking”.

3.2 Factors for travel apps adoption

Some experiments showed that smartphone apps influence to change travel choices towards sustainability patterns (Shaheen et al. 2016). A lot of research is being done recently to find out what factors influence the adoption of travel app usage. Although there is a difficulty to quantify the importance of each of the factors studied.

Self-interest was found as the primary interest of trip efficiency improvement for the travel apps adoption intention (Dastjerdi et al. 2019). The main motive (63% of survey respondents) to adopt UbiGo app was the curiosity to know the integrated mobility service could offer them. Many of the respondents stated the desire to not own a car due their work and cost. Ubigo participants expectations regarding the use of travel applications were "To reduce their travel costs, facilitate payment, gain access to more modes of transport, they expected the application to be easy to use and safe" (Sochor, Strömberg y Karlsson 2015).

The app involvement is related to the hedonic and utilitarian benefits perceived (Fang et al. 2017). Hedonic and utilitarian benefits could be classified as self-interest benefits.

Cost and time savings would be utilitarian motives to start to use an app. Real-time and reliable travel information are (also utilitarian motives) an important aspect for commuter travel choice. Travel apps could offer easily that specific information to the commuters. According to (Li, Chen y Tian 2021), “traffic information is strictly in accordance with real-time traffic conditions rather than historical data”.

A survey was carried out for commuters and it revealed that apps like Google Maps do not compete with specific transit apps that include real-time information because daily commuters require that specific information of their routes (Romero et al. 2020).

Regarding the driving time estimation reliability of the apps, Google Maps underestimates the total driving trip time in urban areas when parking places are scarce (Wagner et al. 2021). The estimate does not include the specific time spent parking and walking time to the car from the origin and from the car to the destination. A time estimation model was developed to search for on-street parking (Mannini et al. 2017) and it could supplement the driving time estimate provided by travel apps.

To be entertaining, enjoyable (Gupta y Dogra 2017) and easy to use (Gupta y Dogra 2017; Dastjerdi et al. 2019; Fang et al. 2017) are important factors for using apps. Those aspects are generally called as hedonic motivation, that influences behavioral intention to use apps. These factors are related to the performance app, that is an influential factor for using apps that involves several features. Based on a hedonic motivation perspective, regarding the game elements of app including self-monitoring, information sharing and bonus point collection could be considered as game elements of the app (Seebauer, Stolz y Berger 2015).

There are also individual motivations that come from social aspects. (Seebauer et al., 2015) relate that social motivation to social comparisons and assert the possibility of competition between them if individuals share their information through social media. “In the field of social psychology, sociology and marketing, this is known as social value reflecting the (positive or negative) outcomes of the ownership and use of a product for one’s (self-) identity and social status. It is viewed as the product’s ability to develop social self-concept”. According to (Fang et al. 2017), social interaction is a factor to influence use intention of travel apps.

Social motivation could be also related to the privacy. Maybe it should not be called social motivation, but more precisely privacy barrier. Real-time information is required by the apps, and it could be provided by the transport authorities and operators or by the users. Regarding the users, not all of them share their information or evaluation services. Privacy, safety and even security could be the cause to not share information (Magano y Cunha 2019). Regarding collaborative travel, an study was carried out and concluded that safety has a highly importance, being data privacy a core issue (location data being made available to other users) (Dickinson et al. 2017).

Related to safety, privacy and security in collaborative travel is social trust. The strength of social ties plays a marked role in collaborative travel. Successful implementation is more likely in communities where social ties are established (Dickinson et al. 2017), or in regions where social trust is high.

If the app only suggested traveling with someone who is in your circle of friends, or acquaintances, it might work. But there would be a great difficulty in defining which is each person's circle of friends. The user could define a list of friends, or at least "travel friends".

In addition, environmental-friendly attributes are another notable non-monetary aspect to app adoption (Seebauer, Stolz y Berger 2015). In the specific case of car sharing, (Mattia, Guglielmetti Mugion y Principato 2019) affirm that “Environmental drivers affect the intention to re-use free-floating car sharing to a lesser extent than the utilitarian motives”.

This would confirm (Dastjerdi et al. 2019) when they state that self-interest as the primary interest to app adoption. “Environmental awareness, favorable attitude toward travel information technologies, performing conservation behavior, and a personal desire to participate in organized environmental activities, affect individuals’ perceptions of the benefits of the travel app (Mehdizadeh Dastjerdi et al. 2019).

For increasing the apps usage, segmentation of the target population is recommended to better customize to user’s profiles (Andersson, Winslott Hiselius y Adell 2018). It is important to know the target population, their needs and expectations, and to account for specific groups of users (Dastjerdi et al. 2019). (Dickinson et al. 2015) state the need to identify and attract potential users and illustrate how the travel app might meet their needs and benefit them.

There is an important relationship between the personality of individuals and the degree of acceptance of the technology. The idea of technophilia indicates the affinity for technology. According to (Svendsen et al. 2013),“the pattern of influence (from personality traits to technology acceptance) will differ depending on the technology or service in question”. (Velazquez, Kaplan y Monzon 2018) point out that user’s expectations on the app, affinity for technology (technophilia) and the previous use of other transport apps are factors that influence app use intentions. Technophilia is a statistically significative factor for explaining the willingness to use a travel app both everyday and exceptional trips (Seebauer, Stolz y Berger 2015).

Travel app developers and transport operators could focus their campaigns to strengthen the travel app involvement and transit use on the technophiles (Seebauer, Stolz y Berger 2015), due to those are easier to engage and they may convince to others. The difficulty to approach the individual’s affinity for the technology might be reduced thanks to a study of (Seebauer, Stolz y Berger 2015). They have established the validity of a technophilia measure through a survey of seven questions.

"Public engagement is important in ensuring the success of the system implementation" (Seebauer, Stolz y Berger 2015), due to "public acceptability of sustainable solutions could be triggered by public engagement". Therefore, technophiles are a proper segment to start to use the apps. Psychological involvement is related to the social benefits perceived, and the hedonic and utilitarian too (Fang et al. 2017).

Regarding sociodemographics, the age is a factor that explains the willingness to use a travel app (Seebauer, Stolz y Berger 2015). (Dickinson et al. 2017) tested a collaborative travel app, and age emerges as a smaller barrier to app adoption. In addition, (Seebauer, Stolz y Berger 2015) found that technophilia attribute allows more precise customer segmentation than its sociodemographic proxies age and gender.

According to (Fang et al. 2017), both app design and performance attributes are important factors for the use adoption. (Andersson, Winslott Hiselius y Adell 2018) agreed that appealing design is an essential factor for app usage and (Dastjerdi et al. 2019) remarks that design needs to be implemented from an user's perspective.

In addition, there are some technological factors that also influence to use the apps. Relative advantage is the name of the degree to which an innovation is perceived as being better than the previous ways of performing the same task and (Fang et al. 2017) affirm is a factor that influence potential users to app adoption. Other significant technical factor is what is called as app portability, that is related to use the app through the different mobile operating systems (Android, Mac Os, etc.) (Rogers 1995).

4. DISCUSSION AND CONCLUSIONS

In the last decades, governments have been applying different types of intervention programs in existing transport systems, besides large investments to upgrade service quality, in order to reduce car use. But these interventions have produced usually small impacts.

The advent of smartphones could overcome these limitations and travel apps are a promising tool. Some objective key aspects of travel apps that can improve the current information is manyfold:

- Apps provide a lot of information about travel alternatives (both real and non-real time). Non-users tend to have a notable misperception about public transport and travel apps could easily provide accurate, useful information. Real-time information may be a powerful tool provided by apps and this real time information may be highly enriched if it could reinforce the operators' information with information created by the very users.

- Apps provide personalized advice, based upon registered information. A plan for commuting over a period (for example, each week) is known to be an effective measure.

As a consequence of the previous aspects, apps provide travel time and travel cost savings, usually by means of combination of different modes of travel, this including park and ride.

Apps are a tool of persuasive strategies for sustainable travel behaviour in several aspects:

- Individualized advise is an effective persuasive technique. Apps ~~can~~ provide feedback information about one's behaviour, which is a successful factor for promoting a sustainable travel behaviour.
- Social comparisons can affect notably the individual behaviour.
- comparison of behavior among travel app users could reinforce adoption

Some are strong factors for adoption:

- Curiosity is an initial strong motivation.
- Appealing design, portability and performance attributes are important factors for app adoption. Being entertaining, enjoyable and easy to use are other important factors. Self-monitoring or information sharing can be considered entertainment elements of the application.
- Privacy, and even security, could be the cause not to share information. Many users do not want to share their information. Clear policies in this field are a must.
- Expectations of increased utility (reduce travel costs, have access to more travel modes, etc.) may influence the adoption of apps.
- Social motivation is related to the social comparison and there is a possibility of competition between individuals if they share their information through social networks.
- Social acceptability may be triggered by public engagement.

Environmental motives are not important factors for adoption, although some analyses point out that having a good image of oneself influences behaviour. But compared to utilitarian motives, environmental ones are less important.

In any case, app design and implementation require some population segmentation:

There are groups of people who are more likely to use apps. These groups are suitable segments to start using the applications because they could generate public acceptance or could make an interesting advertisement for the applications. Technophiles are an obvious group to start with.

Regarding sociodemographics, age is a factor that explains most of the willingness to use a travel application. Older people are less prone to app adoption.

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ESTUDIO PARA LA IMPLEMENTACIÓN DE UNA APLICACIÓN MÓVIL PARA VIAJES COMPARTIDOS DE LA COMUNIDAD ACADÉMICA ENTRE SU VIVIENDA Y EL CAMPUS UNIVERSITARIO. FACULTAD DE INGENIERÍA, UNIVERSIDAD NACIONAL DE COLOMBIA - SEDE BOGOTÁ

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RESUMEN

El presente proyecto se plantea como una solución para la disminución de contagio de Covid-19, a partir de la evaluación de diferentes alternativas para el desplazamiento bioseguro desde y hacia el campus de la Universidad Nacional de Colombia Sede Bogotá en el marco de la convocatoria “Hacia el regreso seguro al campus” de la Facultad de Ingeniería. La alta probabilidad de contagio representa un riesgo para las personas que hacen uso del transporte público colectivo dentro de la ciudad, lo que incluye a la mayoría de las personas de la comunidad universitaria que usan este como su principal medio de transporte.

Por ello, se realizó una investigación y estructuración de una aplicación móvil la cual tiene como propósito el uso de carro compartido y se coordinen grupos de bicicletas para movilizarse en estos trayectos.

Como metodología se analizó información de residencia de la comunidad universitaria a partir de bases de datos y encuestas, estas últimas también permitieron identificar vehículos disponibles y disposición para viajar en carro y bicicleta. Por otra parte, se analizaron otras aplicaciones existentes que facilitan la interacción entre las personas para compartir vehículo o generar grupos de ciclistas. Una de las principales razones por las que la gente no usa la bicicleta es la inseguridad, por lo que generar grupos de ciclistas permitiría a los usuarios sentirse más seguros gracias al acompañamiento brindado por otros compañeros. Además, se evidenció un alto interés de los encuestados por participar de estos grupos y se observó que los viajes en bicicleta dentro de la facultad se duplicarían respecto al antes y después de la emergencia sanitaria, pasando del 15% al 30%.

Finalmente, con el apoyo de un profesional especializado se inició la estructuración y generación de una aplicación móvil que contenga las principales funciones necesarias para la creación de grupos para la movilidad segura.

1. INTRODUCCIÓN

La elaboración del proyecto se proyectó para ser una herramienta fundamental como medida de prevención del contagio, de modo que llegado el momento de retornar al campus universitario sea posible hacerlo exitosamente, con la logística implementada.

La metodología de trabajo cumplió con los siguientes objetivos: Recopilar y analizar información de residencia de los miembros de la comunidad universitaria, vehículos disponibles y disposición para realizar viajes en otros modos de transporte (carro y bicicleta) considerando el acompañamiento y la creación de grupos para un viaje bioseguro.

Por otra parte, se planteó analizar aplicativos existentes en el mercado, que facilitan la interacción entre la persona que posee el vehículo particular y aquellos que comparten un origen o destino cercano a su vivienda, sitio de estudio, sitio de trabajo y/o ruta de transporte; y a su vez se propuso comunicar y juntar a aquellas personas que usan la bicicleta como medio de transporte, creando grupos de ciclistas que cumplan con las características mencionadas anteriormente y que puedan realizar su viaje compartido de forma segura, esto con el fin de incentivar el uso de la bicicleta como medio de transporte sostenible; principalmente se busca que estos aplicativos sean adaptables al contexto universitario y la situación de emergencia sanitaria actual.

Una vez realizada toda la investigación, se plantea, con el apoyo de un equipo de trabajo conformado por profesionales, estudiantes o técnicos especializados, la estructuración de un aplicativo móvil con las siguientes funciones:

• Notificar la ubicación de los usuarios, conductor y pasajeros con el mismo origen, destino o cercanos a la ruta, en tiempo real para la opción de carro compartido.
• Notificar el horario de partida y número de cupos dentro del vehículo, para la opción de carro compartido.
• Para viajes que no tienen el mismo punto de origen, notificar sitios de encuentro con su respectivo horario entre el conductor y los usuarios ubicados en un radio cercano al trayecto.
• Notificar la ubicación y horario de partida de los usuarios, que implementan el uso de bicicleta para transportarse desde y hacia el campus.
• Proporcionar información actualizada a los usuarios de los protocolos de bioseguridad establecidos por el Ministerio de Salud, asegurando el cumplimiento de estos.

El proyecto tiene en cuenta las diferentes opciones para la movilidad, por lo que se pueden llevar a cabo este tipo de viajes asegurando el cumplimiento de todos los protocolos de bioseguridad establecidos por el Ministerio de Salud.

1.1 Carro y bicicleta compartida

1.1.1 Carro compartido

El carro compartido, es una alternativa de movilidad en la cual un grupo de personas que presentan orígenes o destinos similares, comparten un vehículo, ya sea para realizar un viaje puntual o recurrente. Esta práctica, genera diferentes beneficios en materia de movilidad, como reducir la congestión vehicular.

Fig. 1 - Semana del carro compartido, Bogotá. Fuente: http://gaia.gobiernobogota.gov.co/noticias/inscr%C3%ADbete-en-las-rutas-de-la-semana-del-carro-compartido

1.1.2 Bicicleta compartida

La bicicleta se considera una opción sostenible de movilidad, que además mejora la salud integral de quienes hacen uso de ella. Sin embargo, la percepción de inseguridad en la ciudad de Bogotá es un limitante para algunos, por lo que generar grupos que permitan una mayor sensación de seguridad favorece el uso de este modo de transporte.

1.2 Alternativas ya existentes para uso de carro compartido y/o grupos de viajes en Bicicleta

Hoy en día existen diferentes alternativas en el mercado para realizar viajes compartidos, por lo cual, es importante resaltar las características principales de cada una de ellas, ya que algunas funcionan en páginas web, y otras utilizan diferentes herramientas como aplicaciones móviles o páginas en redes sociales.

1.2.1 Nivel Nacional

Se presentan algunas aplicaciones existentes en Colombia para realizar viajes compartidos.

a) Wheels Social

Es una aplicación móvil que permite a sus usuarios ponerse en contacto para concretar viajes compartidos en vehículos particulares, servicios de taxi o planes en bicicleta. Es un servicio seguro y confiable ya que solo se permite la interacción entre colegas de la organización que lo implementa.

La herramienta permite que los usuarios se encuentren en uno de los cuatro roles por cada trayecto que quieran realizar: Conductor, Pasajero, Compartidor de Taxi y Ciclista. Para realizar un match o coincidencia, la aplicación muestra la lista de personas que coinciden con sus intereses de movilidad para que puedan coordinar su viaje compartido. De esta forma se generan las métricas de movilidad con reportes de CO2 ahorrado por los miembros de la organización al compartir con Wheels. Actualmente la aplicación móvil no se encuentra disponible para su uso.

Fig. 2 - Wheels Social, movilidad sostenible.

Grupos de personas que interactúan:

- Colegas: Miembros de una comunidad, como, por ejemplo, universidad o trabajo.
- Contactos: Vecinos, personas que desarrollan actividades deportivas en gimnasios u otras actividades.
- Amigos: Círculo de amigos más cercano. Se pueden importar por medio de la información disponible en redes sociales o la lista de contactos del celular.

Beneficios que se presentan en cada rol del usuario:

- Pasajero: Disfruta del confort que brinda el realizar un viaje en carro particular, a su vez, se pueden presentar ahorros en costos de transporte y tiempos de viaje.
- Conductor: Presenta ahorros en costos de combustible y estacionamiento.
- Compartidor de Taxi: Se divide la tarifa entre los que usarán el servicio, generando ahorros en costos de transporte.
- Ciclista: Se realiza el viaje acompañado de otros ciclistas, esto puede representar un mayor respaldo y seguridad durante el trayecto.

Secuencia lógica para realizar el viaje

Al momento de programar un viaje por medio de la aplicación, se tienen en cuenta los siguientes aspectos:

1. Se crea una cuenta, generalmente relacionada con un correo de uso institucional.
2. Se define una red de confianza, esta red se puede definir a partir de un convenio o equipo de trabajo definido previamente entre una organización, como, por ejemplo, en desarrollado en el año 2017 entre la aplicación y la Universidad de Monterrey.
3. Programación de rutas desde y hacia el trabajo, universidad o sitio de interés, ingresando los puntos de origen-destino. Si es miembro de un grupo institucional de la organización correspondiente, el usuario verá las rutas de sus colegas en el mapa. Para definir rutas se tienen en cuenta los siguientes aspectos para cada rol:

a. Conductor: puede diseñar su ruta o seguir la que el sistema de Google Maps le recomienda.
b. Pasajero: puede definir cuanta distancia está dispuesto a caminar hacia el punto de encuentro con otros usuarios.
c. Compartidor de Taxi: el usuario busca conductores o compartidores de taxi para solicitar un cupo.
d. Ciclista: el usuario define cuanto está dispuesto a pedalear y puede diseñar su ruta según sus preferencias o puede seguir las recomendaciones dadas por Google Maps.

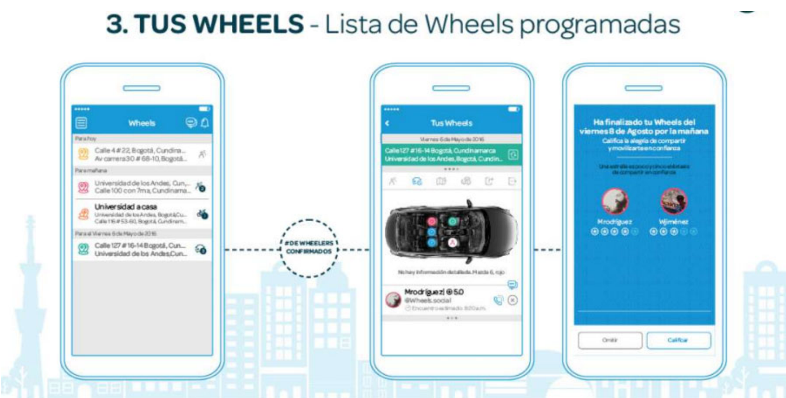


Fig. 3 - Wheels Social, movilidad sostenible.

4. Se escogen los compañeros de viaje y se crea una lista de viajes compartidos programada. En caso de que no se genere un "match", el sistema muestra que no se tienen coincidencias disponibles. En caso de que sí se generen coincidencias, el sistema muestra el número de personas interesadas en compartir el viaje y envía una notificación al conductor informándole el lugar y la hora de encuentro con cada persona. El sistema cuenta con un chat, en donde se confirma el viaje y se pueden realizar algunas sugerencias o consideraciones correspondientes para el viaje.

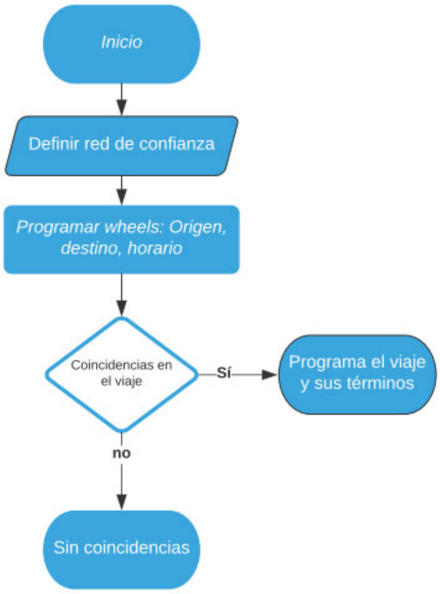


Fig. 4 – Secuencia lógica del funcionamiento de la aplicación Wheels. Fuente: Elaboración propia.

Posibilidad de uso de la plataforma en la universidad Nacional, teniendo como piloto la comunidad de la facultad de ingeniería:

Teniendo en cuenta, que la aplicación Wheels Social, se ha encontrado disponible en Colombia y que se tienen referencias de algunos acercamientos de dicha aplicación con la Alcaldía de Cali, se realizó un contacto directo con uno de sus creadores, el Economista Wilber Jiménez. En la reunión, se evaluó la posibilidad de uso de la plataforma para el desarrollo de este proyecto, sin embargo, actualmente la plataforma no se encuentra disponible para su uso, por lo cual, esta opción se descarta.

b) Transportáme
Es una plataforma que sirve como canal de comunicación entre conductores y pasajeros para que acuerden compartir viajes en sus rutas habituales contribuyendo a la movilidad sostenible. El viaje se puede realizar en la ciudad o entre ciudades de Colombia.

Roles que puede tener el usuario y sus beneficios:

Incluyen los siguientes tipos de viajes en los cuales pueden participar de manera diferente:

Fig. 5 - Opciones de la aplicación

- Carpooling

Al igual que todas las aplicaciones mencionadas Transpórtame cree que una manera de mejorar la movilidad de manera sostenible es el carro compartido. Ellos permiten conectar a personas con el mismo punto de destino, brindan la posibilidad de que los conductores se registren (creación del usuarios y perfiles), registran el vehículo, publican ruta de viaje y los asientos disponibles que poseen. Y los pasajeros realizan la elección a partir de lo publicado por los conductores.

Los beneficios que se tienen como usuario de Carpooling y que implementan la mayoría de las aplicaciones de carro compartido son:

- Asiento propio.
- Compartir los gastos de las rutas con otros usuarios.
- Ayuda a eliminar la contaminación de CO2.

- Motopooling

Al igual que el carro compartido el conductor de la moto indica cuál es su ruta de viaje y si tiene espacio disponible, y de acuerdo con estas decisiones el pasajero decide si tomar el viaje compartido.

Los beneficios de la moto compartida son:

- Viaja en el menor tiempo posible.
- Compartes los gastos de las rutas con otros usuarios.
- Reduce contaminación por CO2
- Evita acumulación de motos en la calle.
- Conecta personas con el mismo destino, creando conexiones.

1.2.2 Nivel Internacional

Se revisaron algunas plataformas existentes a nivel mundial como las que se presentan a continuación.

a) Ciclogreen

Herramienta Española que fomenta la movilidad sostenible en las universidades, empresas y pequeñas ciudades (bicicleta, patineta, transporte público, coche compartido, entre otros). Ayuda a cuantificar y a ahorrar el CO2 originado por los desplazamientos que se realizan a diario. Incentiva a los usuarios con retos y premios.

Funciona en varias plataformas que permiten el suministro de información, registro, y monitoreo dentro de las comunidades que usan la aplicación.

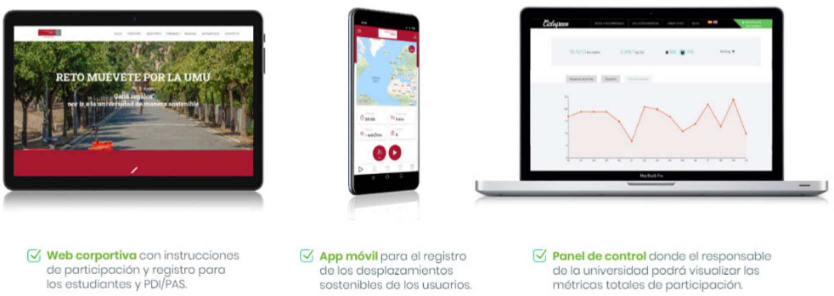


Fig. 6 – Plataformas de Ciclo Green.

Su incentivo al uso por parte de los estudiantes es una de sus grandes fortalezas, pues tienen implementado un sistema de retos que, al momento de cumplirlos, permite la obtención de premios y buenas calificaciones dentro de la aplicación.

Fig.7 - Incentivo de uso de la App.

Su herramienta de carro compartido es similar a las demás, donde el conductor registra ruta, días y hora de llegada, la app le indica a los posibles interesados las opciones que hay para que, por medio de un chat privado, se ponga en contacto con el conductor.

Fig. 8 - Funcionamiento de Ciclo Green.

El uso de un perfil privado con las estadísticas de cada usuario incentiva aún más el transporte sostenible, ya que relaciona cantidad de emisiones ahorradas y la quema de calorías.

Fig. 9 - Perfil privado de los usuarios.

La plataforma recibe gran cantidad de datos de movilidad, que pueden ser visualizados para identificar patrones de movilidad. De igual manera los datos podrían ser utilizados posteriormente para estudios de movilidad.

Fig. 10 - Datos para estudios posteriores de movilidad.

Su éxito se ha demostrado ya en otras universidades españolas.

Fig. 11 - Uso de CicloGreen en otras universidades.

b) BlaBlaCar

Es una aplicación móvil europea para compartir vehículo para viajar entre ciudades. Está presente en España desde enero de 2010, BlaBlaCar se considera la mayor red social de viajes de larga distancia en coche compartido, con más de 90 millones de usuarios en 22 países (5 millones en España). La red social pone en contacto a las personas que quieren realizar un trayecto común y coinciden (conductor y pasajero) para realizarlo el mismo día.

Los usuarios pueden adquirir los siguientes roles:

- Conductor: Ahorran en costos del viaje relacionado con costos del vehículo y reciben acompañamiento durante trayectos largos. Puede escoger cuantos pasajeros está dispuesto a llevar y el punto de partida.
- Pasajero: Se ahorra costo de viaje y algunas veces puede ser menor el tiempo de viaje.

Se puede verificar el perfil de conductores y pasajeros permitiendo tener referencias de los usuarios. Según cifras de BlaBlaCar al implementarse el uso de carro compartido en el 2018 se ahorró la emisión de 16 millones de toneladas de CO2.

Forma de pago:
Los usuarios comparten los gastos del viaje sin obtener beneficio. Para ello, BlaBlaCar recomienda en su plataforma una aportación por usuario y trayecto de 0,06 euros por kilómetro, apropiada para la compartición de gastos inherentes a la conducción (gasolina, peaje, mantenimiento, seguros, impuestos, etc.) y limita la aportación máxima que pueden solicitar los conductores de tal manera que no se superen estos gastos y exista un abuso económico por parte de los usuarios.

Secuencia para realizar el viaje y funcionamiento de comunicación:

El conductor es el encargado de publicar origen destino y número de cupos disponibles, después de esto, por medio de un chat entre el pasajero y el conductor se acuerda el punto de encuentro (punto de inicio del viaje) y el punto de llegada.

Popularidad en el mercado:

Según cifras estipuladas por Blablacar cuentan con más de 90 millones de usuarios en 22 países que actualmente cuentan con el servicio, en los cuales han compartido más de 30 billones de kilómetros ya horrado 1,4 billones de euros. Cuenta con 2.8 millones de opiniones entre los usuarios.

c) 1.5 Socialización de diferentes aplicaciones móviles de viajes compartidos en el mundo

- Universidad Politécnica de Cataluña:

Reunión con el profesor Carles Labraña, el cual es un Ingeniero Civil experto en temas de movilidad compartida en Europa, específicamente en el desarrollo de aplicaciones MaaS. En la reunión se realizó la exposición del proyecto y se obtuvieron diferentes elementos que se deben tener en cuenta para el desarrollo del algoritmo de coincidencias, lo aspectos de seguridad, definición de corredores, funciones de la aplicación y posibles proyecciones.

- Universidad de Brasilia:

Reunión con el profesor Pastor Willy Gonzales Taco, el cual es un Ingeniero Civil experto en desarrollo de aplicación móviles para viajes compartidos en la ciudad de Brasilia, participando en proyectos como Caronaphone y diferentes investigaciones en Carona Solidaria.

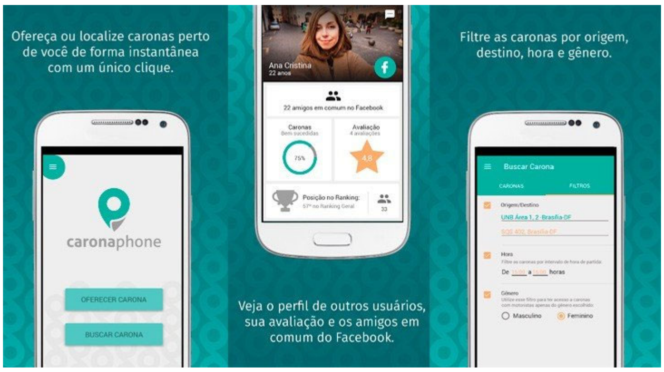


Fig. 12 - Caronaphone.

En esta reunión se realizó una exposición del proyecto UNviaje de la universidad Nacional y el proyecto de Carona solidaria CaronaPhone de la Universidad de Brasilia. En esta reunión, Márcio Batista que fue uno de los creadores de esta aplicación no expuso todos los aspectos tenidos en cuenta para el Design Thinking, los algoritmos de coincidencias, el sistema de interacción con redes sociales, cifras en Brasil de reducción de emisión de contaminantes, entre otros.

2. BASES DE DATOS

2.1 Recolección por medio de encuestas

Como método de participación para la comunidad académica de la Facultad de ingeniería y a modo de actualización de datos, se propuso difundir un formulario en el cual se conociera tanto datos de residencia como preferencias de viaje de acuerdo con los modos de transporte, al igual que el grado de motorización con el que contaríamos para llevar a cabo el proyecto.

Para ello se realizó la pieza gráfica que se muestra a continuación, en la cual como incentivo se promueve la rifa de 3 chaquetas de la TiendaUN que fueron donadas por una empresa externa, y donde también se especifica en qué consiste el proyecto.

Fig. 13 - Póster para viajes compartidos. Fuente: Elaboración propia

Se tuvieron 880 respuestas. Con el apoyo del grupo Ingnova, se realizó una segunda pieza de difusión:

Fig. 14 - Nuevo diseño de Póster para viajes compartidos. Fuente: Elaboración propia

En los resultados obtenidos, se observa el principal vínculo con la universidad de los encuestados:

Fig. 15 - Resultados del formulario vínculo con la universidad. Fuente: Elaboración propia

Dentro de su preferencia, presentan la variación que podemos ver en la siguiente ilustración donde tanto el uso de la bicicleta como del vehículo particular tuvieron prevalencia con aumento de aproximadamente 50% a la hora de desplazarse durante la emergencia sanitaria. Mientras que el transporte público disminuyó igualmente un 50% su uso.

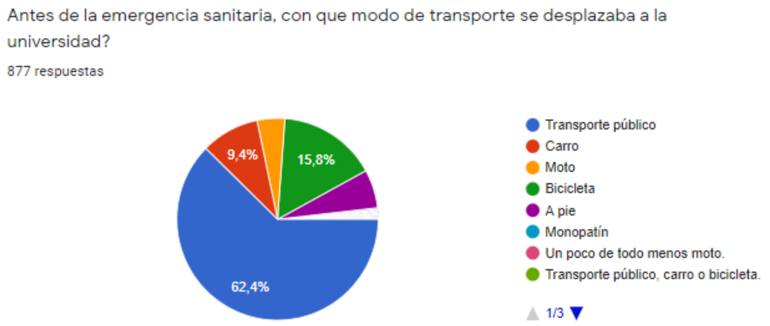


Fig. 16 - Resultados del formulario preferencias declaradas. Fuente: Elaboración propia

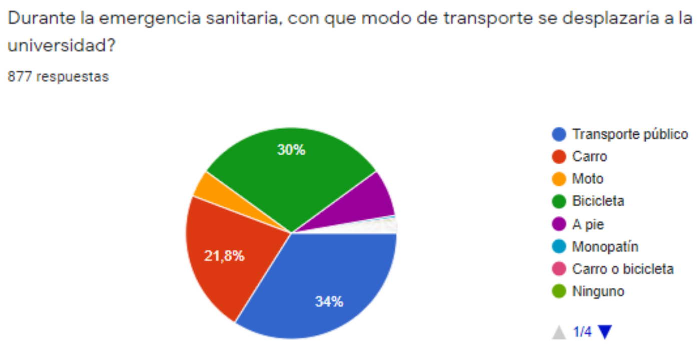


Fig. 17 - Resultados de preferencias de viaje según el modo, antes y ahora en la emergencia sanitaria. Fuente: Elaboración propia

De igual modo, dentro de la encuesta se consultó la intención de participar activamente en el proyecto, obteniendo un resultado positivo con un 85,3% de respuestas afirmativas de participación; a aquellas personas que respondieron que no participarían se les facilitó un espacio en el cual expresaron que su motivo de rechazo era debido a la emergencia sanitaria ya que contaban con familiares de alto riesgo, o el hecho de vivir muy cerca de la universidad para lo cual no requieren ningún tipo de transporte.

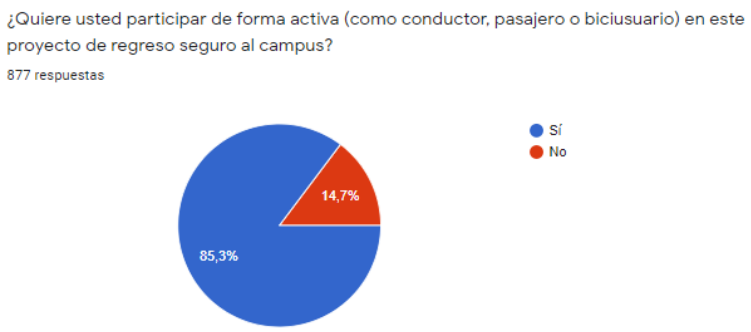


Fig. 18 - Resultados intención de participación. Fuente: Elaboración propia

A partir de las encuestas se realizaron algunos mapas para georreferenciar la ubicación según algunos datos como el tipo de vinculación, disponibilidad de vehículo particular, disposición a movilizarse en bicicleta entre otros. Con el fin de realizar algunos análisis de manera visual.

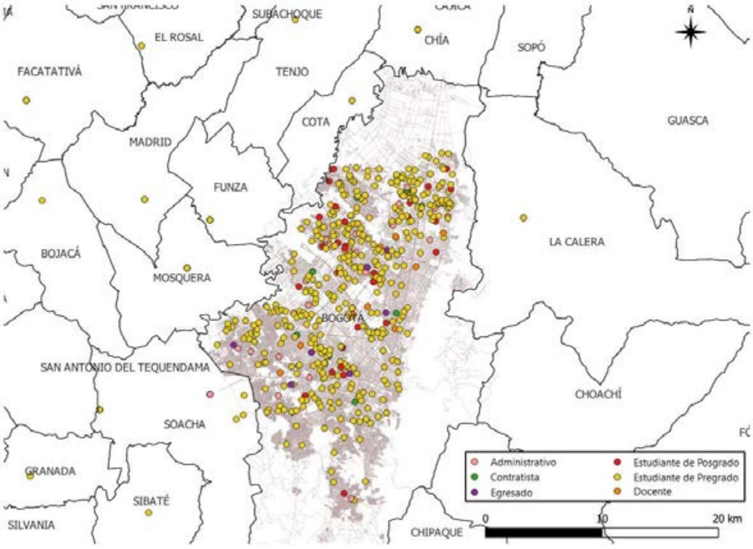


Fig. 19 - Tipo de vinculación de los encuestados. Fuente: Elaboración propia

En la ilustración anterior se evidencia que la mayoría de los encuestados son estudiantes de pregrado y que estos están distribuidos por toda la ciudad y en los municipios aledaños. Por otra parte, como es evidente también de las bases de datos los administrativos y docentes se localizan más hacia el norte y occidente de la ciudad.

En la siguiente ilustración se georreferenciaron los encuestados según el modo de transporte que usaban antes de la emergencia sanitaria, como es lógico alrededor de la universidad se ven en verde algunos miembros que se desplazan a pie. En azul, los que se desplazaban en transporte público, en naranja, aquellos que ya usaban la bicicleta y en negro los que utilizaban el carro particular.

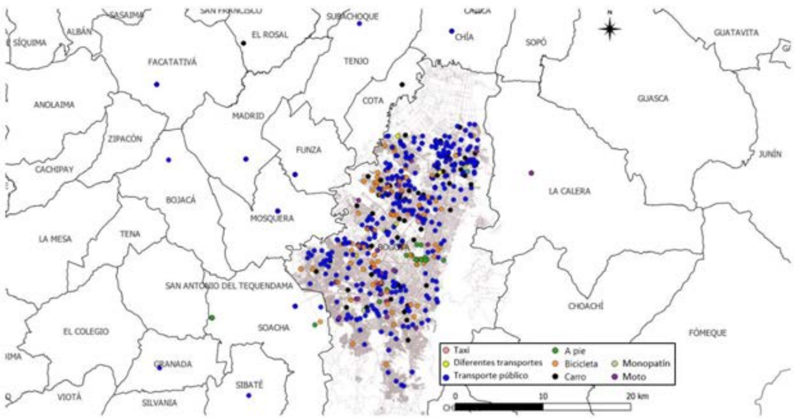


Fig. 20 - Transporte utilizado para los desplazamientos desde/ hacia la Universidad antes de la emergencia sanitaria. Fuente: Elaboración propia

Con la siguiente ilustración podemos ver que quienes tienen una mayor disposición a usar la bicicleta son aquellos que se desplazaban en transporte público, a pie y los que ya hacían uso de la bicicleta.

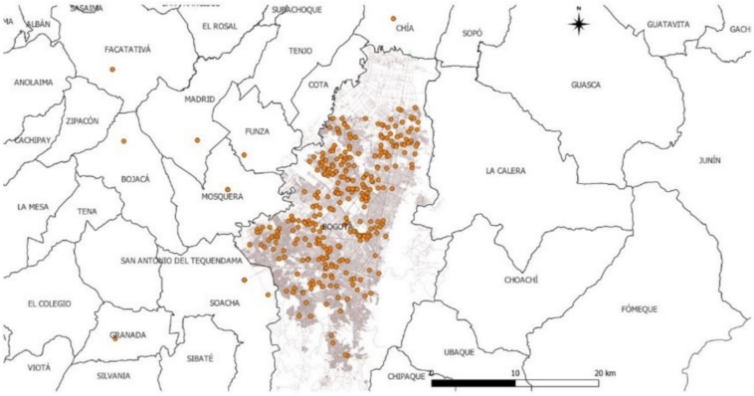


Fig. 21 - Disposición a viajar en bicicleta desde/ hacia la Universidad. Fuente: Elaboración propia

A continuación, se evidencia la disponibilidad de carro de los encuestados, en verde se muestran los que poseen vehículo. Aunque están distribuidos, aún son pocos por lo que se seguirán realizando encuestas e incentivando a los conductores a hacer parte activa de este proyecto.

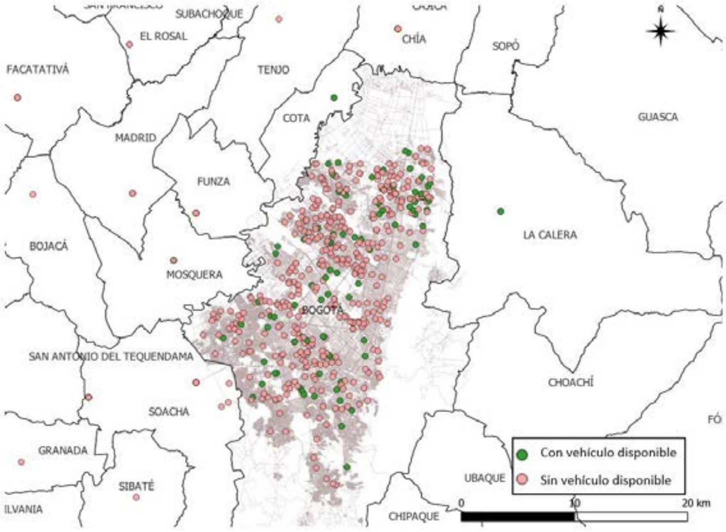


Fig. 22 - Disponibilidad de vehículo particular.Fuente: Elaboración propia

2.2 Bases de datos obtenidas

De acuerdo con las bases de datos suministradas hasta la fecha, se ha avanzado en la georreferenciación de las direcciones para determinar varios indicadores útiles del proyecto, poder realizar análisis espaciales y determinar en cierta medida la viabilidad del proyecto.

La base de datos correspondiente a los contratistas de la facultad de ingeniería cuenta con 620 registros con dirección en Bogotá. La georreferenciación de estas direcciones se presenta en la Fig. 23, donde se puede visualizar la distribución de los lugares de residencia a lo largo de la ciudad.

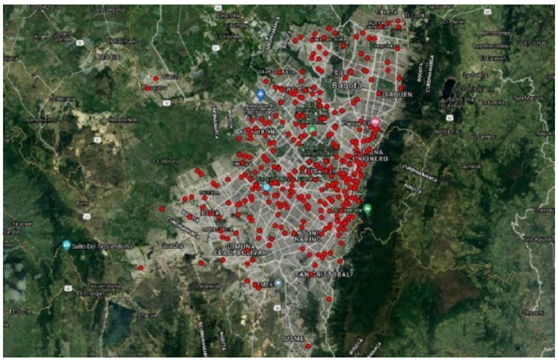


Fig. 23 - Georreferenciación de Contratistas de la Facultad de Ingeniería. Fuente: Elaboración propia

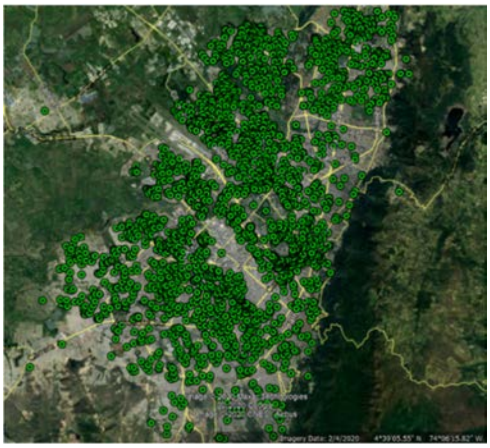


Fig. 24 - Georreferenciación de estudiantes de la Facultad de Ingeniería. Fuente: Elaboración propia

La base de datos de estudiantes de la facultad de ingeniería contenía 8851 registros, de los cuales 2739 tienen como lugar de residencia Bogotá, 2545 de ellos cuentan con dirección y son los que se observan en la imagen. A partir de la georreferenciación de los estudiantes es 1921onsider ver que están distribuidos en toda la ciudad y será 1921onsider la generación de grupos que puedan viajar juntos. Es importante tener en cuenta que las direcciones suministradas son las que tenían los estudiantes al ingresar a la 1921onsiderer1921 por lo que no hay 1921onside de que sean las mismas actualmente, además se debe 1921onsiderer que son solo un cuarto del total de estudiantes inscritos.

3. PROTOCOLOS DE BIOSEGURIDAD

Según la resolución número 000677 del 24 de abril de 2020, se presentan las siguientes acciones para tener en cuenta:

- Realizar una capacitación para aplicar las medidas indicadas en el protocolo.
- Implementar actividades que permitan garantizar la protección integral.
- Proveer a los empleados los elementos de protección personal, que deben utilizarse obligatoriamente durante el desarrollo de sus actividades.

- Registrar su estado de salud en la aplicación Corona App.
- Reportar cualquier caso sospechoso de coronavirus.
- Tener información acerca de algún caso de contagio por parte de la familia, su lugar de trabajo u otro entorno.
- Vigilancia del cumplimiento de los protocolos, (por parte de la entidad a cargo o representante).
- Las medidas propiciadas deben llevarse a cumplimiento mientras dure la declaratoria de la emergencia sanitaria.

3.1 ¿Qué es la bioseguridad?

"El conjunto de medidas preventivas que tienen por objeto eliminar o minimizar el factor de riesgo biológico que pueda llegar a afectar la salud, el medio ambiente o la vida de las personas, asegurando que el desarrollo o producto final de dichos procedimientos no atenten contra la salud y seguridad de los trabajadores".

3.2 Medidas Generales

A. Lavado de manos.
   a. Realizar el lavado de manos con agua limpia, jabón y toallas desechables.
   b. Disponer de alcohol mínimo al 60% y máximo 95%.
   c. Tener un sitio destinado a la ubicación del alcohol, de ubicación fácil de divisar.
   d. Se debe realizar la desinfección de manijas, puertas, junto con todas las superficies con las que es necesario entrar en contacto.
   e. Facilitar la información a los trabajadores.

B. Distanciamiento físico.
   a. Permanecer mínimo a 2 metros de distancia, evitando el contacto directo.
   b. Organizar y optimizar el espacio.
   c. No deben permitirse reuniones sin mantener la distancia mencionada.

C. Elementos de protección personal.
   a. La empresa debe definir los elementos de protección personal a utilizar.
   b. El empleador debe entregar los EPP.
   c. Los EPP no desechables deberán ser lavados y desinfectados, son de uso personal.

D. Manejo del tapabocas.
   a. Es de uso obligatorio en el transporte público y áreas donde se encuentre cualquier otro individuo.
   b. El tapabocas debe cubrir la boca y la nariz (ubicar cubriendo encima de la nariz y debajo del mentón).
   c. Se permite el uso de tapabocas de tela.
   d. Evitar el contacto de las manos con el tapabocas.

E. Limpieza y desinfección
   a. Desarrollar un protocolo de limpieza, definiendo el procedimiento, frecuencia, la persona responsable, los elementos de desinfección empleados, entre otros.
   b. La limpieza de elementos de contacto directo (pisos, paredes, puertas, ventanas, divisiones, muebles, sillas) debe ser de la mayor frecuencia posible.
   c. Procedimiento a realizar a inicio y fin de la jornada.
   d. Elaborar fichas técnicas e instructivos para realizar desinfección.
   e. Especificar las dosis y naturaleza química de los productos a utilizar.

F. Prevención y manejo de situaciones de riesgo de contagio.
   a. Es necesario conocer a organización de la empresa, el proceso ejecutivo de las tareas, tiempo de exposición, características del trabajador (estado de salud, edad, sexo).
   b. Prevenir la transmisión del virus por elementos contaminados (superficies, máquinas, elementos de protección).
   c. Se debe conocer las condiciones de salud de los trabajadores (estado de salud, hábitos, estilo de vida). Y las condiciones de su medio de trabajo.

G. Vigilancia de la salud.
   a. Asegurarse que se cumpla el reglamento de prevención.
   b. No permitir el ingreso de personas con temperatura igual o mayor a 38°C.
   c. Información del trabajador su EPS y ARL.
   d. Se debe señalar el número máximo de personas que estarán en una misma instalación.
   e. Garantizar la correcta circulación del aire.

H. Desplazamiento en Medios de transporte.
   a. Cumplir con el uso de los elementos de protección (Se pueden incluir guantes).
   b. Distancia en vehículo de 1 metro.
   c. Garantizar que el vehículo se encuentre limpio y desinfectado, al iniciar y finalizar la ruta debe realizarse limpieza.
   d. Incentivar el uso de otros medios de transporte como moto, bicicleta, realizando limpieza de cascos, guantes y manubrios.
   e. Planificar las rutas a recorrer.
   f. Retirar del vehículo elementos como alfombras, tapetes, forros acolchados u otro elemento que no puede ser desinfectados o lavados.
   g. Al recibir dinero puede hacerlo con guantes o puede desinfectarse las manos cada vez que realice contacto con dinero, se recomienda al pasajero en lo posible pagar el dinero exacto para evitar cambios y mayor manipulación.
   h. No es permitido consumir alimentos ni bebidas dentro del vehículo.
   i. Reportar si el conductor o el usuario presentan síntomas del covid.
   j. Llevar un kit de prevención personal.

I. Plan de comunicación.

J. Todos los trabajadores o relacionados deben contar con un medio de comunicación para informar acerca de cualquier anormalidad que se presente.

3.3 Propuesta de protocolo para conductores

- Debe proporcionar sus datos personales al registrarse como conductor, para garantizar la seguridad de los usuarios.
- Deben retirarse del vehículo, las alfombras, tapetes o forros que no puedan limpiarse o lavarse.
- Desinfección del vehículo antes y después del recorrido.
- Debe portar con sus propios elementos de protección personal, (Tapabocas, gel anti-bacterial, alcohol del 60%-95%)
- Debe mantener el vehículo con buena ventilación.
- No debe prestar el servicio si su temperatura es igual o superior a 38°C.
- Debe tener el reglamento sobre las medidas de prevención en un lugar visible

3.4 Propuesta protocolo para pasajeros

- Debe registrar sus datos personales al registrarse como pasajero.
- Adquirir y portar su kit de protección personal (tapabocas, gel anti – bacterial)
- No puede usar el servicio si su temperatura es igual o superior a 38°C.
- Debe cumplir con el reglamento de prevención.
- Debe reservar el servicio con anticipación o cancelarlo con considerable anterioridad.

3.5 Propuesta para bici usuarios

- Trazar la ruta de recorrido que se realizará.
- Portar los elementos de kit de protección personal.
- Desinfección del manubrio, casco, guantes, entre otros.

4. ESTRUCTURACIÓN Y DESARROLLO DE LA APLICACIÓN

4.1 Aplicación Web Progresiva o PWA

Una Aplicación Web Progresiva (PWA) permite al usuario tener la experiencia de una aplicación móvil con algunas diferencias y ventajas. Inicialmente está aplicación se descarga directamente desde una página web, generando un acceso directo en la pantalla del móvil similar (o igual) a una aplicación descargada desde la Play Store o App Store.

Entre las ventajas que presenta está aplicación se encuentran el bajo costo de desarrollo, la capacidad de acceder a ella en modo offline o con una conexión “lenta”, ya que almacena alguna información directamente en el dispositivo móvil y puede acceder al GPS del teléfono, puede ser usada en cualquier sistema operativo adaptándose a este. Además, está actualizada sin necesidad de hacer posteriores descargas y permite una navegación segura (HTTPS).

4.2 Historias de Usuario

Los usuarios que ingresen a la aplicación contarán con la posibilidad de seleccionar el rol que desea realizar para el viaje. Existe el rol de pasajero, conductor y bici usuario. En la siguiente imagen se muestran las opciones en la navegación que se tiene según corresponda:

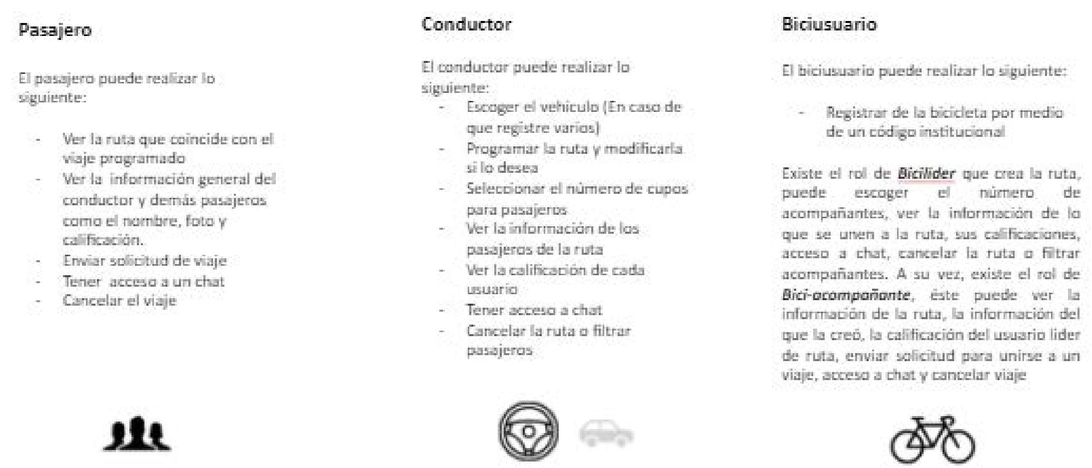


Fig. 25 – Funciones según los roles definidos. Fuente: Elaboración propia

4.3 Nombre de la aplicación

En el formulario que se realizó, se presentó una lista de posible nombre que tendrá la aplicación. A continuación, se presentan los resultados obtenidos:

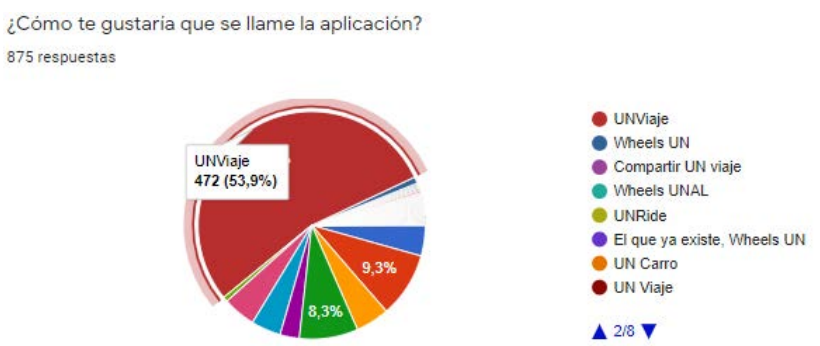


Fig.26 - Resultados del nombre de la aplicación. Fuente: Elaboración propia

El nombre definido para la aplicación es “UNviaje”. A continuación, se presenta un primer diseño del logo propuesto para la aplicación:

Fig. 27 - Logo de la aplicación. Fuente: Elaboración propia

4.4 Diseño del prototipo

Para el diseño del prototipo se realizó la selección de imágenes de dominio público, que se relacionaran con espacios que proporciona la universidad, como son las plazas y edificios que son muy conocidos, con el objetivo de hacer familiar, cercana y asequible la aplicación, para todos los miembros de la comunidad académica. Se propusieron ideas en cuanto al diseño más cómodo y funcional, de manera que en la PWA direccionara al sitio correspondiente y brindara a los usuarios todo lo que necesitan para realizar el proceso de forma adecuada, teniendo en cuenta las características en otras aplicaciones de movilidad.

En primera instancia, la página principal se enfoca en el registro a la aplicación. Ya que nuestro principal interés es el de seguridad en cuanto a la salud e integridad personal, se estructuró como única forma de acceso el registro con usuario institucional, garantizando la identificación de quiénes están usando el servicio. Se solicitan los datos personales, complementando de esta forma las bases de datos ya existentes, inclusive, actualizando las mismas, ya que se le ofrece al usuario actualizar su perfil.

Fig. 28 – Inicio de sesión, registro y acceso. Página principal. Fuente: Elaboración propia

Fig. 29 - Cambio de contraseña. Fuente: Elaboración propia

En la Fig. 29 podemos observar la opción de cambio de contraseña. Como es común en la creación de perfiles es necesario poder tener esa opción para aumentar la seguridad y en caso de que se haya olvidado. Una vez completadas las casillas se mandará un mensaje directamente al correo informando el cambio de contraseña y quedará guardado hasta que se desee volver a realizar el proceso.

Fig. 30 – Registro general complementario. Fuente: Elaboración propia

Fig. 31 - Escoger rol para viaje. Fuente: Elaboración propia

En la Fig. 31, se puede observar que, estando ya registrado como miembro de la aplicación por la condición de pertenencia en la Institución académica, el usuario debe seleccionar su vínculo de participación, con las opciones disponibles, conductor, bici usuario, o pasajero, de acuerdo a lo que considere el propósito de su vinculación, este aspecto es muy importante, ya que hará una nueva clasificación de cuánto es la demanda de vehículos por el número de pasajeros registrados, junto con las coincidencias en cuanto a localidades o puntos de partida estimados para el viaje, esto quiere decir que en cuanto mayor sea el número de usuarios registrados, a su vez el sistema será más óptimo, ya que se contarían con múltiples coincidencias para realizar su transporte, seleccionando la opción que sea más favorable. En el caso de los Bici-usuarios (Fig. 33) según los informes dados por las encuestas, incrementó el número de personas que utilizarían la bicicleta, debido a que su vivienda se encuentra cercana a la Universidad, esto además de ser un beneficio ambiental y sostenible, es una forma de seguirlo fomentando, ya que transportarse en grupo es tener la seguridad de llegar al destino sin posibles situaciones riesgosas como son las que se registran por robos o asaltos, además se pide como parte de la vinculación el registrar la bicicleta con el protocolo propio de la universidad para la protección de los elementos personales. Para quienes seleccionen la opción de conductor (Fig. 32) deben ingresar la placa y el color del vehículo como parte obligatoria del registro, ya que así se hará una rápida distinción de este, puede seleccionar más de una opción de vinculación, si solamente desea hacerlo como pasajero, al únicamente seleccionar esta opción ya quedará completo su registro.

Fig. 32 – Perfil solicitado para registrarse como conductor. Fuente: Elaboración propia

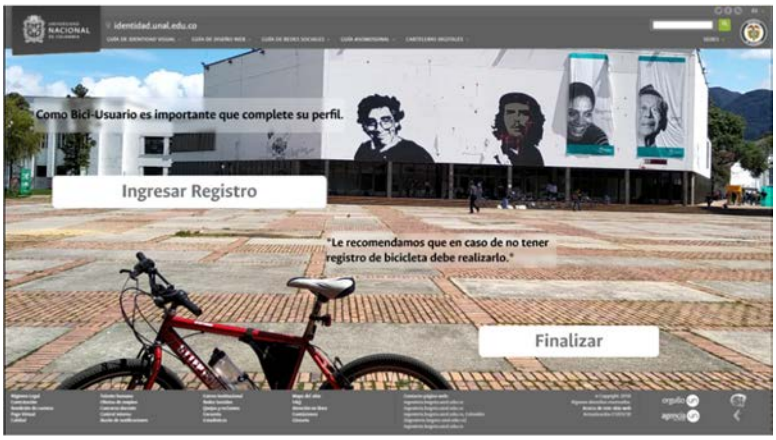


Fig. 33 – Perfil solicitado para registrarse como Bici – usuario. Fuente: Elaboración propia

Fig. 34 - Perfil solicitado para navegación. Fuente: Elaboración propia

En la Fig. 34 anterior se puede observar el mapa principal, el cual consta de un mapa de geolocalización (GoogleMaps) que permite visualizar la localización actual dentro de la zona de Bogotá y algunos de sus municipios aledaños. Tenemos las opciones básicas de punto origen y hora de salida, claves para lograr el match entre los usuarios. En el punto de origen se puede variar entre la dirección ingresada inicialmente en el registro y la ubicación proporcionada por el mapa; y en la hora de salida se visualizará opciones de 5 am a 8 pm en un rango de 15 min entre cada opción de salida. Finalmente se puede ver el destino, este incluye las diferentes entradas de la universidad y la modalidad de usuario con la que desea iniciar su viaje.

Finalmente se puede ver el número de coincidencias con los conductores (Fig. 35), el perfil de la persona con la que deseas viajar (Fig. 36) y finalmente el mensaje de confirmación (Fig. 37).

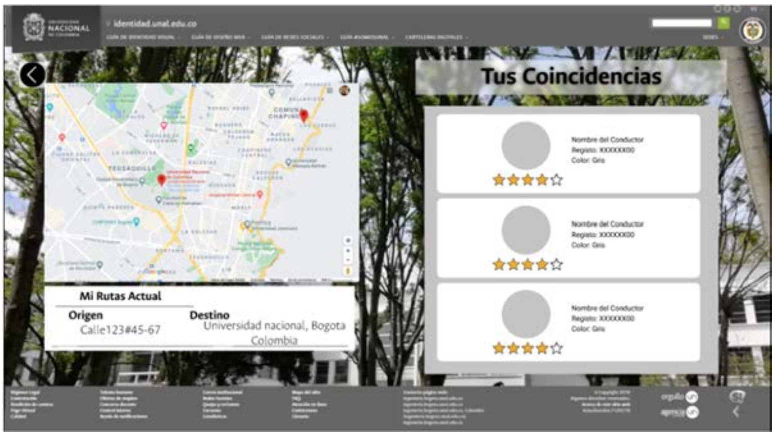


Fig. 35 – Coincidencias. Fuente: Elaboración propia

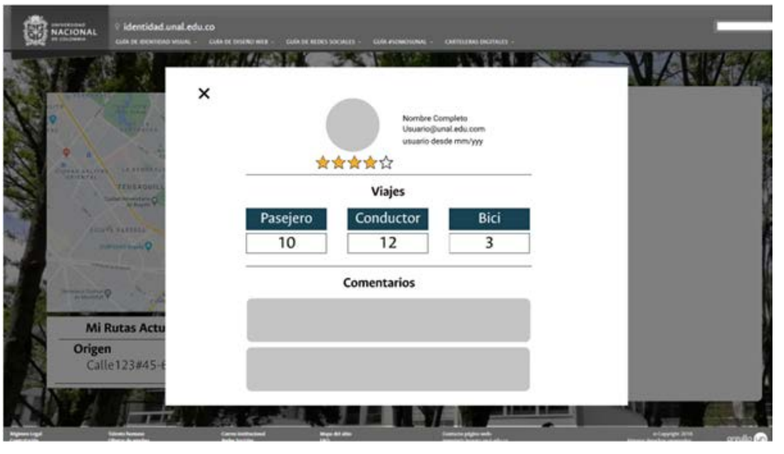


Fig. 36 - Perfil compañero de viaje. Fuente: Elaboración propia

Fig. 37 - Confirmación de viaje. Fuente: Elaboración propia

4.5 Programación

La base de programación que usamos para la PWA es un entorno de NodeJs, con la arquitectura del paquete ExpressJs y otros paquetes como firebase, PM2 y otros para la organización de accesos atreves de Parse (es un motor de NoSQL Basado en MongoDB) entre otras comunicaciones esto con el fin de tener una aplicación web con la mejor adaptación multiplataforma (PWA) orgánica y funcional sobre cualquier tipo de dispositivo.

Actualmente se cuenta con 2 servidores, uno de pruebas y uno master para producción, el cual cuenta con un sistema operativo Ubuntu 18.04, El segundo server es una réplica que consta con sistema operativo igual que el de producción, el cual tiene capacidad de 1GB en RAM y 8GB en disco duro, los deploy constan con Travis CI, el cual nos permite un manejo sobre las publicaciones y continuo monitoreo de cambio en código entre el servidor y el repositorio para soporte entre otros ajustes sobre código fuente.

Internamente entre los servidores tenemos un sistema simple NGINX que cumple su función de servidor web también esta NodeJs como entorno de ejecución y NPM para la instalación y ejecución de paquetes Javascript como secundario se está usando YARN como gestor de paquetes de respaldo el cual está ejecutando al tiempo con NPM para no generar error entre estos gestores de paquetes, en cuanto a GIT se está usando el GIT oficial de Ubuntu, y se está trabajando con Travis CI para testing code y continuous deployments.

En la siguiente imagen podemos ver gráficamente la arquitectura de la PWA.

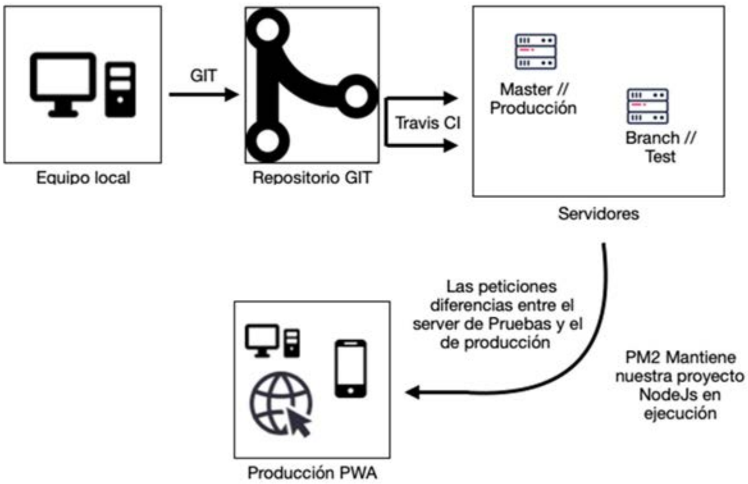


Fig. 38 – Arquitectura PWA. Fuente: Elaboración propia

5. ANÁLISIS ESTADÍSTICO DE LOS RESULTADOS OBTENIDOS

La base de datos utilizada fue obtenida a partir del desarrollo de una encuesta divulgada por correo masivo al personal administrativo, docentes, estudiantes, egresados, investigadores, empleados y contratistas de la Universidad Nacional de Colombia

De la encuesta realizada se obtuvieron un total de 880 respuestas, contando con registros de desde el mes de septiembre hasta el mes de diciembre del año 2020. Para del desarrollo de los análisis estadísticos de las respuestas obtenidas, es importe definir el estudio a realizar. El estudio para la creación de la aplicación define las posibles rutas de viaje que se comparten entre individuos que se desplazan desde y hacia el campus de la Universidad Nacional, es por esta razón, que los análisis se dividen por zonas de la ciudad, en este caso por localidades, tomando que referencia los individuos que se desplazan desde el sur, norte, oriente y occidente.

Teniendo en cuenta que los individuos que se ubiquen, por ejemplo, en el sector norte de la ciudad, pueden compartir su viaje con otros individuos que se ubiquen en este sector próximos a la ruta de viaje, en la Fig. 7.1 se define la división de los análisis estadísticos a realizar de la base de datos de estudio, partiendo principalmente de la georreferenciación de las respuestas obtenidas. Dado esto, a partir del análisis espacial de los datos, se divide la base de datos, obteniendo como resultado lo siguiente:

a. Zona norte: comprendida por los individuos que viven en las localidades de Barrios Unidos, Chapinero, Engativá, Suba, Teusaquillo y Usaquén y los municipios del área metropolitana de Bogotá: Cajicá, Chía, Cogua, Cota, El Rosal, la Calera, Sopó, Subachoque, Tenjo, Tocancipá y Zipaquirá.

b. Zona Sur: comprendida por los individuos que vienen las localidades de Tunjuelito, Usme, Puente Aranda, Kennedy, Ciudad Bolívar, Fontibón, Bosa, Candelaria, San Cristóbal, Antonio Nariño, Mártires, Rafael Uribe, Santa Fe y los municipios del área metropolitana de Bogotá: Bojacá, Facatativá, Funza, Granada, Madrid, Mosquera, Sibaté y Soacha.

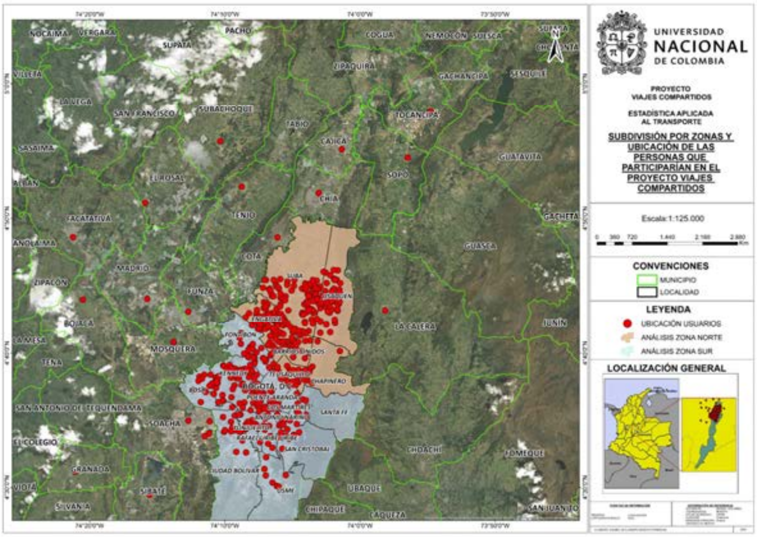


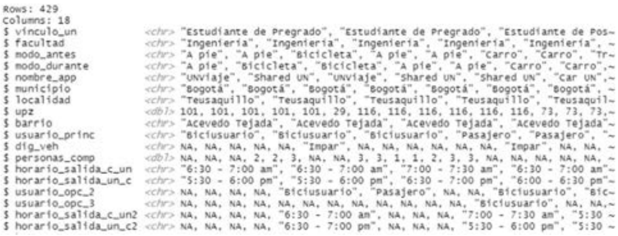
Fig. 39 - Subdivisión por zonas del análisis estadístico. Fuente: Elaboración propia.

El alcance definido comprende un análisis en la **zona norte** de la ciudad de Bogotá y su área metropolitana. A continuación, se presenta una descripción de la base de datos seleccionada:

- Individuo o unidad de análisis: usuario de la aplicación.
- Población: La población objetivo para este proyecto son los 7408 estudiantes de la facultad de ingeniería, incluyendo también personal administrativo, contratistas, empleados, investigadores, egresados y docentes, teniendo alrededor de 9000 personas en total.
- Muestra: Respuestas de la encuesta realizada. Se tiene un total de 429 respuestas de personas pertenecientes a la universidad Nacional de Colombia, que se ubican en la zona norte descrita anteriormente y respondieron que si estarían interesadas en participar en la aplicación.
- Variable: Vínculo con la universidad, Facultad a la que pertenece, Municipio en que vive, Localidad, UPZ, Barrio, hora de salida desde el hogar, hora de salida desde la universidad, modo de transporte antes de la emergencia sanitaria, modo de transporte que usaría durante la emergencia sanitaria, rol principal, secundario y terciario que desarrollaría dentro de la aplicación.

Las variables contenidas dentro de la base de datos son variables categóricas, excepto la upz y con cuantas personas estaría dispuesto a compartir el vehículo, estas dos son variables cuantitativas, como se muestra en la Fig. 40. En total se tienen 18 variables, de las cuales se realizó una selección de las que podrían caracterizar de una mejor forma el análisis planteado en la pregunta del primer punto, encontrándose así en el desarrollo de gráficos de frecuencias, matriz de correlación de Pearson y ACM.

Algunas de las respuestas obtenidas en el formulario presentaban pequeñas variaciones, por ejemplo, para el caso de modo de transporte que utilizaba antes de la emergencia sanitaria, fue necesario depurar y uniformizar la base de datos, ya que algunas personas tenían respuestas que no se encontraban dentro de las opciones definidas o escritas de otra forma, por ejemplo: la palabra “Carro” y “carro”, aunque signifiquen lo mismo, una está escrita con la primera letra en mayúscula y la otra no, por lo cual, al momento de realizar el análisis estadístico en R, se toman como dos variables categóricas diferentes, lo mismo ocurre con el municipio, localidad, el vínculo y el rol; ya que por ejemplo, “Bogotá”, se encontraba escrita con tilde o sin tilde, o también se encontraron 2 municipios de residencia en zonas alejadas del área de influencia, por lo cual, estos datos se descartaron dentro del análisis realizado.



```
Rows: 429
Columns: 18
$ vinculo_un          <chr> "Estudiante de Pregrado", "Estudiante de Pregrado", "Estudiante de Pos~
$ facultad            <chr> "Ingenieria", "Ingenieria", "Ingenieria", "Ingenieria", "Ingenieria", ~
$ modo_antes          <chr> "A pie", "A pie", "Bicicleta", "A pie", "A pie", "Carro", "Carro", "Tr~
$ modo_durante        <chr> "A pie", "Bicicleta", "Bicicleta", "A pie", "A pie", "Carro", "Carro",~
$ nombre_app          <chr> "UNViaje", "Shared UN", "UNViaje", "Shared UN", "Shared UN", "Car UN",~
$ municipio           <chr> "Bogotá", "Bogotá", "Bogotá", "Bogotá", "Bogotá", "Bogotá", "Bogotá", ~
$ localidad           <chr> "Teusaquillo", "Teusaquillo", "Teusaquillo", "Teusaquillo", "Teusaquil~
$ upz                 <dbl> 101, 101, 101, 101, 101, 29, 116, 116, 116, 116, 116, 116, 73, 73, 73,~
$ barrio              <chr> "Acevedo Tejada", "Acevedo Tejada", "Acevedo Tejada", "Acevedo Tejada"~
$ usuario_princ       <chr> "Biciusuario", "Biciusuario", "Biciusuario", "Pasajero", "Pasajero", "~
$ dig_veh             <chr> NA, NA, NA, NA, NA, "Impar", NA, NA, NA, NA, NA, NA, "Impar", NA, NA, ~
$ personas_comp       <dbl> NA, NA, NA, 2, 2, 3, NA, NA, 3, 3, 1, 1, 2, 3, 3, NA, NA, NA, NA, NA, ~
$ horario_salida_c_un <chr> "6:30 - 7:00 am", "6:30 - 7:00 am", "7:00 - 7:30 am", "6:30 - 7:00 am"~
$ horario_salida_un_c <chr> "5:30 - 6:00 pm", "5:30 - 6:00 pm", "6:30 - 7:00 pm", "6:00 - 6:30 pm"~
$ usuario_opc_2       <chr> NA, NA, NA, NA, "Biciusuario", "Pasajero", NA, NA, "Biciusuario", "Bic~
$ usuario_opc_3       <chr> NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, "Biciusuario", NA, NA,~
$ horario_salida_c_un2 <chr> NA, NA, NA, NA, "6:30 - 7:00 am", NA, NA, NA, "7:00 - 7:30 am", "5:30 ~
$ horario_salida_un_c2 <chr> NA, NA, NA, NA, "6:30 - 7:00 pm", NA, NA, NA, "5:30 - 6:00 pm", "5:30 ~
```

Fig. 40 - Estructura de la base de datos inicial. Fuente: Elaboración propia.

De las 18 variables presentadas anteriormente, se seleccionaron las siguientes variables categóricas para el análisis estadístico:

- vinculo_un
- facultad
- modo_antes
- modo_durante
- municipio
- localidad
- usuario_princ
- usuario_opc_2
- usuario_opc_3

5.1 Tablas y gráficas de frecuencias

5.1.1 Vinculo de cada uno de los usuarios con la Universidad Nacional

Considerando los vínculos obtenidos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Administrativo	17	0.039627040	3.96
2	Contratista	5	0.011655012	1.17
3	Docente	11	0.025641026	2.56
4	Egresado	3	0.006993007	0.70
5	Estudiante de Posgrado	30	0.069930070	6.99
6	Estudiante de Pregrado	363	0.846153846	84.62

Tabla 1 - Tabla de frecuencias vinculo_UN. Fuente: Elaboración propia.

De la tabla 1 se resalta que la variable "Estudiante de pregrado" es la que más se presenta dentro de la base de datos realizada, teniendo esta una frecuencia relativa en porcentaje de 84%. Dado esto, los análisis que se van a realizar con respecto a los modos de transporte y lugares de residencia representan un tamaño de la muestra mayor para esta variable, generando así mayores correspondencias con la variable "vinculo_un Estudiante de pregrado", observada como una de las representativas para el modelo.

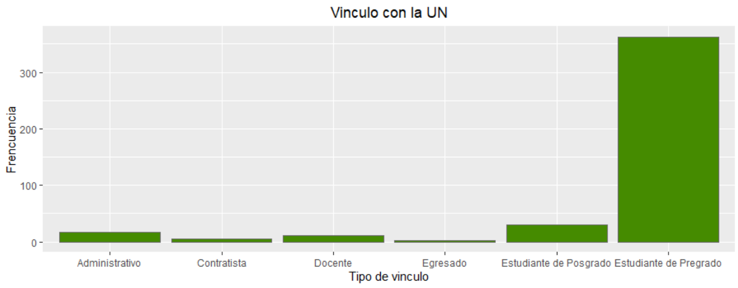


Fig. 41 - Gráfico de frecuencias vinculo_UN. Fuente: Elaboración propia

Como aporte al problema de investigación, se tiene que los resultados obtenidos en cuanto a la relación de los modos de transporte vienen en mayor medida por las respuestas a la encuesta realizada de los estudiantes de pregrado de la universidad Nacional, según se observa en la figura 7.2.

5.1.2 Facultad a la que pertenecen

Considerando la facultad a la que pertenecen los individuos presentes en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Artes	15	0.034965035	3.50
2	Ciencias	15	0.034965035	3.50
3	Ciencias Agrarias	9	0.020979021	2.10
4	Ciencias Económicas	14	0.032634033	3.26
5	Ciencias Humanas	7	0.016317016	1.63
6	Derecho, Ciencias Políticas y Sociales	5	0.011655012	1.17
7	Ingeniería	358	0.834498834	83.45
8	Medicina	4	0.009324009	0.93
9	Medicina Veterinaria y de Zootecnia	1	0.002331002	0.23
10	Nivel Central	1	0.002331002	0.23

Tabla 2 - Tabla de frecuencias facultad. Fuente: Elaboración propia

Teniendo en cuenta que uno de los objetivos principales del proyecto es que en la primera etapa se caracterice de forma aproximada a los usuarios de la facultad de ingeniería; la tabla 1, muestra que los análisis a realizar en cuanto a modo de transporte, representan en mayor medida a personas que pertenecen a dicha facultad, teniendo esta un frecuencia de 358 y una frecuencia relativa en porcentaje de 83,45%, por lo cual, se cumple con uno de los primeros objetivos definidos para la población de análisis, obteniendo así, un tamaño de la muestra que genera mayores correspondencias con la variable facultad de ingeniería, observada como una de las representativas para el modelo.

En la figura 42 se observa la representación gráfica de la variable "facultad", donde se resalta la diferencia que presenta la facultad de "Ingeniería" respecto a las demás, siendo esta, representativa en el desarrollo del problema estadístico planteado.

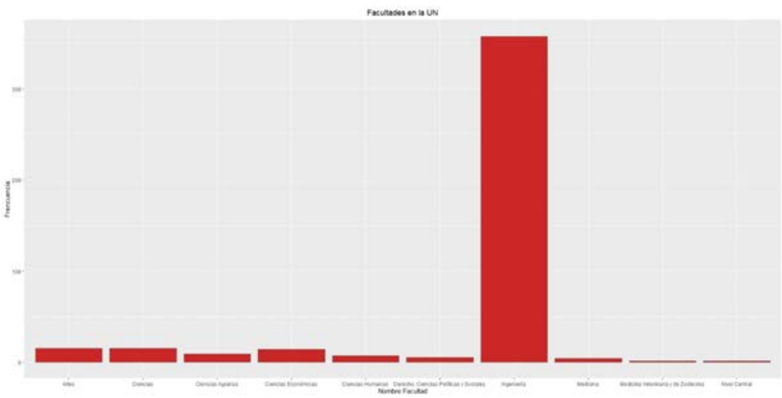


Fig. 42 - Gráfico de frecuencias facultad. Fuente: Elaboración propia.

5.1.3 Modo de transporte con el cual se desplazaba antes de la emergencia sanitaria ocasionada por el covid-19

Considerando los modos de transporte con los cuales se desplazaban los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	A pie	19	0.044289044	4.43
2	Bicicleta	72	0.167832168	16.78
3	Carro	56	0.130536131	13.05
4	Monopatín	2	0.004662005	0.47
5	Moto	10	0.023310023	2.33
6	Taxi	1	0.002331002	0.23
7	Transporte público	269	0.627039627	62.70

Tabla 3 - Tabla de frecuencias modo_antes. Fuente: Elaboración propia

Se observa que el transporte público es el modo de transporte más utilizan quienes respondieron la encuesta, presentando una frecuencia de 269, con una frecuencia relativa en porcentaje de 62,70 %. Esta información es importante para contrastar los cambios de modo de transporte que se pueden presentar durante la emergencia sanitaria, con el fin de atacar estos frentes a partir del desarrollo de la aplicación móvil. Se observa una frecuencia relevante de personas que se movilizan en bicicleta y carro, los cuales pueden ser usuarios potenciales de la aplicación móvil.

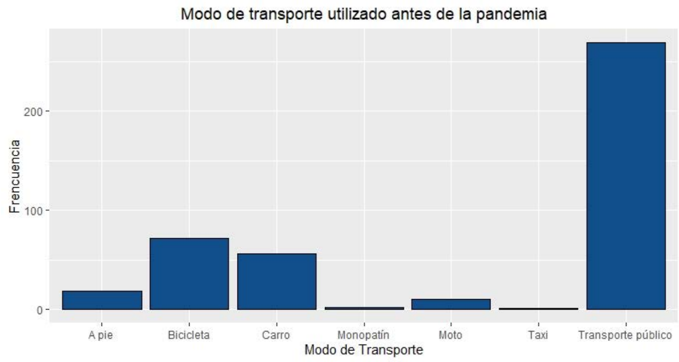


Fig. 43 - Gráfico de frecuencias modo_antes. Fuente: Elaboración propia

En la fig. 43 se presenta de manera gráfica lo mencionado anteriormente, donde sobresale el modo de transporte público, bicicleta y carro.

5.1.4 Modo de transporte con el cual se desplazaría durante la emergencia sanitaria ocasionada por el covid-19

Considerando los modos de transporte con los cuales se desplazarían los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	A pie	21	0.048951049	4.90
2	Bicicleta	138	0.321678322	32.17
3	Carro	119	0.277389277	27.74
4	Monopatín	2	0.004662005	0.47
5	Moto	8	0.018648019	1.86
6	Transporte público	141	0.328671329	32.87

Tabla 4 - Tabla de frecuencias modo_durante. Fuente: Elaboración propia

Se observa un aumento significativo en las personas que se movilizarían en bicicleta, pasando de una frecuencia de 72 a 138; lo mismo ocurre con carro pasando de una frecuencia de 56 a 119 y una reducción en el uso de transporte publico pasando de una frecuencia 269 a 141. Esta información es un insumo fundamental ya que se observa un cambio significativo en los modos de transporte, aumentando así considerablemente los usuarios que se movilizarían en carro y bicicleta, los cuales serían usuarios potenciales de la aplicación móvil.

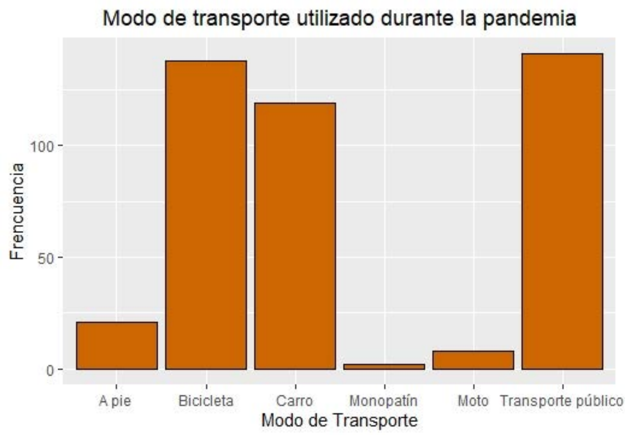


Fig. 44 - Gráfico de frecuencias modo_durante. Fuente: Elaboración propia

La fig. 44 contiene el gráfico de frecuencias que representa lo mencionado anteriormente, siendo esto un insumo fundamental para resolver el problema estadístico planteado, ya que caracteriza los cambios en modos de transporte presentados.

5.1.5 Localidad en la que vive

Considerando la localidad en la que viven los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Barrios Unidos	26	0.06060606	6.06
2	Chapinero	8	0.01864802	1.86
3	Engativa	118	0.27505828	27.51
4	Municipios externos	47	0.10955711	10.96
5	Suba	127	0.29603730	29.60
6	Teusaquillo	40	0.09324009	9.32
7	Usaquén	63	0.14685315	14.69

Tabla 5 - Tabla de frecuencias localidad. Fuente: Elaboración propia

Se resalta que las localidades de Suba y Engativá son las que presentan una mayor frecuencia respecto a las demás localidades, teniendo así un valor de frecuencia de 127 y 118 respectivamente, junto con un valor de frecuencia en porcentaje de 29,60 % y 27,51 %. A partir de este análisis, se puede concluir las localidades con las cuales, a partir del estudio de los modos de transporte de los individuos que las habitan, pueden presentar una relación con la cual se puedan obtener correspondencias para realizar viajes compartidos.

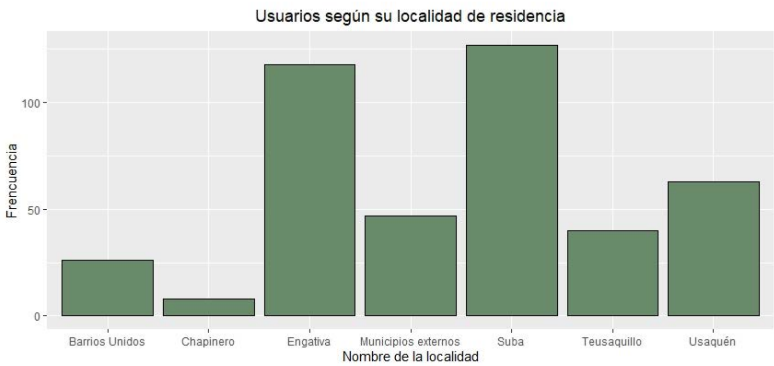


Fig. 45 - Gráfico de frecuencias localidad. Fuente: Elaboración propia

En el gráfico 45 se presenta el gráfico de frecuencias obtenido donde se sobresalen laslocalidades de Suba y Engativá.

5.1.6 Usuario principal de uso de la aplicación

Considerando el rol principal de uso de la aplicación los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Biciusuario	132	0.3076923	30.77
2	Conductor (Con vehiculo disponible)	71	0.1655012	16.55
3	Pasajero	226	0.5268065	52.68

Tabla 6 - Tabla de frecuencias usuario principal. Fuente: Elaboración propia

Se observa que el usuario "pasajero" presenta una mayor frecuencia, con una frecuencia de 226 y una frecuencia relativa en porcentaje de 52,68 %. Este análisis es importante ya que el número de vehículos particulares debe satisfacer la demanda de pasajeros observada y su aporte a la solución del problema estadístico es importante, ya que se deriva de los modos de transporte que el individuo usa.

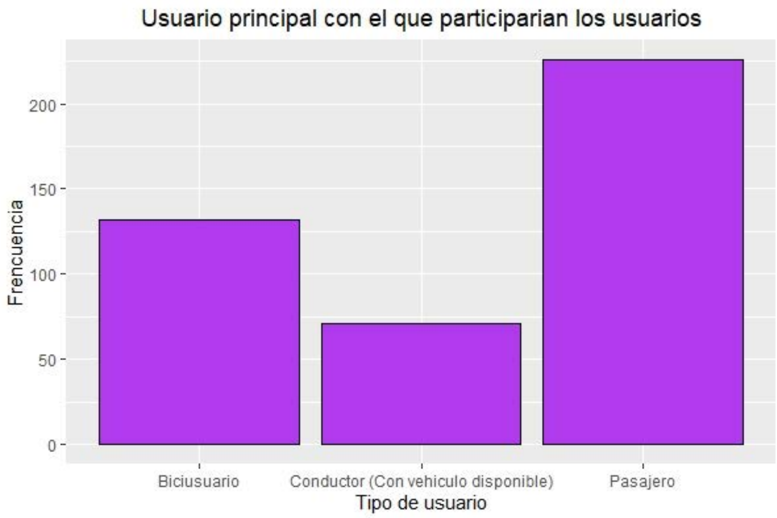


Fig. 46 - Gráfico de frecuencias usuario principal. Fuente: Elaboración propia

5.1.7 Segundo rol de Usuario en la aplicación

Considerando el segundo rol de uso de la aplicación los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Biciusuario	95	0.2214452	22.14
2	No interesado	271	0.6317016	63.17
3	Pasajero	63	0.1468531	14.69

Tabla 7 - Tabla de frecuencias segundo rol. Fuente: Elaboración propia

A partir de la tabla de frecuencias obtenida se puede concluir que 271 individuos (63,17%), no están interesados en ejercer un segundo rol dentro de la aplicación, mientras que biciusuario, es el segundo rol que predomina, con un total de 95 individuos (22,14 %).

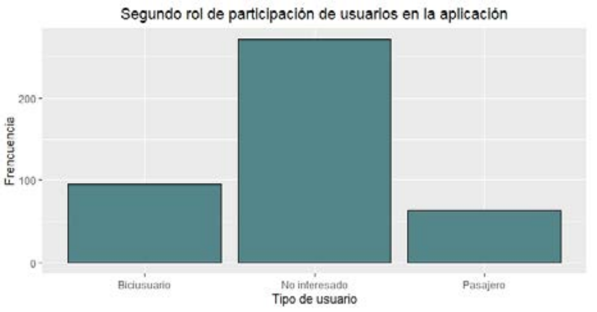


Fig. 47 - Gráfico de frecuencias segundo rol. Fuente: Elaboración propia

En la figura 47 se presenta el gráfico obtenido, donde se resalta un alto porcentaje de usuarios no interesados en desarrollar un segundo rol en la aplicación, siendo esto un insumo relevante para resolver el problema estadístico debido a su relación directa con los modos de transporte que el individuo utilizaría.

5.1.8 Tercer rol de Usuario en la aplicación

Considerando el tercer rol de uso de la aplicación los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Biciusuario	26	0.06060606	6.06
2	No interesado	403	0.93939394	93.94

Tabla 8 - Tabla de frecuencias tercer rol. Fuente: Elaboración propia

A partir de la tabla de frecuencias obtenida se puede concluir que 403 individuos (93,94%), no están interesados en ejercer un tercer rol dentro de la aplicación, mientras que biciusuario, es el rol que se mantiene, con un total de 26 individuos (6,06 %). Esto permite identificar que los modos de transporte, objeto de análisis del problema estadístico planteado, presentan una alta relación con el rol principal seleccionado.

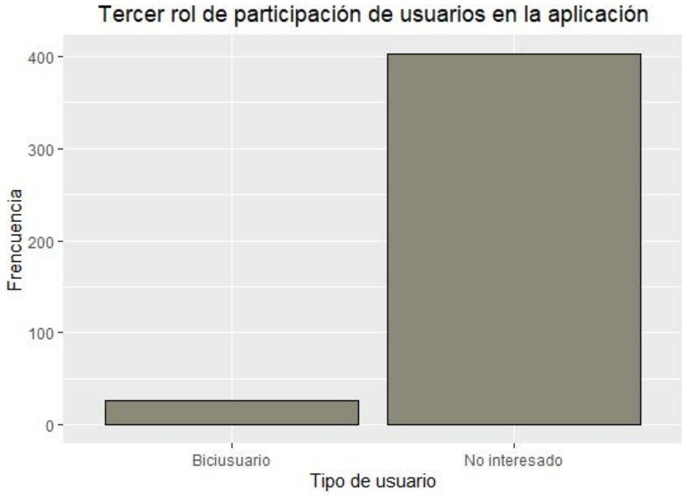


Fig. 48 - Gráfico de frecuencias tercer rol. Fuente: Elaboración propia

5.1.9 Municipios de residencia – Zona Norte

Considerando el tercer rol de uso de la aplicación los individuos en la zona de influencia norte definida anteriormente, se realiza la respectiva tabla de frecuencias:

	Variable	Frecuencia	Frec. Relativa	Porcentajes%
1	Cajicá	6	0.12765957	12.77
2	Chía	10	0.21276596	21.28
3	Cogua	1	0.02127660	2.13
4	Cota	3	0.06382979	6.38
5	El Rosal	2	0.04255319	4.26
6	La Calera	3	0.06382979	6.38
7	Sopó	2	0.04255319	4.26
8	Subachoque	1	0.02127660	2.13
9	Tenjo	1	0.02127660	2.13
10	Tocancipá	1	0.02127660	2.13
11	Zipaquirá	17	0.36170213	36.17

Tabla 9 - Tabla de frecuencias municipios de residencia. Fuente: Elaboración propia

Aunque se observa una baja frecuencia para los municipios analizados, se resalta el municipio de Zipaquirá, con una frecuencia de 17 y una frecuencia relativa en porcentaje de 36,17 %. Esto es un insumo importante ya que en estos municipios se pueden analizar los diferentes modos de transporte partiendo de que debido a su alta distancia con el campus universitario, los modos de transporte tienden a ser transporte público, moto y automóvil.

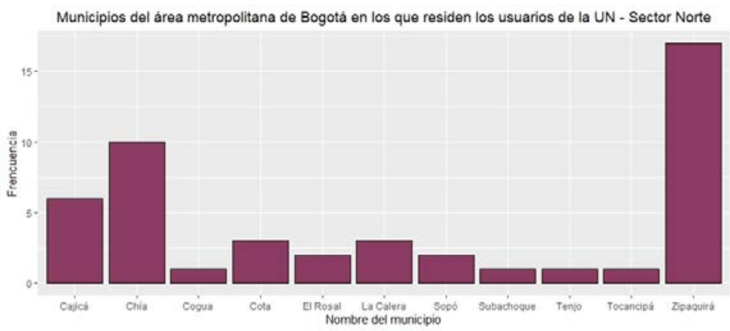


Fig. 49 - Municipio de residencia. Fuente: Elaboración propia

5.2 Tablas y gráficos de contingencias

5.2.1 Localidad vs vinculo

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta su localidad de residencia y el vínculo que este tiene con la universidad, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	Barrios Unidos	Chapinero	Engativa	Municipios externos	Suba	Teusaquillo	Usaquén
Administrativo	0	0	10	1	4	2	0
Contratista	0	0	0	0	2	2	1
Docente	1	1	0	0	4	3	2
Egresado	0	0	1	0	1	1	0
Estudiante de Posgrado	2	0	9	0	9	4	6
Estudiante de Pregrado	23	7	98	46	107	28	54

Tabla 10 - Tabla de contingencia localidad vs vinculo. Fuente: Elaboración propia

Nuevamente se destaca que “estudiante de pregrado” es la variable que presenta un mayor número de registros, esto contrastado con las localidades de Engativá y Suba. Municipios externos se incluye dentro de este análisis, sin embargo, este se estudia con una mayor profundidad más adelante. Para realizar un análisis más a fondo, es importante relacionar las variables de localidad y vinculo, con los modos de transporte usados antes y durante la emergencia sanitaria.

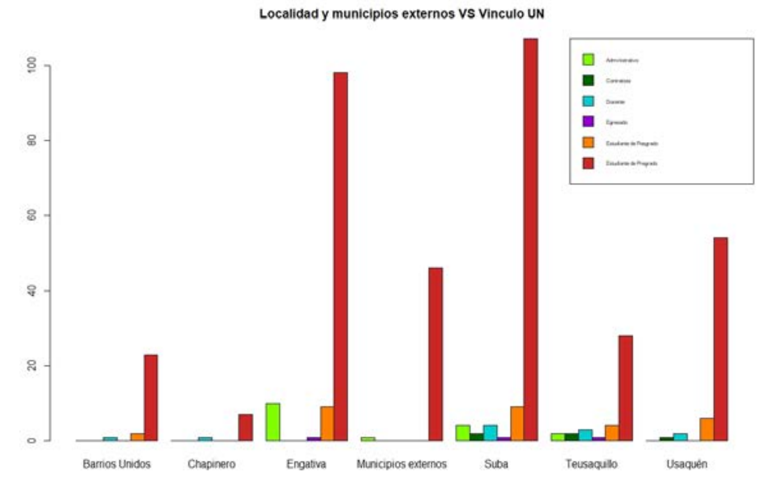


Fig. 50 - Gráfico de contingencias localidad vs municipio. Fuente: Elaboración propia

En el gráfico anterior se resalta lo mencionado con respecto al mayor número de registros para estudiantes de pregrado en las localidades de Suba, Engativá, Usaquén, Municipios externos y Teusaquillo. Es importante considerar la cercanía que estas localidades tienen al campus universitario, por ejemplo, las personas que residen próximas a la universidad nacional que viven en la localidad de Teusaquillo, tienden a desplazarse a pie o en bicicleta, mientras que las personas que residen los municipios externos tienden a desplazarse en trasporte público, moto o carro. Estos análisis se desarrollan a profundidad en las siguientes tablas de contingencias.

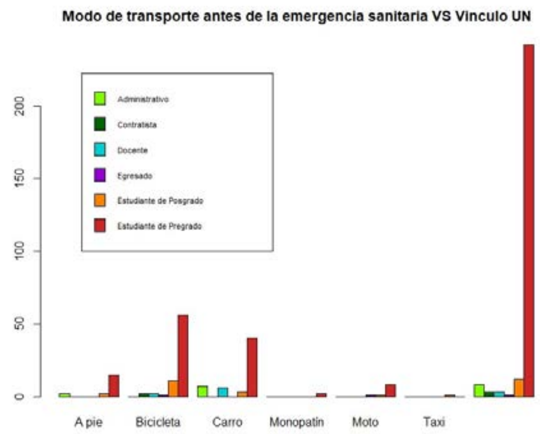
5.2.2 Vinculo vs modo antes

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta el vínculo que el usuario tiene con la universidad, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	A pie	Bicicleta	Carro	Monopatín	Moto	Taxi	Transporte público
Administrativo	2	0	7	0	0	0	8
Contratista	0	2	0	0	0	0	3
Docente	0	2	6	0	0	0	3
Egresado	0	1	0	0	1	0	1
Estudiante de Posgrado	2	11	3	0	1	1	12
Estudiante de Pregrado	15	56	40	2	8	0	242

Tabla 11 - Tabla de contingencia Vinculo vs modo antes. Fuente: Elaboración propia

Según lo presentado en la tabla de contingencias anterior, los estudiantes de pregrado tienden a desplazarse más en transporte público, caso contrario a los docentes, ya que según los resultados estos tienden a desplazarse más en carro particular. Esta tabla refleja un frente importante a trabajar en el desarrollo del proyecto y es el de incentivar a que más docentes se unan al proyecto de carro compartido, ya que estos pueden aportar más vehículos particulares para satisfacer la demanda de pasajeros. En el siguiente gráfico se presenta la información descrita en la Tabla 11, donde se resalta que una vez describan los resultados obtenidos en el modo de transporte que usaría durante la emergencia sanitaria, se realiza análisis del problema estadístico planteado.



TP

Fig. 51 - Gráfico de contingencias Modo antes vs vinculo. Fuente: Elaboración propia

5.2.3 Vinculo vs modo durante

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta el vínculo que el usuario tiene con la universidad, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	A pie	Bicicleta	Carro	Monopatín	Moto	Transporte público
Administrativo	1	2	8	0	0	6
Contratista	0	2	2	0	0	1
Docente	0	2	7	0	0	2
Egresado	0	3	0	0	0	0
Estudiante de Posgrado	2	16	3	0	1	8
Estudiante de Pregrado	18	113	99	2	7	124

TP

Tabla 12 - Tabla de contingencia Vinculo vs modo durante. Fuente: Elaboración propia

Según los registros presentados en la tabla de contingencias anterior, se observa que los estudiantes de pregrado reducirían considerablemente el uso del transporte público durante la emergencia sanitaria hacia un eventual regreso a las actividades presenciales pasando de 242 a 124 registros, y a su vez, estos migran al uso de carro particular pasando de 40 a 99 registros. Se observa que, para los demás vínculos, no se presenta un cambio significativo en el modo de transporte utilizado antes y durante la emergencia sanitaria, por lo cual, se puede concluir que el vínculo “estudiante de pregrado”, es el que presenta una mayor relación en cuanto a los cambios que se pueden presentar en los desplazamientos.

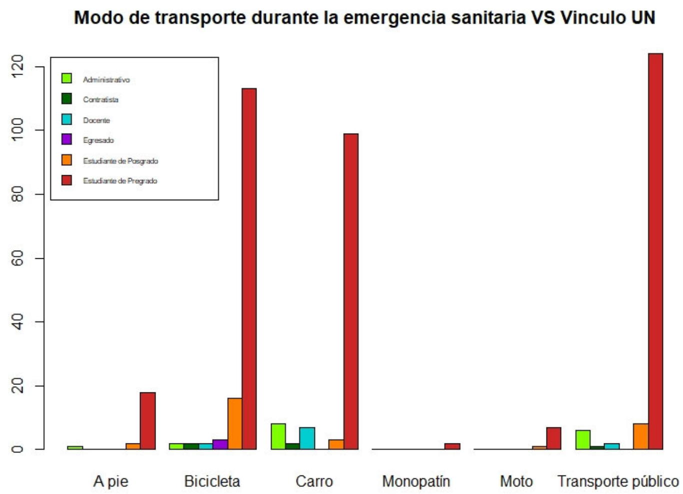


Fig. 52 - Gráfico de contingencias Modo durante vs vinculo. Fuente: Elaboración propia

Los análisis descritos anteriormente se pueden visualizar de una mejor forma comparando las figuras 51 y 52, donde se observa el cambio de las alturas de las barras según el modo de transporte.

5.2.4 Localidad vs modo antes

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta la localidad de residencia del usuario, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	A pie	Bicicleta	Carro	Monopatín	Moto	Taxi	Transporte público
Barrios Unidos	0	7	4	0	1	1	13
Chapinero	1	0	1	0	0	0	6
Engativa	0	33	16	0	2	0	67
Municipios externos	0	0	3	0	4	0	40
Suba	0	16	17	0	1	0	93
Teusaquillo	18	14	1	2	1	0	4
Usaquén	0	2	14	0	1	0	46

Tabla 13. - Tabla de contingencia localidad vs modo antes. Fuente: Elaboración propia

Se observa que antes de la emergencia sanitaria, el modo de transporte público es el que se utiliza mayormente por cada localidad, excepto en la localidad de Teusaquillo, ya que como se había analizado anteriormente, su proximidad con la universidad hace que la mayoría de las personas se desplace a pie o en bicicleta. Se resalta que las localidades de Suba, Engativá, y Usaquén son las que presentan un mayor número de registros en cuanto a modos de transporte como el transporte público y carro particular.

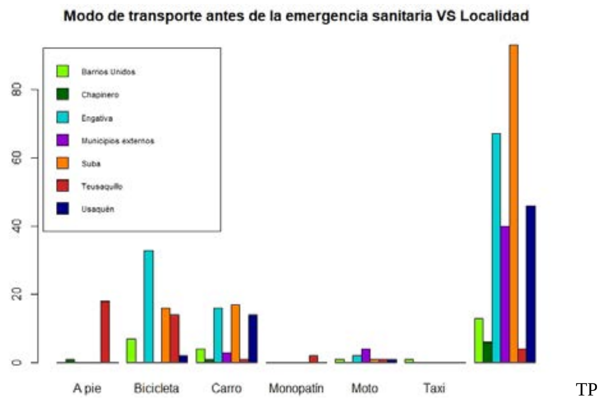


Fig. 53 - Gráfico de contingencias Modo antes vs localidad. Fuente: Elaboración propia

Es importante analizar la localidad vs el modo de transporte durante la emergencia sanitaria con el fin de obtener una respuesta al problema estadístico planteado

5.2.5 Localidad vs modo durante

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta la localidad de residencia del usuario, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	A pie	Bicicleta	Carro	Monopatín	Moto	Transporte público
Barrios Unidos	0	17	5	0	0	4
Chapinero	2	2	1	0	0	3
Engativa	4	53	26	0	1	34
Municipios externos	0	0	10	0	4	33
Suba	1	34	43	0	2	47
Teusaquillo	14	19	2	2	0	3
Usaquén	0	13	32	0	1	17

Tabla 14 - Tabla de contingencia localidad vs modo durante. Fuente: Elaboración propia

Según los registros presentados en la tabla de contingencias anterior, se observa que los usuarios de las localidades de Suba, Engativá y Usaquén reducirían considerablemente el uso del transporte público durante la emergencia sanitaria hacia un eventual regreso a las actividades presenciales pasando de 93 a 47, 67 a 34 y 46 a 17 registros respectivamente, y a su vez, estos migran al uso de carro particular pasando de 17 a 34, 16 a 26 y 14 a 32 registros respectivamente.

También se observa un importante aumento del uso de la bicicleta en localidades como Engativá, Suba, Barrios unidos y Usaquén; por lo cual, estas localidades presentarían una gran posibilidad de uso del aplicativo para realizar viajes compartidos en carro particular y la conformación de grupos de ciclistas.

Si se compara la Fig. 53 con respecto a la Fig. 54, se observa el contraste que se presenta con respecto a los modos de transporte por localidad utilizados antes y durante la emergencia sanitaria, siendo este un insumo relevante para resolver el problema estadístico planteado.

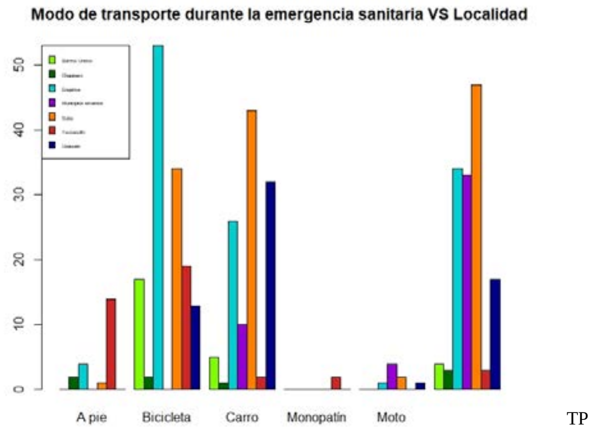


Fig. 54 - Gráfico de contingencias Modo durante vs localidad. Fuente: Elaboración propia

5.2.6 Municipio vs modo antes

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta el municipio de residencia del usuario, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	Carro	Moto	Transporte público
Cajicá	0	0	6
Chía	0	0	10
Cogua	0	0	1
Cota	1	0	2
El Rosal	1	0	1
La Calera	0	1	2
Sopó	0	0	2
Subachoque	0	1	0
Tenjo	0	0	1
Tocancipá	0	0	1
Zipaquirá	1	2	14

Tabla 14 - Tabla de contingencia Municipio vs modo antes. Fuente: Elaboración propia

Para poder analizar la tabla anterior, es importante revisar la tabla que relacione el modo de transporte durante la emergencia sanitaria vs el municipio.

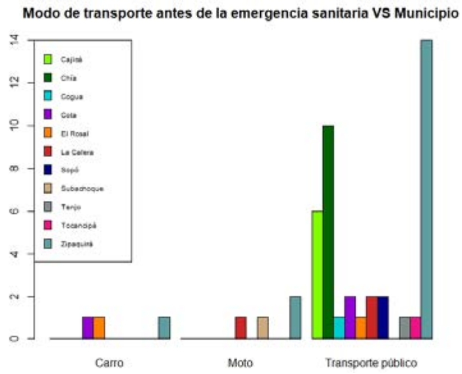


Fig. 55 - Gráfico de contingencias Modo antes vs Municipio. Fuente: Elaboración propia

5.2.7 Municipio vs modo durante

Considerando que dentro del objetivo del problema estadístico se tiene analizar los modos de transporte antes y durante la emergencia sanitaria presentada por el covid-19, teniendo en cuenta el municipio de residencia del usuario, es importante relacionar estas variables a partir de una tabla de contingencias, tal como se ve en la siguiente tabla:

	Carro	Moto	Transporte público
Cajicá	0	0	6
Chía	1	0	9
Cogua	0	0	1
Cota	1	0	2
El Rosal	1	0	1
La Calera	1	1	1
Sopó	0	0	2
Subachoque	0	1	0
Tenjo	1	0	0
Tocancipá	0	0	1
Zipaquirá	5	2	10

Tabla 15 - Tabla de contingencia Municipio vs modo durante. Fuente: Elaboración propia

Se observa que se presenta poca diferencia entre el modo de transporte utilizado antes de la emergencia sanitaria y después de la misma. Aunque se resalta que se presenta un leve aumento del uso del carro particular durante la emergencia sanitaria como se puede observar si se compara la Fig. 55 y Fig. 56.

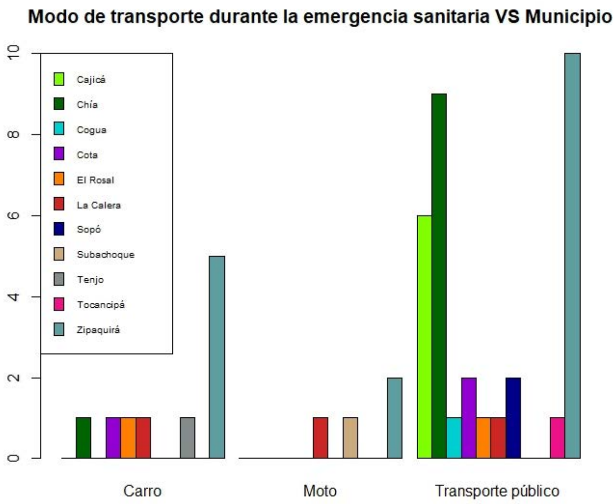


Fig. 56 - Gráfico de contingencias Modo durante vs Municipio. Fuente: Elaboración propia

5.3 Matriz de correlación de Pearson

En el anexo A, se presenta la tabla de Burt de frecuencias relativas realizada para desarrollar los análisis estadísticos de correlación de Pearson. Realizando una exploración inicial de las potenciales relaciones que se pueden presentar entre las variables, considerando también los análisis realizados por medio de tablas y gráficos de contingencias y de frecuencias, en la Fig. 57, se presenta el resultado de los análisis de correlación obtenidos:

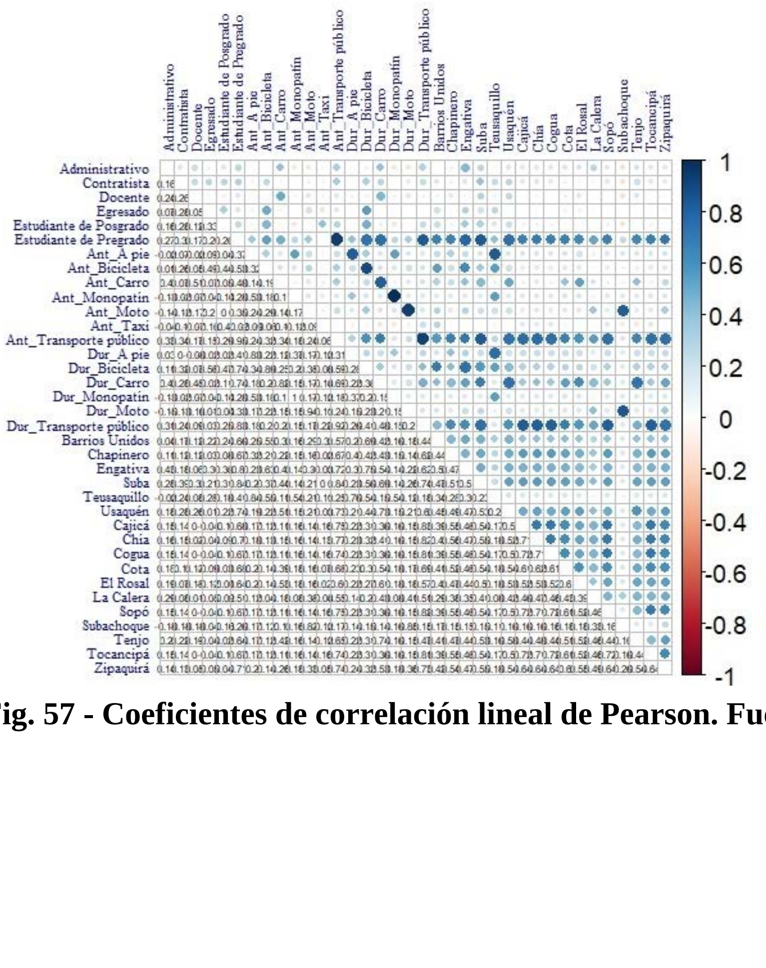


Fig. 57 - Coeficientes de correlación lineal de Pearson. Fuente: Elaboración propia

Observando las diferentes correlaciones obtenidas, se reafirma los supuestos planteados anteriormente, ya que se evidencia que la variable “estudiante de pregrado”, presenta una mayor correlación con la mayoría de las demás variables analizadas, esto corrobora los resultados obtenidos en cuanto a frecuencias y contingencia. Si analizamos los modos de transporte que son el objetivo principal de este análisis, se observa que transporte publico presenta una alta correlación con las demás variables. Por su parte, algunas variables como moto, monopatín, vinculo administrativo, egresado, docente y contratista, presentan poca correlación con la mayoría de las variables de análisis, por lo cual, su uso es poco relevante dentro de la solución del problema estadístico. También se evidencia una alta correlación de localidades como Engativá y Usaquén con respecto a varias de las variables utilizadas, aunque, a manera general, las localidades y municipios si son relevantes dentro de los análisis realizados.

5.4 Análisis de Correspondencias Múltiples (ACM)

Contrastando los resultados obtenidos anteriormente en cada uno de los análisis estadísticos realizados anteriormente, es importante aplicar un análisis de correspondencias múltiples con el fin de corroborar la relación existente entre las variables categóricas, esto de forma gráfica, a partir de los respectivos gráficos biplot obtenidos. Para este análisis, se utilizan las variables de vinculo_un, modo_antes, modo_durante, municipio y localidad. El siguiente gráfico muestra la varianza representada en cada una de las dimensiones contenidas dentro del ACM:

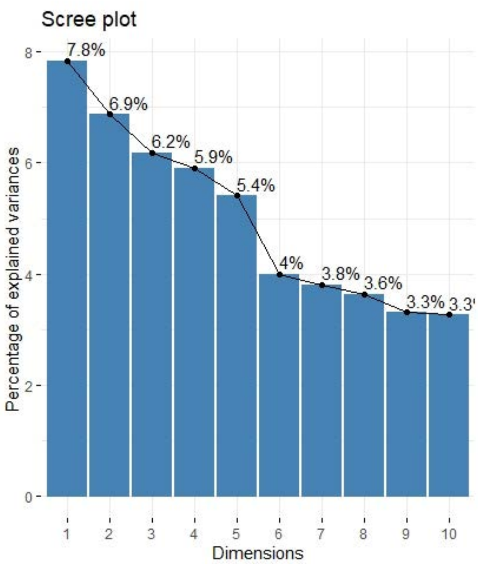


Fig. 58 - Varianza para cada dimensión. Fuente: Elaboración propia

El gráfico Biplot de correspondencias múltiples agrupa los análisis estadísticos de las primeras dos dimensiones.

	Dim 1	Dim 2	Dim 3	Dim 4	Dim 5
vinculo_un	0.0507050	0.01492978	0.07443590	0.01029841	0.1851428
modo_antes	0.5658525	0.75377881	0.80494832	0.88195720	0.6578468
modo_durante	0.6078269	0.70638982	0.81772441	0.87771447	0.6724284
municipio	0.5545850	0.25726166	0.24445404	0.07255927	0.1206911
localidad	0.8087095	0.53478565	0.09692396	0.10372327	0.1482212

Tabla 16 - Varianza por cada dimensión. Fuente: Elaboración propia

Teniendo en cuenta lo explicado anteriormente, a continuación, se presenta el respectivo gráfico biplot de ACM:

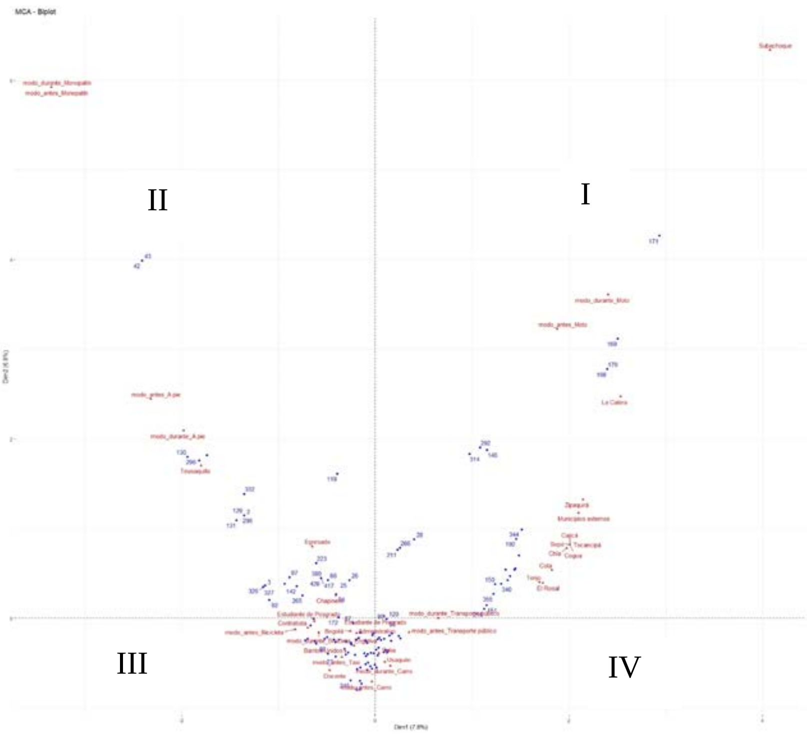


Fig. 59 - Biplot de correspondencias. Fuente: Elaboración propia

Analizando los planos factoriales obtenidos se presenta una relación entre los resultados estadísticos obtenidos anteriormente, ya que "estudiante de pregrado", se encuentra próximo al punto donde cortan el eje de la dimensión 1 y 2, esto se traduce a que esta variable forma un clúster con las demás variables, por lo cual, se evidencia una relación directa entre estas variables que se encuentran agrupadas. Teniendo en cuenta esto, analizamos las variables principales para saber la relación que existe entre estas:

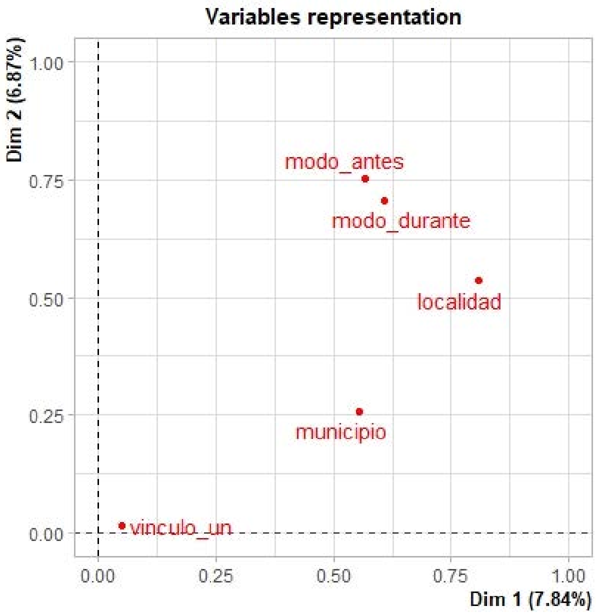


Fig. 60 - Representación de las variables. Fuente: Elaboración propia

Se observa que las variables se ubican en el mismo cuadrante, presentando una cercanía entre los modos de transporte utilizados como se espera que suceda. El siguiente gráfico muestra la relación existente entre los registros analizados, donde se destaca una estrecha relación entre la mayoría de los registros presentados, sin embargo, se observan algunos registros que se encuentra bastante alejados con respecto a los demás, por lo cual, se concluye que estos no son relevantes dentro de la solución del problema estadístico:

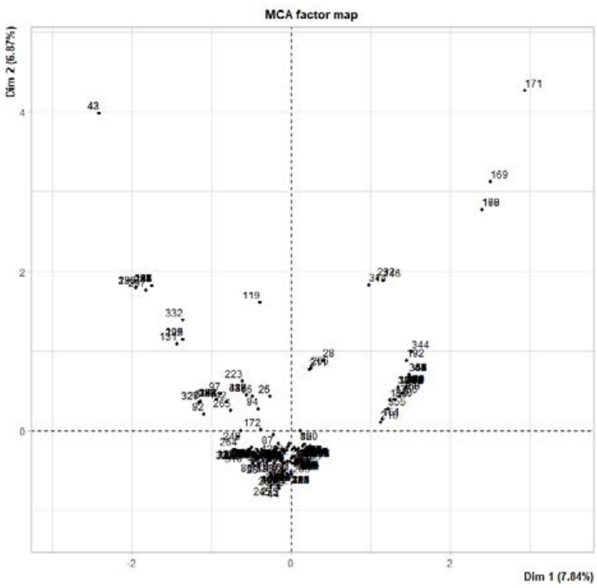


Fig. 61 - Representación de los registros. Fuente: Elaboración propia

En la siguiente imagen se presenta la información del biplot de correspondencias, en el cual se destaca la conformación de clusters y también se descartan variables como modo de transporte a pie o transporte en moto dentro del análisis ya que no son relevantes.

Se destaca también la agrupación que se refleja en el cuadrante 4 de los municipios del área metropolitana, ya que como era de esperarse, existe una estrecha correlación entre estos, por lo cual, el análisis de modos de transporte es relevante para los clusters que se identificaron.

6. CONCLUSIONES

- Se evidencia un interés por parte de la comunidad académica en formar parte del proyecto compartiendo su vehículo o formando grupos de bicicleta para desplazarse hacia el campus universitario, contando con respuestas positivas en las encuestas de un 85.3% de los encuestados.
- Con ayuda de herramientas tecnológicas como lo son la PWA podemos generar soluciones modernas a problemas relacionados con movilidad, que además se acomodan a inconvenientes actuales como lo es la pandemia provocada por el COVID-19.
- Se presenta un interfaz amigable y fácil de usar, adaptable a usuarios sin experiencia tecnológica y que evidencias que es una app que puede ser usada por una comunidad mucho mayor que incluya desde niños mayores de 10 años hasta adultos mayores.
- Este proyecto busca ampliarse a las demás facultades de la Universidad y se contempla la posibilidad de que sea útil también en otros entornos como otras universidades, empresas o entidades.
- Debido a que no se han retomado actividades presenciales dentro de la Universidad, no ha sido posible contar con viajes que hagan uso de esta herramienta, pero tiene la ventaja de ser útil, también cuando se normalice la situación por COVID-19.
- El análisis estadístico realizado arroja una alta correlación entre la variable "estudiante de pregrado" con la mayoría de las demás variables tenidas en cuenta. Es importante para posteriores análisis tratar de ampliar la información recolectada con los demás vínculos de la universidad con el fin de poder caracterizar de una manera más amplia el comportamiento de otros individuos.

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THE CHALLENGE OF SUSTAINABLE UNIVERSITY MOBILITY: COMPARING THE ACCESSIBILITY AND QUALITY OF PUBLIC SPACE OF 14 CAMPUSES IN MADRID

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ABSTRACT

The 6 public universities od Madrid Region are developing a coordinated strategy to implement Sustainable University Mobility Plans (SUMPs) in their 14 campuses. To this end, a combination of mobility survey and data collection inventory were carried out to set a common methodological basis.

Based on data obtained in the inventory, indicators were designed to measure the accessibility and quality of urban space (for instance, pedestrian and cycling areas with respect to total area, percentage of the campus area occupied by parking facilities, etc), combining quantitative and qualitative aspects adapted to the reality of each campus.

Then, taking these indicators as reference, a comparative analysis of the 14 campuses was performed to identify mobility weaknesses and strengths to support the efficient implementation of the SUMPs.

The results showed that campuses with higher accessibility and compactness have a more integrated and higher quality public space, besides a stricter parking control policy. These characteristics are associated with a lower proportion of trips by car and a higher number of walking trips.

1. INTRODUCTION

The university campuses of the 20th century provided an opportunity for the application of modern theories regarding the city and the building. Campuses occupied vast non-central areas, despite being easily accessible by public transport. They gathered all the necessary attributes of a functionally well-defined urban community.

However, the distorted evolution of this model has generated increasingly segregated and dispersed spaces, which are difficult to access. Currently, the unsustainable mobility pattern of university campuses, in which the large number of trips attracted by individual vehicles stands out, requires strategic actions to foster the use of public transport and active mobility.

On the other hand, universities are a good experimentation ground for innovative ideas in the field of sustainable mobility. Most students do not own their own vehicle, and are more open to alternative ways of transport, especially non-motorised modes (Whalen et al., 2013).

Aligned with the effort fostered by the Community of Madrid to decarbonise urban mobility, the 6 public universities od Madrid Region are developing a coordinated strategy to implement Sustainable University Mobility Plans (SUMPs) in their 14 campuses.

The aim of this study is to perform a comparative analysis of the accessibility and spatial characteristics of these 14 campuses. To this end, they were classified and separated in three groups, according to public transport accessibility and urban configuration. As a second step, quantitative and qualitative indicators were employed to analyse the strengths and weaknesses of the mobility infrastructure of each type of campus. Finally, this technical analysis was contrasted with the perceived quality of the campuses by their users, to establish guidelines to support the design and effective implementation of the SUMPs.

1.1 Background

In recent decades, an increasing number of researchers have questioned the possibility of reducing travel demand, mainly by single-occupancy vehicle, through changes in the built environment (Arellana et al., 2020; Bozovic et al., 2020; Koszowski et al., 2019; P. J. Lamíquiz-Daudén & López-Domínguez, 2015; Lee & Moudon, 2006; Valenzuela-Montes & Talavera-García, 2015). As seminal papers, stand out the pioneer study of Newman & Kenworthy (1989) about the association between urban density and car dependence, and the study of Cervero y Kockelman (1997), concerning the influence of the built environment on travel demand and modal choice through three main dimensions, so-called '3 Ds': ‘density’, ‘diversity’ and ‘design’.

Density combined with diversity approaches the origin to the destination, allows for better quality transport infrastructure, reduces the need for parking and foster a more diversified urban environment. (Cervero & Duncan, 2003; Lehmann, 2016). On the other hand, urban design characteristics such as street network density, block size, sidewalk width, urban furniture and tree-lined streets qualify the urban space and distinguish car-oriented environments from pedestrian ones (Ewing et al., 2006; Ewing & Handy, 2009).

Ewing & Cervero (2001) added two more dimensions to the ‘3 Ds’: ‘destination accessibility’, which measures the ease of access to travel attractions, and ‘distance to transit’, related to proximity to rail stations or bus stops. ‘Demand management’, such as parking supply and cost, would be a sixth ‘D’ (Ewing & Cervero, 2010).

Despite the extensive literature on the subject, there are few studies on university campuses, major traffic generators that demands large parking areas. Balsas (2003) highlights that campuses layout varies according to their urban or peripheral location: suburban campuses generally have a more horizontal and dispersed configuration, apart from being more automobile dependent than urban ones. The distance to the city centre also affects the possibility of walking, cycling and use the public transport.

Accessibility plays a key role in the choice of more sustainable modes of commuting to the campus: 32% of the public transport users of the Autonomous University of Barcelona justify their modal choice by the existence of good public transport service options connecting their place of residence with the university, 30% by comfort, 12% by travel time and 10% by lack of private car or motorbike (Miralles-Guasch & Domene, 2010).

Built environment factors associated with campus active mobility includes proximity, mixed use development, street connectivity and accessibility (Ramakreshnan et al., 2020), as well as bicycle and pedestrian facilities, such as continuity and width of pedestrian paths, lighting, pedestrian signage, disabled-users accessibility, shading elements, safe and separate bike lines, bicycle parking lots, showering facilities, and traffic-calming schemes (Bonham & Koth, 2010; Menini et al., 2021). This schemes must be combined with transportation demand management (TDM) strategies, which include parking policies, subsidies for public modes of transit, rideshare programs, park and ride facilities, etc (Balsas, 2003; Delmelle & Delmelle, 2012).

The combination of the active modes with public transport, providing a well-defined walking and cycling network, has been shown to be effective in the case of longer travels: commuters to university campuses use public transport more often when such facilities are properly provided (Dehghanmongabadi & Hoşkara, 2018). Still, walking and cycling continue to play a marginal role as means of transport, and their infrastructure is continuously neglected in the planning of the campuses. Due to insufficient infrastructure, empirical findings show that there is an unsatisfied demand for non-motorised modes, especially for cycling (Miralles- Guasch & Domene, 2010).

2. CASE STUDY

The case study relies on the 14 campuses of the 6 public universities of Madrid Region: Universidad Autónoma de Madrid (UAM), Universidad Complutense de Madrid (UCM), Universidad Politécnica de Madrid (UPM), Universidad Carlos III de Madrid (UC3M), Universidad Rey Juan Carlos (URJC) and Universidad de Alcalá de Henares (UAH).

Table 1 presents the university population and area of each campus, as well as the modal split.

Name of the campus	University	University population	Area (ha)	Modal shift (%)			
				Car / motorbike	PT	Walking	Cycling
Cantoblanco	UAM	3220	125	36	61	3	0
Somosaguas	UCM	9840	36	32	65	2	1
Ciudad Universitaria	UPM / UCM	25774	480	28	63	7	2
Montegancedo	UPM	2720	23,5	51	47	1	1
Campus Sur	UPM	5062	25	34	61	3	2
Getafe	UC3M	16220	16,8	31	49	20	0
Leganés	UC3M	9101	7,7	44	44	11	1
Colmenarejo	UC3M	1554	7,5	61	36	3	0
Alcorcón	URJC	4914	29,3	38	56	5	1
Fuenlabrada	URJC	13503	50	41	54	5	0
Móstoles	URJC	9781	25,7	46	48	6	0
Madrid – Vicálvaro	URJC	16519	7,5	28	65	6	0
Científico – tecnológico	UAH	14255	76,3	69	28	2	1
Histórico	UAH	10194	82,9	23	58	18	0

Table 1 – Public University Campuses in Madrid

3. METHODOLOGY

In order to obtain information and data on the existing mobility infrastructures, a form was sent to the universities, requesting general data on the campuses. This data was checked and complemented through technical visits and orthophoto analysis to produce a complete inventory, including data such as number of public transport stops, parking places, pedestrian and motorized traffic area, length of cycle paths, etc.

From this inventory, a series of quantitative indicators were generated. Qualitative indicators were also defined to assess the spatial configuration and quality of public spaces on the campuses. The table 2 in the section 4 shows all the quantitative and qualitative indicators used in this study, as well as their results.

In the case of qualitative indicators, reference values from 1 to 6 were used: from “Poor” to “Excellent”. The spatial configuration (compact or dispersed) was defined based on the average of two qualitative indicators: “Density of users” and “Mixed use”. The quality of public spaces was determined by the average of 4 indicators: “Street furniture”, “Continuity and maintenance of the pedestrian network”, “Percentage of tree-lined streets” and “Landscape maintenance”.

Finally, to contrast this technical analysis with the perception of campus users, a survey among the university community was carried out to find out about mobility patterns and users' opinion regarding mobility infrastructure and services. For this study, two questions of the survey related to campus infrastructure were used:

The question “F1: Value the quality of your campus' infrastructure and transportation services” provided a rating from 1 to 6 (from poor to excellent) for the following items:

- Good road access (A)
- Availability of car parking spaces (B)
- Availability of charging points for electric vehicles (C)
- Availability of motorbike parking spaces (D)
- Good access by public transport (E)
- Good access by bicycle (F)
- Availability of bicycle parking spaces (G)
- Good condition of sidewalks and pedestrian tracks (H)
- Proper lighting (I)
- Sufficient vegetation and shade (J)
- Security in accesses and parking (K)

The question “S7: Write down any improvements you deem necessary for your campus” requested a complementary point of view to the previous question (F1), while making it possible to particularize the answer for each campus.

3.1 Campus typology according to accessibility and spatial configuration

For subsequent analysis, campuses have been classified into three types, according to their accessibility to public transport and spatial configuration.

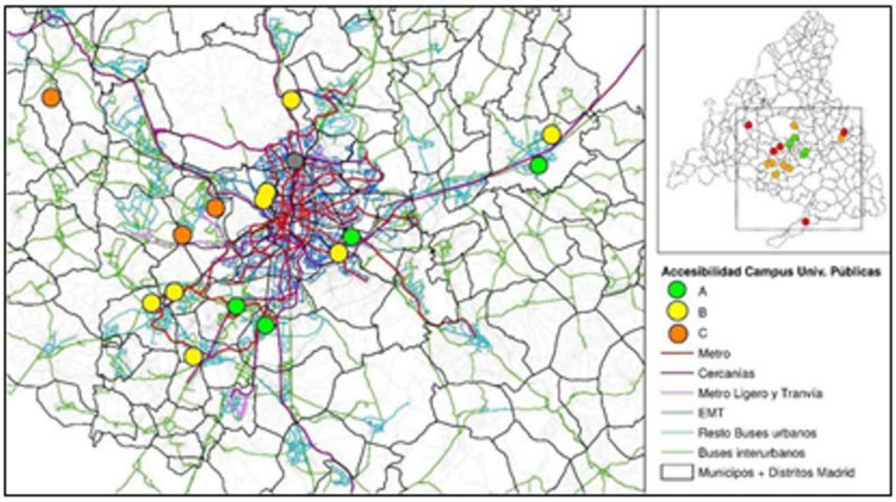

Fig. 1 – Campus typology according to accessibility and spatial configuration

- Type A: Compact urban campuses with access to the Metro/Cercanías: Leganés (UC3M), Getafe (UC3M), Madrid-Vicálvaro (URJC) and Campus Histórico (UAH).
- Type B: Dispersed urban campuses with access to the Metro/Cercanías: Ciudad Universitaria (UPM + UCM), Campus Sur (UPM), Cantoblanco (UAM), Alcorcón (URJC), Fuenlabrada (URJC), Móstoles (URJC) and Científico-Tecnológico (UAH).
- Type C: Dispersed peri-urban campuses without access to Metro/Cercanías: Colmenarejo Campus (UC3M), Somosaguas Campus (UCM) and Montegancedo (UPM).

According to this classification, the analysis of the indicators identified the strengths and weaknesses of the mobility infrastructure and quality of public spaces of each type of campus.

4. RESULTS

Type A campuses have high density of construction and users, as well as other uses other than educational one (housing, cultural, commerce and support services). They are located in areas of higher density and mixture of uses, as is the case of the historic centre of Leganés and Alcalá de Henares.

Furthermore, they have greater connection with the surrounding areas, maintaining a dialogue with the surrounding infrastructure and proposing activities open to the neighbouring population. Compared to the other groups, it presents a lower percentage of trips by car or motorbike, and a higher proportion of walking trips.

Type B campuses occupy larger terrains and have low density, as well as few uses other than educational ones. This classification includes both central campuses of Madrid (Ciudad Universitaria and Campus Sur) and located in subcentres of the Madrid Region (e.g. Alcorcón, Móstoles and Fuenlabrada).

Except for the Ciudad Universitaria, which is open and maintains a good connection with the dense and diversified district of Moncloa, the others have little relation to the surrounding area. This connection is hampered by perimeter closures and large metropolitan infrastructures, such as motorways and train lines.

Type C campuses occupy large areas in transition zones between urban and rural/natural environment, presenting low density, as well as an accentuated monofunctionality: apart from educational and administrative use there have few support services such as cafeteria and reprographics. The connection with the surrounding area is virtually non-existent.

However, this problem is more related to the distance separating these campuses from the nearest centralities than to the existence of barriers or lack of access. The absence of adequate support services to the university community makes it difficult to stay long periods of time on campus and acts as another factor, apart from distance, that encourages people to travel by car. Compared to the others, this group presents a higher proportion of trips by car or motorbike, and a lower proportion of walking trips.

These results are in line with the references consulted (Balsas, 2003; P. J. Lamíquiz-Daudén & López-Domínguez, 2015; Newman, P. and Kenworthy, 1989; Ramakreshnan et al., 2020).

Table 2 summarizes the result of each indicator by university campus, integrating quantitative and qualitative indicators. In green: type A campuses, in yellow: type B campuses and orange: type C campuses.

	INDICATOR	UAM	UCM	UCM + UPM	UPM		UC3M			URJC				UAH	
		Cantoblanco	Somosaguas	Ciudad Universitaria	Montegancedo	Campus Sur	Getafe	Leganés	Colmenarejo	Alcorcón	Fuenlabrada	Móstoles	Madrid Vicálvaro	Científico-tecnológico	Campus Histórico
Quantitative indicators	Nº of public transport stops - less than 1000m	25	44	196	45	82	100	124	6	54	39	74	81	65	201
	Number of parking places/100 campus users	21	24	10	34	19	6	7	14	14	11	10	3	20	2
	% of car parking places with access restriction	10%	25%	0%	11%	12%	87%	100%	47%	26%	6%	34%	43%	0%	76%
	Car parking places/Total parking places	97%	98%	97%	97%	96%	87%	98%	100%	98%	98%	97%	97%	98%	98%
	Disabled parking places/Total parking places	3%	1%	2%	1%	1%	0%	0%	0%	2%	2%	2%	3%	2%	2%
	Electric car parking places /Total parking places	0%	0%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
	Motorbike parking places/Total parking places	0%	0%	1%	1%	3%	12%	1%	0%	0%	0%	1%	0%	0%	0%
	Electric charging points/10000 users	0	0	0	26	2	6	4	0	0	0	3	0	0	0
	Area dedicated to pedestrians	7%	7%	5%	4%	6%	21%	36%	20%	12%	16%	24%	21%	8%	No data
	Length bike lanes/100 m street (m)	12	0	22	33	0	0	0	0	0	0	0	7	73	No data
	Bycicle parking places/Total parking places	2,4%	0,9%	5,0%	2,6%	0,0%	32,8%	20,4%	5,3%	13,7%	3,1%	6,9%	6,2%	12,2%	19,3%
Qualitative indicators	Users density	3	3	2	2	3	5	6	3	2	3	4	6	2	5
	Mixed use	5	4	4	3	3	4	5	2	3	3	3	4	4	6
	Quality and state of maintenance of the pedestrian network	3	3	3	2	2	5	6	5	4	4	4	3	2	5
	Urban furniture	4	2	2	2	2	5	6	5	3	3	3	4	2	5
	Tree-lined streets	5	2	6	4	5	4	4	4	2	2	2	6	4	2
	Landscape maintenance	4	3	3	4	3	5	6	6	4	3	3	4	2	4

Table 2 – Results of indicators by university campus.

4.1 Accessibility to public transport

Both type A and type B campuses have good accessibility due to the proximity of the Metro and Cercanías train station, as well as numerous urban and intercity bus lines. Type Cs do not have good accessibility. Usually, there are few bus lines departing from specific locations in Madrid city or other parts of the Madrid Region. The frequency of these buses is low, and users spend a lot of time on the journey.

4.2 Parking facilities

The parking offer changes significantly according to the type of campus. Type A campuses stand out for the low number of parking spaces per user and a higher percentage of parking spaces with access restriction.

Despite good accessibility by public transport, especially in the case of the URJC and UPM campuses, which are accessible by Metro, Type B campuses have a wide range of parking and little or no restriction policy. Naturally, this is also the case for Type C campuses, justified by poor accessibility by public transport.

These results reinforce the results obtained by Balsas (2003) Delmelle & Delmelle (2012) and Ewing & Cervero (2010) regarding parking control policy and lower proportion of car trips

All campuses offer more than 87% of their parking spaces for cars, at the expense of spaces reserved for motorbikes and people with disabilities. None have a parking policy based on HOV criteria (High Occupancy Vehicles). They also do not have a significant number of parking spaces reserved for electric vehicles and/or equipped with electric charging points.

4.3 Pedestrian and cycling infrastructure

Due to their compact configuration, type A campuses prioritize the pedestrian space. This situation varies for type Bs and Cs. The campuses of the Universidad Rey Juan Carlos y Colmenarejo (UC3M) concentrate most of the road system, as well as parking lots in the peripheral area. In contrast, the interior preserves large fully pedestrian areas. This configuration has the advantage of maintaining the continuity of the pedestrian zone and establishing a balance between the road system and the pedestrian space.

On the other hand, the UAM, UCM, UPM and Científico-Tecnológico (UAH) campuses prioritise the road system, which impairs the continuity and fluidity of the pedestrian space.

Regarding cycling infrastructure, although none of the campuses have a suitable cycling network, that is, continuous and extended, some stand out for a greater extension and balance between segregated cycle lanes and road system, as well as more bicycle storage facilities, as for example, Ciudad Universitaria (UCM + UPM).

Most campuses prioritise the shared use of road space with bicycles without adopting calm traffic strategies and proper signage. Type A campuses and those of the URJC that belong to group B are cyclable over most of their surface, without the need to compete for space with vehicles. However, in a scenario of greater use of bicycles to commute to campus, measures should be adopted to avoid conflicts with pedestrians, such as bicycle dismounting zones.

The Getafe and Leganés (UC3M) campuses have a higher supply of bicycle parking spaces than the others. This is possibly the result of a combination of factors: central location, more developed cycling infrastructure in the surrounding area and parking restriction policy, which mainly affects students.

Bicycle-friendly campuses also have more safety concern, locating the facilities in high-traffic locations and adopting surveillance and access control strategies.

4.4 Quality of public space

The quality of the public space is the result of the combined analysis of 4 indicators: 'urban furniture', 'continuity and conservation of the pedestrian network', 'percentage of tree-lined streets’ and 'landscape maintenance'.

Being more compact, type A campuses have a more integrated space that favours the creation of convivial areas. On the other hand, these campuses spend fewer resources in the care of public space: they stand out for the quantity and quality of urban furniture, diversity of herbaceous plants with a high level of maintenance and good condition of the sidewalks.

In this sense, the Campus Histórico (UAH), for example, benefited from the pedestrianization plan developed by the City Council of Alcalá de Henares for the historic centre.

Unlike the previous case, the dispersed configuration of the campuses of groups B and C makes it difficult to create convivial spaces, as well as install and maintain urban furniture and the landscaping. The great distance between buildings and the excess of public space do not favour the appropriation of space by people. In the case of the UPM, UAM and Científico-Tecnológico (UAH) campuses, the car-oriented design prioritises the road system and fragments the space.

These results are in line with Cervero & Kockelman (1997); Ewing et al. (2006) and Ewing & Handy (2009).

In contrast, Colmenarejo (UC3M) stands out for its high quality of public space: the campus concentrates educational and administrative activities in a limited space, while the rest of the campus integrates a green area (Botanical Garden) with impeccable maintenance that also acts as a convivial space.

4.5 Perceived quality of campuses according to users

Table 3 shows the results of the assessment of campus infrastructure according to the perception of its users, according to a rating from 1 to 6 (from poor to excellent).

Name of the campus	University	A	B	C	D	E	F	G	H	I	J	K
Cantonlanco	UAM	5	5,1	2	3,9	4,7	3,9	3,8	4,5	4,5	4,8	4,6
Somosaguas	UCM	4,8	5,1	1,8	4	4,3	3,2	3,4	4,2	4	4	4,3
Ciudad Universitaria	UCM / UPM	4,8	3,8	2	3,6	4,8	4,2	3,8	4,3	4,3	4,3	4,2
Montegancedo	UPM	4,6	4,9	1,5	3,9	3,1	2,3	2,9	3,9	4	4,6	4,3
Campus Sur	UPM	4,8	5,2	1,7	4,1	4	3,3	3,3	4	3,7	4,5	3,7
Getafe	UC3M	4,9	4,5	2,5	3,4	4,5	3,8	3,9	4,7	4,6	4,3	4,5
Leganés	UC3M	4,6	2,6	1,8	3	4,5	3,7	4,2	4,5	4,7	4,3	4,4
Colmenarejo	UC3M	3,9	4,5	1,5	2,9	3,4	3,3	3,6	4,3	4	4,5	4,5
Alcorcón	URJC	5,2	4,7	1,9	3,5	4,5	4,1	3,7	4,7	4,5	3,6	4,3

Table 3 – Perceived quality of campuses according to users

According to the users' assessment, type A campuses stand out for their good accessibility by car and public transport, the quality of public space and the security. Weaknesses are related to the low availability of car, motorbike and bicycle parking facilities.

Most Type B campuses also stand out for their good accessibility by car and public transport. The evaluation of public space and security varies from campus to campus. According to the users, some have a lack of vegetation and shade, as is the case of Alcorcón and Móstoles. Others, lack of lighting and security, such as Campus Sur.

Regarding type C campuses, the most notable strengths were road access by car and parking lots, as well as quality of public space. Weaknesses are poor accessibility by public transport and by bicycle.

All campuses have a low supply of charging points for electric vehicles.

5. CONCLUSIONS

The comparative study of the 14 campuses showed that besides good accessibility, type A campuses have a higher degree of compactness than the others, which is related to a more integrated and higher quality public space, as well as a stricter parking policy. These characteristics are associated with a lower proportion of trips by car and a higher number of walking trips, which coincides with the references of the consulted studies on the relationship between modal choice and the 6 Ds: “density”, “diversity”, “design”, “destination accessibility”, “distance to transit” and “demand management”.

On the other hand, type B and C campuses stand out for their dispersed configuration, lower quality of public space, when compared to type

A campuses, and absence of control over parking, which is associated with a higher proportion of car trips, and a lower proportion of walking trips. This situation is aggravated in the case of type C campuses, which have low accessibility by public transport.

These conclusions are reinforced by the perception of users, which reinforces the need to improve accessibility in public transport, pedestrian and cycling infrastructure and the quality of public space on university campuses.

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NUEVOS VEHÍCULOS Y FORMAS DE MOVILIDAD
NEW VEHICLES AND MEANS OF MOBILITY

FACTORES CLAVE EN LA ADOPCIÓN DE LAS MOTOS DE USO COMPARTIDO EN NÚCLEOS URBANOS DE ESPAÑA

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RESUMEN

En el contexto de la economía colaborativa, están surgiendo distintas opciones de movilidad urbana a la demanda. Dentro de esta nueva tendencia, las motos de uso compartido o motosharing —conocidas por los términos en inglés moped scooter sharing— están experimentando un gran auge en muchas ciudades del mundo, particularmente en Europa.

Asimismo, estos servicios de motos eléctricas generarían una serie de beneficios, como la reducción del ruido, contaminación del aire o congestión vial, con importantes implicaciones en la mejora de la habitabilidad y la calidad de vida en las ciudades.

Hasta la fecha, se han realizado numerosas investigaciones sobre diferentes opciones de movilidad compartida, como es el caso del carsharing o bikesharing, pero apenas se han estudiado los servicios de motos compartidas. Por lo tanto, se ha realizado un modelo logit ordenado generalizado, a fin de identificar los factores clave que determinan la adopción y la frecuencia de uso de este sistema de movilidad en áreas urbanas. Para ello, se han explotado los datos recopilados de una encuesta online difundida en diferentes ciudades de España, el país con la mayor implementación de motos compartidas.

Los resultados del modelo muestran el papel fundamental de algunas variables sociodemográficas y atributos de movilidad urbana, como la edad, el nivel de educación o el número de viajes realizados en un día laborable, mientras que otras variables como las opiniones y actitudes personales, por lo general, no se han encontrado estadísticamente significativas. Asimismo, se proporciona una mejor comprensión de este sistema de transporte, así como algunas implicaciones en la movilidad, de gran interés tanto para los operadores como para los planificadores de transporte a la hora de diseñar acciones y políticas que aborden esta reciente alternativa de movilidad urbana.

1. INTRODUCCIÓN

Comprender los patrones de movilidad urbana de los habitantes es crucial para los planificadores urbanos, administradores y proveedores de transporte. De hecho, los cambios demográficos en las ciudades están cambiando los patrones de movilidad y buscando formas sostenibles de transporte urbano para abordar las externalidades provenientes del transporte urbano, como la contaminación, el cambio climático, la congestión o la falta de espacio urbano. La movilidad inteligente es uno de los componentes principales para lograr una ciudad inteligente, un concepto destinado a mejorar la calidad de los ciudadanos que ha adquirido una importancia cada vez mayor en las políticas urbanas (Neirotti et al., 2014).

En ese contexto, en muchos centros urbanos han aparecido servicios innovadores de movilidad compartida, como el uso compartido de automóviles, el uso compartido de bicicletas, el viaje en bicicleta o el uso compartido de scooters (tanto ciclomotores como patadas) y han aumentado su demanda progresivamente, causando un cambio notable en la oferta de transporte. y promoviendo una movilidad urbana más ecológica. Se pueden encontrar muchas contribuciones de investigación recientes en el campo de la movilidad compartida, en particular el uso compartido de automóviles, el uso compartido de bicicletas públicas o el alquiler de vehículos. Sin embargo, casi no se han dedicado esfuerzos a la literatura científica para explorar los servicios de uso compartido de scooters con ciclomotor, una alternativa de transporte que ha experimentado un auge en los últimos años en muchas ciudades del mundo, particularmente en países europeos.

Por lo tanto, se necesitan más esfuerzos para explorar la adopción de sistemas de uso compartido de scooter de ciclomotor en áreas urbanas. Esta investigación lleva a cabo una primera visión de la adopción y la frecuencia del uso del uso compartido del scooter ciclomotor. Como aspecto innovador, cubre tanto a los usuarios como a los no usuarios del uso compartido de scooters de ciclomotores para identificar los factores explicativos que determinan la adopción y el uso de esta alternativa de movilidad en áreas urbanas.

Además, también se analiza su relación e impacto en modos de transporte alternativos (por ejemplo, automóvil privado, transporte público, etc.). Esto nos permitiría identificar segmentos específicos del mercado de usuarios de esta alternativa de movilidad y dirigir adecuadamente los esfuerzos de políticas para promover este medio de transporte ecológico en las zonas urbanas. Con ese fin, desarrollamos un modelo *logit ordenado generalizado (gologit)* basado en una encuesta en línea realizada en diferentes ciudades de España, el país con la mayor presencia de servicios de uso compartido de scooters en todo el mundo hasta la fecha.

Este documento está estructurado de la siguiente manera. Después de este capítulo introductorio, la Sección 2 proporciona una base útil sobre la movilidad compartida en general y el uso compartido de scooters de ciclomotores en particular.

La encuesta realizada y la muestra de datos utilizada para esta investigación se describen en la Sección 3. La Sección 4 describe la metodología de logit ordenada generalizada adoptada para explorar la adopción de servicios de uso compartido de scooters por parte de las personas. La sección 5 presenta y discute los resultados. Finalmente, la Sección 6 trata las principales conclusiones.

2. REVISIÓN DE LA LITERATURA / ESTADO ACTUAL

2.1 Movilidad compartida y comportamiento de viaje

Los servicios de movilidad compartida están interrumpiendo los sistemas de transporte urbano al influir en los patrones de viaje y competir con modos más tradicionales (Henao, 2017). Según Shaheen Y Chan (2016), la movilidad compartida es una estrategia de transporte innovadora que permite a los usuarios obtener acceso a corto plazo a los modos de transporte según sea necesario, lo que ha traído grandes cambios en, p. propiedad del automóvil o cómo las personas planean y hacen sus viajes. La primera implementación de esta forma de servicios de movilidad urbana abarcó esquemas de bicicletas compartidas, seguidas de los sistemas de autos compartidos. Más recientemente, el uso compartido de scooters de ciclomotores se ha convertido en un modelo innovador para compartir vehículos en áreas urbanas, con algunas características específicas que lo convierten en una opción interesante a tener en cuenta al viajar o conducir por el centro de la ciudad. La introducción de estos servicios tiene implicaciones para el comportamiento del viaje y el cambio modal, así como los impactos en el sistema general de transporte.

Se pueden encontrar muchas contribuciones recientes en la literatura en el campo de la movilidad compartida y el comportamiento de viaje. Por ejemplo, en los Estados Unidos (EE. UU.), Se ha observado que los primeros en adoptar servicios de movilidad compartida tienden a ser adultos jóvenes altamente educados que viven en áreas urbanas (Buck et al., 2013, Rayle et al., 2014; Taylor et al., 2015). Otros estudios basados en estadísticas descriptivas como Circella, et al. (2018) mostraron que la popularidad de estos servicios es particularmente alta entre los millennials y aquellos que viven en las densas partes centrales de las ciudades. De acuerdo con Taylor et al. (2015), la oferta de movilidad compartida más amplia podría tener implicaciones para las preferencias del usuario, p. impactando decisiones de propiedad de vehículos privados o patrocinio de transporte público. La literatura actual ha cubierto principalmente el uso de bicicletas compartidas, autos compartidos y servicios de viajes a pedido, mientras que casi no se han dedicado contribuciones al uso compartido de motos. De hecho, la escasez de literatura científica sobre el uso compartido de motos es un punto subrayado por Howe y Bock (2017). Hasta donde sabemos, el estudio de Degele et al. (2018) es la única investigación científica existente sobre el uso compartido de scooters hasta la fecha. Identificó segmentos de clientes de uso compartido de scooters basados en el uso de datos en Alemania, pero no exploraron la adopción o las percepciones de las personas hacia esta alternativa de movilidad en áreas urbanas ni abordaron su impacto en los modos de transporte alternativos.

2.2 El reciente aumento del motosharing

Bicisharing fue el primer esquema de movilidad compartida introducido en las zonas urbanas, en la década de 1990, seguido de los sistemas de uso compartido de automóviles eléctricos que comenzaron a funcionar en la década de 2000. Luego, el uso compartido de scooters estilo ciclomotor se implementó por primera vez en San Francisco (EE. UU.) En 2012, y desde 2015 su desarrollo de mercado ha comenzado a extenderse por todo el mundo.

Durante 2016 y 2017, hubo un auge en el mercado internacional y se desplegaron 8,000 ciclomotores (Stephanou, 2017) alcanzando un total de 25,000 scooters de ciclomotores en todo el mundo (Howe, 2018). En 2018, más de 60 ciudades en todo el mundo adoptaron este tipo de servicios de movilidad, con una estimación de 1,8 millones de usuarios registrados (Howe, 2018), y muchas otras ciudades han planeado introducir sistemas de uso compartido de scooters en los próximos años. Hasta la fecha, España es el país con la mayor implementación de servicios de uso compartido de scooters en todo el mundo, alcanzando una flota de 9,000 ciclomotores y un crecimiento del mercado del 500% en 2018, y comprende el 35% de la flota mundial en todo el mundo (Howe, 2018).

Al igual que el carsharing, existen dos tipos principales de sistemas existentes: sistemas basados en estaciones y sistemas de flotación libre (Howe y Bock, 2017). Alrededor del 99% de los sistemas de uso compartido de scooters de ciclomotores existentes en todo el mundo son de libre flotación, y más del 97% de los ciclomotores son eléctricos (Howe, 2018).

Representan un modo de transporte atractivo para ciertos segmentos de la población urbana ya que, de manera similar a otras opciones de movilidad compartida, los usuarios de motonetas compartidas obtienen los beneficios de un vehículo privado sin los costos y las cargas de su propiedad (Shaheen et al., 2016 ; Shaheen et al., 2017b). Por lo general, las personas acceden a scooters de ciclomotores al unirse a una empresa que administra y mantiene una flota de ciclomotores en varios lugares. Los usuarios pagan una tarifa cada vez que usan un scooter, mientras que los operadores de estos proporcionan combustible, estacionamiento y mantenimiento (Shaheen et al., 2015). Los sistemas de uso compartido de scooters con ciclomotor generalmente están restringidos a áreas urbanas, debido a la menor velocidad de los scooters y su segmento de mercado más pequeño en comparación con otros modos compartidos, p. auto compartido. Sin embargo, en los últimos años, el mercado potencial está floreciendo a escala global (Keogh, 2017).

Este innovador servicio de movilidad también puede aumentar la accesibilidad y flexibilidad proporcionadas por los servicios de transporte público de ruta fija y horario fijo. En comparación con el uso compartido de bicicletas, un sistema en funcionamiento durante años en muchas ciudades, compartir ciclomotores es una opción más rápida, que permite a los usuarios cubrir distancias más largas y también con un mayor atractivo en ciudades no planas (Kafyeke, 2017).

En España, todos los operadores de uso compartido de scooters se basan en servicios de libre flotación, en los cuales los usuarios pueden elegir libremente sitios de entrega de scooters dentro de un área de servicio definida. Además, el cien por ciento de los ciclomotores operados en España son eléctricos, lo cual es particularmente relevante ya que en este país los vehículos eléctricos no tienen restricciones de estacionamiento en los centros de las ciudades y generalmente se benefician del estacionamiento gratuito en la calle. Luego, el uso compartido de scooters con ciclomotor proporciona una alternativa accesible y flexible para conducir por los distritos internos de las áreas urbanas. Dado su mayor atractivo en el centro de la ciudad, típicamente con calles estrechas y problemas de congestión recurrentes, esta es en realidad su principal área de operación en las ciudades españolas. Sin embargo, en ciudades medianas, el uso compartido de scooters también tiene una presencia notable en los distritos menos centrales.

Todos los operadores ofrecen precios similares y tienen un esquema basado en el tiempo de uso con una tarifa actual que generalmente se encuentra entre 0.24 € a 0.26 € por minuto. La estructura de precios podría verse como una barrera si el vehículo se alquila por un tiempo prolongado, pero los operadores con frecuencia ofrecen paquetes de promoción que se pueden adquirir por adelantado para obtener un mejor trato, como una forma de fomentar su uso. Como no hay una tarifa de suscripción mensual fija ni una tarifa de suscripción significativa en España, las personas tienden a ser miembros de varios operadores al mismo tiempo. Esto puede hacerlo económicamente favorable para las personas que usan estos sistemas regularmente, ya que algunas aplicaciones móviles ofrecen información integrada sobre el suministro de uso compartido de scooters con ciclomotores (que comprende varios operadores) en ciertas ciudades: la situación de los ciclomotores en tiempo real, el costo estimado de un determinado itinerario , etc. Sin embargo, los procedimientos de reserva y pago aún no están integrados entre los operadores.

Actualmente, hasta 9 empresas diferentes ofrecen servicios de uso compartido de scooters flotantes en España. Debemos recordar que el uso compartido de scooters coexiste con otras alternativas de movilidad compartida en muchas ciudades españolas. El uso compartido de bicicletas y el uso compartido de automóviles basados en estaciones están disponibles en muchas ciudades españolas, mientras que los servicios de alquiler compartido de automóviles son operados en Madrid por cuatro compañías privadas diferentes. Además, hay algunos operadores, como es el caso de Scoot y Movo, que no solo ofrecen scooters, sino que también suministran bicicletas o patinetes como parte de su concepto general de servicio de movilidad. Se espera que esta tendencia de integración de los servicios continúe en los próximos años.

Este reciente crecimiento de los servicios de movilidad compartida como una forma nueva y más sostenible de transporte está contribuyendo a cambiar las tendencias de movilidad de la propiedad al uso del servicio (Ferrero et al.2018).

Además, dado que estos sistemas generalmente emplean ciclomotores totalmente eléctricos, representa una alternativa de transporte ecológica para las zonas urbanas. El uso compartido de scooters de ciclomotores es un nuevo actor para la vida cotidiana de las ciudades que debe ajustarse a las estrategias actuales para la movilidad sostenible. Sin embargo, los instrumentos de planificación aún no incorporan estas formas de movilidad en la mayoría de las ciudades. El uso compartido del scooter presenta muchas incertidumbres, como los niveles de adopción, la rentabilidad, los impactos en la ciudad, etc. Por estas razones, comprender la adopción y el uso del uso compartido del scooter es crucial para que los planificadores, administradores y proveedores de transporte lo inserten correctamente en el sistema de transporte urbano, y lograr una movilidad urbana más sostenible.

3. METODOLOGÍA

3.1 Encuesta *online* sobre el uso de motos compartidas en España

Se realizó una encuesta en línea con el objetivo de capturar los principales factores que determinan la adopción y la frecuencia del uso de motos compartidas para viajes urbanos. Antes de diseñar el cuestionario, se realizaron algunas entrevistas con personas que viven en diferentes áreas urbanas españolas, incluidos usuarios y no usuarios de uso compartido de scooters, así como usuarios y no usuarios de scooters privados. Permitió capturar los principales controladores que influyen en el uso de esta alternativa de movilidad. En la encuesta, se preguntó a las personas sobre cuatro aspectos principales:

- Información socioeconómica y demográfica general: género, edad, ocupación, nivel de educación, ingresos mensuales, estructura del hogar y código postal.
- Movilidad y variables relacionadas con el viaje: propiedad del vehículo, posesión de un permiso de conducir o pase de transporte público, frecuencia de viaje para diferentes medios de transporte, patrones de movilidad en días laborables / fines de semana.
- Actitudes y preferencias personales: evaluación de los factores de elección del medio de transporte en viajes urbanos (precio, disponibilidad de estacionamiento, preocupaciones ambientales, transporte de equipaje, etc.), preocupaciones individuales hacia las nuevas tecnologías (disposición a descargar aplicaciones de noticias, compartir datos personales y compartir información de la cuenta bancaria) y percepciones sobre el papel de la propiedad del vehículo en el futuro.
- Percepciones y uso de servicios de uso compartido de scooter: frecuencia de uso, tiempo de viaje, propósito del viaje, factores de decisión, aspectos a mejorar en los sistemas actuales de uso compartido de scooter e intención de utilizar un ciclomotor o motocicleta compartidos.

Inicialmente se consideraron diferentes métodos para recopilar la información necesaria para el análisis. Las encuestas en línea fueron el enfoque finalmente seleccionado para difundir la investigación, debido a varias razones.

Primero, este método de encuesta permite contactar fácilmente a los usuarios de diferentes medios de transporte, lo cual es particularmente difícil en el caso del uso compartido de scooters dado que los sistemas operativos en España son flotantes. En segundo lugar, a diferencia de los cuestionarios cara a cara, las encuestas en línea permiten recopilar información de personas que viven en diferentes ciudades españolas sin dificultad. En tercer lugar, las encuestas en línea son un enfoque ya seleccionado en otra investigación previa que explora el uso de otras opciones de movilidad compartida (ver, por ejemplo, Casprini et al., 2014 o Shaheen et al., 2017 para compartir el viaje). Luego, las encuestas en línea fueron el método finalmente seleccionado a pesar de su limitación para obtener una mayor representatividad de la población urbana, particularmente aquellos segmentos más antiguos de la población que están menos familiarizados con los servicios basados en aplicaciones.

El cuestionario en línea se distribuyó entre abril y junio de 2018, combinando diferentes alternativas: diseminación a través de aplicaciones de mensajería, diseminación a través de sitios web de redes sociales enfocadas en el uso de diferentes modos de transporte, distribución en línea de desolladores incluyendo el enlace para acceder a la encuesta y explicando el propósito de la investigación, etc. Recibimos un total de 430 respuestas válidas.

3.2 Modelo logit ordenado generalizado

Esta investigación desarrolla un análisis de tipo *logit ordenado generalizado* (gologit) para explorar los factores de decisión que determinan la adopción y la frecuencia del uso de los servicios de uso compartido de scooters para la movilidad urbana diaria en las ciudades españolas.

En particular, los encuestados informaron en la encuesta en línea la frecuencia de uso del uso compartido de scooter, que representa la variable dependiente a modelar. Vale la pena señalar que solo los encuestados que expresaron su conocimiento de la existencia de servicios para compartir scooter de ciclomotor están incluidos en el modelo (n = 355). Dada la naturaleza ordenada y discreta de la variable dependiente, se ha adoptado un marco logit ordenado en lugar de otras alternativas disponibles, como logit multinomial. En el ámbito del transporte, diversa literatura académica ha empleado estos modelos (ver por ejemplo Irawan et al., 2018; Kaplan y Prato, 2012).

La adopción de los sistemas de uso compartido de scooters de ciclomotores se ha tratado como una variable discreta:

- 1 = sistemas de uso compartido de scooters nunca utilizados
- 2 = sistemas de uso compartido de scooters usados ocasionalmente, es decir, menos de una vez por semana
- 3 = sistemas de uso compartido de scooters utilizados con frecuencia, es decir, una vez por semana o más).

Como se señala en Wang et al. (2018), uno de los principales supuestos de los modelos logit ordenados es el de probabilidades proporcionales, es decir, se supone que la relación entre cualquier par de categorías de resultados es similar para todas las categorías de variables. Esta suposición puede violarse en ocasiones, llegando a resultados sesgados. Para evitar este fenómeno, se adopta un modelo *logit ordenado generalizado (gologit)*, que permite relajar el supuesto de probabilidades proporcionales para todas las variables. De este modo, si permitimos que la suposición se viole solo para un conjunto de variables explicativas, la probabilidad de usar sistemas de motosharing adopta la siguiente forma:

$$P(y_n > k) = (exp(\beta_1\, X_{1n} + \beta_{2n}\, X_{2m} - \tau_m))/(1 + exp(\beta_1\, X_{1n} + \beta_{2n}\, X_{2m} - \tau_m)) \qquad (1)$$

donde:

- $j = 1{,}2$
- β_1 es un vector de parámetros que no viola el supuesto de probabilidades proporcionales y está asociado a un subconjunto X1n de variables explicativas observadas
- β_{2n} es un vector de parámetros que varían de acuerdo con el punto de corte del modelo logit ordenado y está asociado a un subconjunto X2m de variables explicativas observadas
- $\tau_{1,2}$ representan los umbrales definidos entre las categorías.

Entonces, el modelo puede expresarse como:

$$y = \{[j_1 \quad if\ U_n \le\ \tau_1], [j_2 \quad if\ \tau_1\ \le U_n \le \tau_2], [j_3 \quad if\ \tau_2 \le U_n]\} \qquad (2)$$

y la probabilidad para cada elección se puede calcular de la siguiente manera:

$$P(y = j_k) =\ F(\tau_k - U_n) - F(\ \tau_{k-1} - U_n) \qquad (3)$$

Una descripción más detallada de los modelos logit y gologit ordenados está más allá del alcance de este documento, y se puede encontrar en Greene y Hensher (2010) y Washington et al. (2010).

4. DISCUSIÓN DE LOS RESULTADOS

Esta sección presenta los resultados del estudio exploratorio sobre las percepciones sobre la frecuencia de uso del uso compartido de scooters en ciudades españolas, a partir del conjunto de datos recopilados en la encuesta en línea. Por un lado, mostramos los resultados de modelado con respecto a la adopción de los usuarios y la frecuencia de uso de los servicios para compartir scooter. Por otro lado, se exploran los efectos en la división modal urbana y el papel en la reducción de la propiedad del vehículo.

4.1. Adopción individual de sistemas de uso compartido de scooters

A continuación, se comentan los resultados para el análisis de modelado que explora la adopción individual de los sistemas de uso compartido de scooter de ciclomotor. La mayoría de las variables explicativas utilizadas en el modelo son categóricas, por lo que es necesario elegir un caso base como referencia para interpretar adecuadamente los resultados del modelado (consulte la Tablas 1 y 2). En el caso de la variable dependiente, las personas que nunca han utilizado los servicios de uso compartido de scooter se consideran el caso base.

Además, los resultados de modelado se muestran una vez que se eliminan aquellas variables explicativas que no son estadísticamente significativas. Con ese fin, se han utilizado diferentes pruebas de razón de probabilidad (LR) para verificar que no se produzca ningún cambio en el ajuste general del modelo al eliminar estos parámetros. También se debe tener en cuenta que las Tablas 1 y 2 incluyen algunos resultados vacíos para el análisis de usuarios frecuentes (columna de la derecha) cuando no se viola el supuesto de probabilidades proporcionales. Por lo tanto, en esos casos se supone que los coeficientes de modelado para usuarios ocasionales y frecuentes son iguales.

Variables		**Occasional users**			**Frequent users**		
		Coeff.	**Std. Error**	**p-value**	**Coeff.**	**Std. Error**	**p-value**
Socioeconomic characteristics	*Age (base case: under 26)*						
	From 26 to 34	0,318	0,559	0,569	2,74	0,88	0.002
	From 35 to 49	-0,036	0,811	0,965	-		
	Above 49	-2,433	1,244	0,051	2,558	1,74	0.142
	Occupancy (base case: student)						
	Employee	-2,114	0,876	0,016	-		
	Part-time employee and student	-1,314	0,735	0,074	-5,401	1,235	0
	Other	-0,453	1,339	0,735	-		
	Education (base case: non-university)						
	University	0,976	0,688	0,156	3,701	1,26	0.003
	Monthly income (base case: below 1,000 Euro)						
	From 1,000 to 2,000 Euro	0,058	0,752	0,939	-3,564	1,367	0.009
	Above 2,000 Euro	0,959	0,982	0,329	-3,899	1,371	0.004
	Dependent on family income	-1,274	0,721	0,077	-6,42	1,375	0
	Household structure (base case: alone)						
	Sharing household	2,504	1,082	0,021	-		
	Family without children	1,766	11	0,109	-		
	Family with children below 25	1,514	1,127	0,179	-		
	Family with children above 26	-13,196	834,392	0,987	-		
	Car ownership (base case: no vehicle)						
	One or more vehicles	2,787	0,691	0	-		

Tabla 1: Adopción por parte de los usuarios de sistemas de uso compartido de scooter de ciclomotor en ciudades españolas: resultados de modelado (características socioeconómicas)

Travel-related attributes	*Driving moto (base case: no)*						
	Yes	1,795	0,517	0,001	-		
	Weekend daily trips (base case: less than 2)						
	From 2 to 3	1,067	0,52	0,04	-3,89	1,013	0
	Above 3	0,651	0,579	0,261	-		
	Ever used carsharing (base case: no)						
	Yes	0,79	0,39	0,043	-		
	Trip frequency in private car (base case: rarely)						
	From once to twice per week	-0,206	0,614	0,737	-3,715	1,038	0
	More than twice per week	-0,87	0,597	0,145	-		
	Never	1,992	0,632	0,002	1,476	0,97	0.128
	Trip frequency in private moto (base case: rarely)						
	From once to twice per week	-1,559	0,928	0,093	4,435	1,329	0.001
	More than twice per week	-0,927	0,707	0,19	-		
	Never	1,979	0,532	0	-0,344	0,78	0.659
	Trip frequency in public transport (base case: rarely)						
	From once to twice per week	-0,211	0,594	0,722	-		
	More than twice per week	-0,985	0,596	0,098	-		
	Never	0,955	1,122	0,394	-		
	Trip frequency on foot (base case: rarely)						
	From once to twice per week	-0,843	0,664	0,204	2,548	1,001	0.011
	More than twice per week	-1,349	0,61	0,027	1,449	0,986	0.142
	Never	-5,328	2,035	0,009	-		
	Trip frequency in taxi (base case: rarely)						
	From once to twice per week	1,006	0,621	0,105	-		
	More than twice per week	0,419	0,739	0,571	-		
	Never	1,054	0,498	0,034	-		
	Trip frequency in bikesharing (base case: rarely)						
	From once to twice per week	0,683	0,909	0,453	-		
	More than twice per week	2,684	1,099	0,015	-0,109	1,024	0.915
	Never	-0,151	0,511	0,767	-		
Attitude	*Share bank account info*	0,638	0,189	0,001	-		
	Environment	0,032	0,177	0,856	1,722	0,345	0,000
	Luggage	-0,22	0,166	0,184	-		
Constant		-5,952	2,095	0,005	-12,462	3,009	0,000
No. obs		335	Log-Likelihood restricted			-283,445	
Log-Likelihood at convergence		-134,161	Mc Fadden's Pseudo R2			0,507	

Tabla 2: Adopción por parte de los usuarios de sistemas de uso compartido de scooter de ciclomotor en ciudades españolas: resultados de modelado.

Con respecto a las características individuales, la adopción de sistemas para compartir scooters está muy relacionada con la edad: las personas de 26 a 35 años muestran una mayor probabilidad de ser usuarios frecuentes de estos sistemas, lo que es consistente con la investigación de Degele et al. (2018) en Alemania.

Esto parece razonable, dado que los adultos jóvenes están más familiarizados con las nuevas tecnologías y generalmente están en buenas condiciones físicas, lo cual es un factor importante al conducir un scooter.

Además, solo aquellos individuos mayores de 50 años mostraron una menor probabilidad de usar esta alternativa de movilidad (coeficiente del modelo -2.43, valor p = 0.05). Vale la pena señalar esto, dado que, al menos en el caso de España, parece que el uso compartido de scooters también es penetrante, a pesar de una menor intensidad, por encima de los adultos de mediana edad.

Los resultados del modelado también señalan que, en comparación con los empleados, los estudiantes presentan significativamente una mayor probabilidad de adoptar sistemas de uso compartido de scooters.

Además, el nivel educativo también influye en la adopción del uso compartido de scooters, ya que tener o cursar un grado universitario aumenta la probabilidad de ser un usuario frecuente de uso compartido de scooters en un 400%, en comparación con tener educación no universitaria. Estos resultados pueden explicarse por la mayor proporción de jóvenes entre los estudiantes, así como por la tendencia más rápida a adoptar avances tecnológicos y servicios innovadores entre personas altamente educadas.

En cuanto a otras variables socioeconómicas, el nivel de ingresos no parece influir en el uso ocasional de los sistemas de uso compartido de scooters. Sin embargo, un mayor nivel de ingresos reduce significativamente la probabilidad de ser un usuario frecuente de esta alternativa de movilidad. Por ejemplo, las personas que ganan más de 2.000 euros son significativamente menos propensas (-480%) a ser usuarios frecuentes de compartir scooters, en comparación con las personas que ganan menos de 1.000 euros. Esto podría explicarse por la tendencia observada en España de un mayor uso del vehículo privado para la movilidad diaria entre las personas ricas. Además, compartir una casa con compañeros de piso / amigos también aumenta la adopción del uso del uso compartido de scooters con ciclomotor, lo que de nuevo estaría muy relacionado con las edades más jóvenes.

Los atributos relacionados con el viaje también mostraron un papel importante al explicar la adopción del uso compartido de scooters. Como era de esperar, las personas que alguna vez condujeron un scooter / motocicleta o utilizaron sistemas de uso compartido de automóviles son significativamente más propensas (500% y 20%, respectivamente) a utilizar el uso compartido de scooter. Por el contrario, la influencia de la frecuencia de los viajes durante los días de semana y fines de semana no está clara en el análisis.

Lo que es más interesante, el modelo también analiza cómo los patrones de movilidad habituales pueden influir en la adopción por parte de las personas del uso compartido del scooter ciclomotor. En particular, las personas que nunca usan un automóvil privado o una moto privada tienen una probabilidad significativamente mayor de haber utilizado el uso compartido de scooters, en comparación con los encuestados que rara vez eligen estas alternativas de movilidad.

Por el contrario, los encuestados que nunca viajan a pie tienen una probabilidad significativamente menor de haber utilizado el uso compartido de scooters eléctricos, lo que puede indicar algún tipo de complementariedad entre estas opciones de movilidad. Además, las personas que viajan a menudo (de una a dos veces por semana) a pie o en moto privada tienen más probabilidades de ser usuarios frecuentes de uso compartido de scooters, en comparación con los encuestados que rara vez utilizan estos medios de transporte.

Finalmente, parece haber algunas sinergias con el uso compartido de bicicletas, ya que las personas que usan con frecuencia sistemas de uso compartido de bicicletas son significativamente más propensas (cociente de probabilidad de 13.6) a haber utilizado alguna vez el uso compartido de scooter de ciclomotor. A partir de los resultados del modelado, no se pueden concluir interacciones entre el uso del uso compartido de scooters y el uso del transporte público.

Con respecto a las actitudes personales de los individuos, solo dos variables resultaron ser estadísticamente significativas al explicar la adopción del uso compartido del scooter ciclomotor. Como se esperaba, es más probable que las personas que deseen compartir información de la cuenta bancaria a través del teléfono celular usen el uso compartido de scooter. Esto parece obvio dado que el pago de servicios para compartir scooter a través del teléfono celular es un requisito para todos los sistemas que operan en España. Además, sentirse preocupado por los problemas ambientales al elegir un modo de transporte aumenta significativamente la probabilidad de ser un usuario frecuente de uso compartido de scooters.

Nuevamente, esto tiene sentido porque todos los scooters que operan en España son totalmente eléctricos, por lo que contribuyen a, p. reducir la contaminación del aire en los centros urbanos. Finalmente, podemos observar que ser sensible a llevar equipaje grande parece reducir la adopción del uso compartido de scooters, pero este efecto no es estadísticamente significativo. Puede considerarse de alguna manera sorprendente que otros factores que potencialmente afectan las opciones de modo, como el precio, la comodidad o la disponibilidad de estacionamiento, no se encontraron estadísticamente significativos al explicar la adopción del uso compartido de scooters.

4.1. Efecto en la movilidad urbana

La Figura 1 muestra la distribución de la división modal urbana durante una semana típica completa para cada grupo de usuarios de uso compartido de scooter. Se pueden observar diferencias notables en algunos casos. Los no usuarios de uso compartido de scooter muestran un uso más intenso del automóvil privado (19.8%) en comparación con los usuarios ocasionales (17.4%) y especialmente los usuarios frecuentes de uso compartido de scooter (13.1%). En este sentido, podríamos inferir que el uso compartido de scooter de ciclomotor parece sustituir en parte el transporte privado.

Luego, promover el uso compartido de scooters con ciclomotor mejoraría la calidad del aire en las zonas urbanas, dado que los vehículos utilizados en estos sistemas de uso compartido son totalmente eléctricos. Además, las condiciones actuales con respecto a la congestión vial y la escasez de espacio en los centros de las ciudades mejorarían si los automóviles privados fueran reemplazados en parte por ciclomotores.

De lo contrario, el uso compartido de scooter también parece capturar la demanda del transporte público y la caminata, ya que los usuarios ocasionales y frecuentes de uso compartido de scooter presentan un menor uso de estos modos en comparación con los no usuarios de uso compartido de scooter. Este hallazgo puede indicar que el uso compartido de scooters de ciclomotores no complementaría sino que sustituirá en parte la movilidad de los peatones y el transporte público, lo que puede conducir a un aumento de la motorización, las tasas de accidentes y la congestión de la carretera, y en consecuencia mover la movilidad urbana hacia la insostenibilidad.

Por lo tanto, el efecto neto del uso compartido de scooters de ciclomotores en la movilidad urbana parece no estar claro en su forma actual de implementación. Sin embargo, los beneficios potenciales del uso compartido de scooters de ciclomotores para la sostenibilidad urbana deberían impulsar a los encargados de formular políticas a promover su uso dentro de un suministro de movilidad integrado junto con los modos de transporte público.

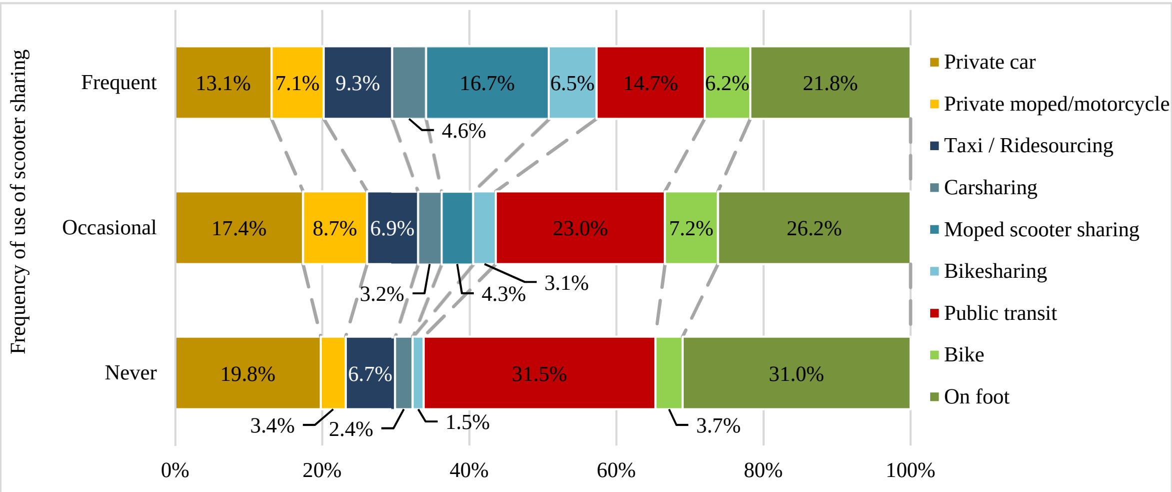

Figura 1: División modal por tipo de usuario que comparte scooter (% de viajes por modo durante una semana típica completa)

Además, podemos ver que los servicios ocasionales de movilidad y uso compartido de vehículos son utilizados con mayor frecuencia por usuarios ocasionales (17,5%) y frecuentes (37,1%) de uso compartido de scooters, en comparación con los no usuarios (10,6%). Esto sugiere que el uso compartido de scooters de ciclomotores es complementario para opciones como el uso compartido de automóviles o bicicletas compartidas, que constituyen alternativas de movilidad más sostenibles en comparación con el automóvil privado.

A este respecto, también puede representar una opción de movilidad atractiva en escenarios de políticas de restricción del uso de vehículos privados en los centros urbanos, como algunas ciudades europeas ya han implementado en los últimos años.

El uso compartido de scooters con ciclomotores es una nueva alternativa de transporte urbano que aumenta la accesibilidad y el suministro de movilidad y, en teoría, podría disminuir la flota existente de vehículos con motor de combustión convencional al impactar en las decisiones de propiedad de vehículos privados. En el cuestionario, se preguntó a los encuestados si consideraban que poseer un vehículo privado seguirá siendo una necesidad en el futuro. Del total de la muestra, el 64,6% de los encuestados declaró que la propiedad del vehículo ya no será una necesidad en el futuro. Sin embargo, los no usuarios de uso compartido de scooters parecen ser más escépticos sobre la renuncia de vehículos privados en el futuro según la Figura 2.

Se observó una mayor proporción de personas no preocupadas por poseer un vehículo en el futuro entre los usuarios de uso compartido de scooters (76.2%), y particularmente entre los usuarios frecuentes (81.6%). Como se discutió, el uso compartido de scooters podría desempeñar un papel en la reducción de la propiedad del vehículo, al proporcionar accesibilidad adicional cuando el transporte público no satisface las necesidades de los pasajeros. Esto puede alentar, al menos a algunos usuarios, a no ser propietarios de un vehículo privado. Este hallazgo puede aplicarse a los usuarios de otros modos de movilidad compartida, p. auto compartido

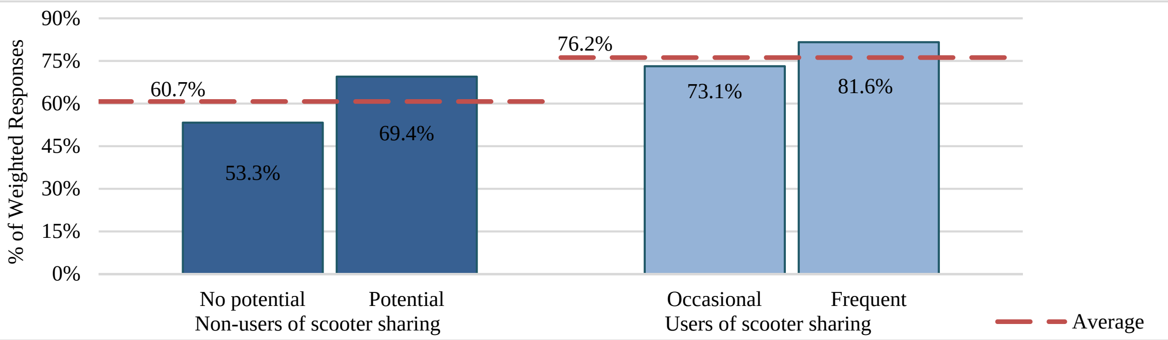

Figura 2: Opiniones sobre si será necesario tener un vehículo privado en el futuro (% de respuestas afirmativas)

Además, una mayor proporción de usuarios potenciales (69.4%) cree que la propiedad del vehículo no será un requisito en el futuro, en comparación con los usuarios no potenciales (53.3%). En lo que respecta a los consumidores potenciales, esta tendencia es relevante porque perciben que estos servicios pueden aumentar las oportunidades de elección de modo y pueden afectar la reducción de las tasas de propiedad de vehículos en las ciudades en los próximos años. En conclusión, el uso compartido de scooters puede capturar la participación modal de los automóviles privados en el futuro y traerá importantes beneficios a la habitabilidad y sostenibilidad urbana, como se ha mencionado.

5. CONCLUSIONES

El estudio exploratorio en esta investigación nos permitió explorar los factores de decisión que determinan la adopción y la frecuencia del uso de servicios de uso compartido de scooters para la movilidad urbana diaria en las ciudades españolas. La primera conclusión es que tanto las características socioeconómicas personales como los atributos relacionados con el viaje evidenciaron un papel importante al explicar la adopción de servicios de uso compartido de scooters entre las personas. Las personas jóvenes y altamente educadas demostraron ser el segmento de la población con una mayor probabilidad de usar esta alternativa de movilidad. Sin embargo, su uso también parece penetrar entre otros rangos de edad, como los adultos de mediana edad. Otras variables, como los niveles más altos de ingresos, parecen desalentar el uso compartido de scooters con ciclomotor, probablemente porque este segmento de la población prefiere usar un vehículo privado para sus viajes diarios en las zonas urbanas. Esto es importante para apuntar a segmentos específicos del mercado de usuarios de esta alternativa de movilidad, dirigir adecuadamente los esfuerzos de políticas para promover estos servicios amigables con el medio ambiente y prever el segmento de población urbana con una mayor probabilidad de adoptar esta alternativa de movilidad en los próximos años.

La segunda conclusión se refiere al estímulo de esta alternativa de movilidad en entornos urbanos. El uso compartido del scooter ciclomotor puede representar un elemento que contribuye a mejorar algunos problemas observados en entornos urbanos, como el aumento de la congestión vial, la contaminación del aire, la falta de espacio público, etc. modos como coche privado o moto, mientras que es complementario para opciones más sostenibles como la movilidad de peatones o bicicletas compartidas. A este respecto, también puede representar una alternativa de movilidad atractiva en escenarios de políticas de restricción del uso de vehículos privados en los centros de las ciudades, como algunas ciudades europeas ya han implementado en los últimos años. Por lo tanto, las administraciones públicas y las autoridades de transporte deben insertar el uso compartido de scooters dentro de sus programas estratégicos para lograr una movilidad urbana más sostenible y fomentar su uso entre otros sectores de la población.

La última conclusión se refiere al impacto del advenimiento del uso compartido de scooters en la movilidad urbana. Tiene impactos positivos en el transporte urbano, p. reduciendo el uso de vehículos y, por lo tanto, mejorando los problemas de congestión vial y la falta de espacio público. Sin embargo, los ciclomotores también captan la demanda del transporte público, por lo que tienen un efecto neto poco claro sobre la sostenibilidad urbana. Este hecho subraya la importancia de integrar los servicios de uso compartido de scooters con el transporte público para promover su uso complementario y llevar la movilidad urbana hacia la sostenibilidad.

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AUTONOMOUS VEHICLE CONTROL IN CARLA CHALLENGE

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ABSTRACT

The introduction of Autonomous Vehicles (AVs) in a realistic urban environment is an ambitious objective. AV validation on real scenarios involving actual objects such as cars or pedestrians in a wide range of traffic cases would escalate the cost and could generate hazardous situations. Consequently, autonomous driving simulators are quickly evolving to cover the gap to achieve a fully autonomous driving architecture validation. Most used 3D simulators in self-driving cars field are V-REP (Rohmer, E., 2013) and Gazebo (KOENIG, N. and HOWARD, A., 2004), due to an easy integration with ROS (QUIGLEY, 2009) platform to increase the interoperability with other systems.

Those simulators provide accurate motion information (more appropriate for easier scenes like robotic arms) but not a realistic appearance and not allowing real-time systems, not being able to recreate complex traffic scenes. CARLA (DOSOVITSKIY, A., 2017) open-source AV simulator is designed to be able to train and validate control and perception algorithms in complex traffic scenarios with hyper-realistic environments.

CARLA simulator allows to easily modify on-board sensors such as cameras or LiDAR, weather conditions and also the traffic scene to perform specific traffic cases. In Summer 2019, CARLA launched its driving challenge to allow everyone to test their own control techniques under the same traffic scenarios, scoring its performance regarding traffic rules. In this paper, the Robesafe researching group approach will be explained, detailing vehicle motion control and object detection adapted from Smart Elderly Car (GÓMEZ-HUÉLAMO, C., 2019) that lead the group to reach the 4th place in Track 3 challenge, where HD Map, Waypoints and environmental sensors data (LiDAR, RGB cameras and GPS) were provided.

1. INTRODUCTION

The development of Autonomous Vehicles (AVs) is continuously evolving. At this moment, none organization has proved a robust testing methodology for L4/L5 AV, levels in which the driver is not involved, at least in most driving situations. As reported by the autonomous driving research community, it is due to, in spite of legal regulations defined in terms of L4/L5 levels, a fully-autonomous driving architecture is still years away, not only due to technical challenges but also due to legal and social ones (Maurer, 2016).

Commonly, most part of the systems that conform an AV are based on Artificial Intelligence (AI), which are trained by extracting patterns of real-world scenarios in order to be used in future actions to produce a specific output. This reasoning force to obtain tons of high-quality data, increasing the development time and cost exponentially when applying a physical approach due to the associated cost of the automated vehicles, the cost of the on-board sensors and the huge driving hours supervised by human beings.

Moreover, the progression of computed-rendered AV simulators enables an alternative way to obtain high-detailed information to validate fully autonomous driving architectures on any traffic situation, being able to recreate specific locations, weather conditions or hazardous traffic conditions without putting in danger any human or material resource.

CARLA is a novel hyper-realistic open-source simulator for autonomous driving research based on Unreal Engine 4 (UE4). The simulator provides an ecosystem of interoperable plugins, realistic physics and image quality, composing scenes by using 3D models of static objects, conforming the environment, and dynamic objects such as pedestrians, cyclists or vehicles, which can be controlled to perform any desired situation (Fig. 1).

Figure 1: CARLA traffic junction.

This simulator provides a wide range of on-board sensors, including cameras (RGB, semantic segmentated and depth) and LiDAR, performing the most common AV perception sensors. These sensors are completely adjustable to project needing, being able to modify their location regarding to the vehicle and also their main features, such as pixels width and height, FOV and distortion for cameras, and number of channels, points-per-second and rotation frequency for LiDAR sensors.

Furthermore, these sensors information and other data relative to the dynamic objects in scene are published using CARLA ROS-bridge, a ROS package that allows communications between the simulator and ROS, enabling interoperability with extern systems such as control and perception modules.

Additionally, traffic scenes can be recreated by using ScenarioRunner, a CARLA developed platform based on OpenScenario (JULLIEN, J., 2009) to define environments of a pre-fixed scenario to allow repeatability, defining the town, static and dynamic objects, weather conditions and also driving behaviors to cope with.

2. CARLA AD CHALLENGE

Until now, realistic AV validation systems where only available for large corporations, preventing smaller research groups from testing their autonomous driving architectures. Taking advantage of CARLA simulator features previously described, CARLA launched the CARLA Autonomous Driving Challenge on February 2019 to democratize autonomous driving development.

CARLA AD Challenge is formed by a collection of routes that AD agents, submitted as Docker images, must complete safely, reaching a destination point following a pre-defined route without traffic infractions. The final score of an agent will depend on the percentage of completed route and the infractions committed during the evaluation (Table 1).

Infractions	Discounted points
Invading lane in the opposite direction	2
Invading a sidewalk	2
Running a stop sign	2
Running a red light	3
Hitting the static scenery	6
Hitting another vehicle	6
Hitting a pedestrian	9

Table 1: Discounted points according to AV committed infraction.

During the challenge, the autonomous agents have to cope with traffic situations inspired by the NHTSA typology, including lane merging and changing, negotiation at intersections and roundabouts, following traffic lights and traffic signs as well as dynamic pedestrians, cyclists and other elements. Same routes may be repeated under different weather and obstacle conditions to test the flexibility of the vehicle, being correspondingly weighed on Eq. 1, where performance score is calculated.

Participants could subscribe up to four different tracks, depending on the information needed by their traffic agent, according to Fig. 2. On Track 1, LiDAR point cloud, GPS and cameras are allowed. On Track 2, autonomous vehicle could only use cameras and location to complete the testing. Tracked 3 grants access to HD Map of the environment, route waypoints to achieve destination and all sensors defined in CARLA (LiDAR, cameras and GPS). Track 4 instead only provides a scene layout of the town where the vehicle is driving along with GPS location.

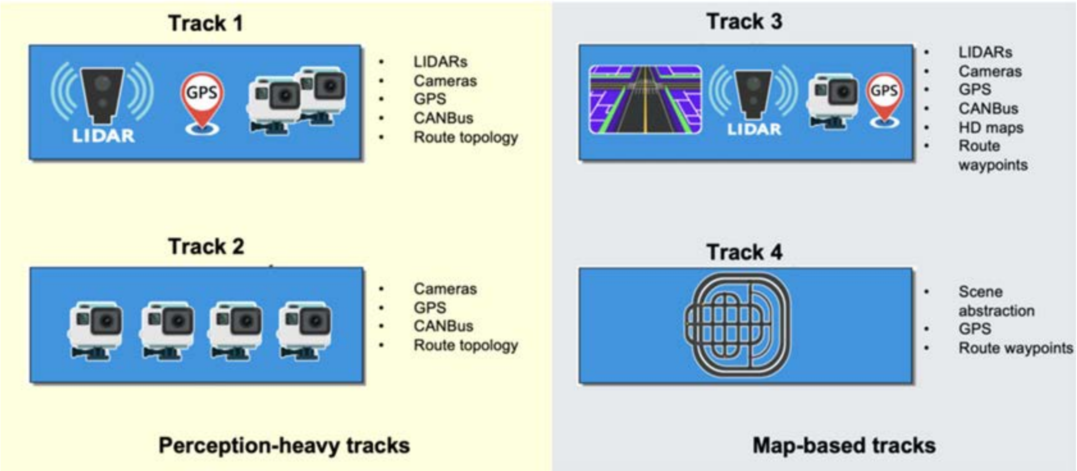

Fig. 2 – CARLA provided sensors information provided on each challenge track.

CARLA AD Challenge started on February 2019, publishing the rules that the candidates would have to follow in order to perform the challenge. The instructions explained how to run CARLA and ScenarioRunner, how to configure it, how to run the evaluation code in order to know the performance of the agent and some tools to analyze and develop car agents.

Later on, online validation stage began, submitting agents code to test their performance on a public server following the challenge rules, allowing for a finest agent tuning than offline stage. Agents must be contained in Docker images in order to be successfully evaluated.

Log files were provided in order to recover information about agent behavior, allowing to reproduce the behavior of the agent during the evaluation tracks in order to know the infractions committed by the vehicle, being able to solve them. Finally, the online testing stage arrived, starting the final evaluation of submitted agents.

In this phase only final score were provided without any log file, not being able to reproduce the behavior undertaken by the autonomous vehicle. The best score achieved by the subsequent agents submitted by the group will be the final score taken into account in CARLA AD Challenge results.

The performance score was calculated following the Equation 1,

$$Score(a) = 1/(R \cdot N) \sum_{i=1}^{R \cdot N} max(100 \cdot C(a, r_i) - I(a, r_i), 0) \quad (1)$$

where a represents the agent under evaluation, C is the amount of route completed for the i-th route, I is the total points discounted due to infractions according to Table 1, R represents the number of repetitions of a route, and N the total number of routes.

3. SUBMITTING CARLA AD CHALLENGE

As described before, CARLA AD Challenge is based on CARLA simulator, which is open-source and constantly evolving. For this reason, submitting to the challenge was a proposal which required much effort and dedication for all our research group.

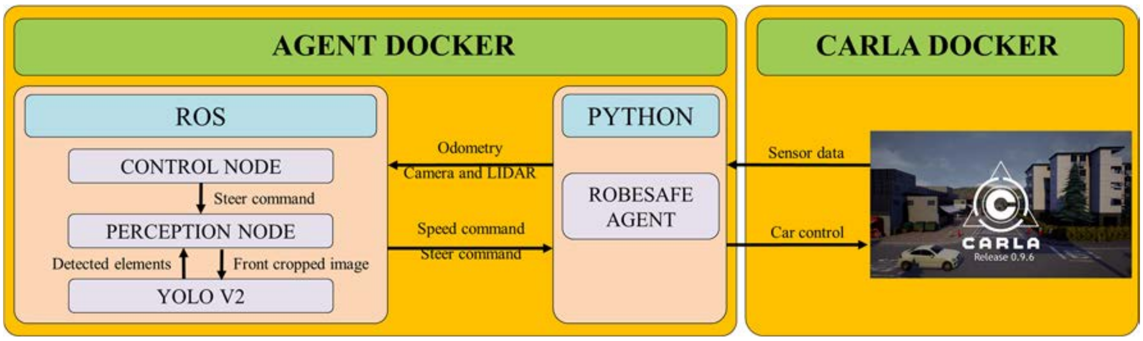

Figure 3: Autonomous agent approach on CARLA AD Challenge.

Since 2016 Robesafe has been developing the Smart Elderly Car, an open-source project to build an autonomous electric vehicle for elderly people to help them with the reduction of their abilities. The Smart Elderly Car was validated both on a real vehicle and V-REP simulator, reproducing use cases and testing its behavior.

When CARLA AD simulator was created, a huge leap in quality was made, freely releasing hyper-realistic simulated environments for autonomous vehicles training and validation. The switching between V-REP and CARLA was necessary to evolve in simulation realism, but it implied the adjustment of all developed systems to this new platform.

The Smart Elderly Car project was based on perception sensors to perceive the surrounding objects, avoiding dynamic obstacles, and GPS and odometry in order to navigate through a specified route.

The map was described using Lanelet 1, defining the context of the External Campus from Universidad de Alcalá.

As CARLA includes a wide range of on-board high-quality perception sensors, the perception module stayed invariable. RGB front camera, along with a YOLOv2 CNN, was used to detect traffic light and its state, vertical and horizontal traffic signs in order to respect traffic rules as well as crossing pedestrians to prevent personal injuries. A specific training was fulfilled in order to detect traffic light state directly as an output from the CNN, saving post-processing time. Also, a top LiDAR sensor was used to detect vehicles inside of the path in order to avoid car crashes.

CARLA simulator planification is based on waypoints, which are a series of points describing the path that the vehicle must follow instead of Lanelet approach, which defines lane edges. In furtherance of overcome this inconvenient, a new controller was implemented, following the waypoints provided by CARLA AD Challenge in Track 3 to successfully complete the route.

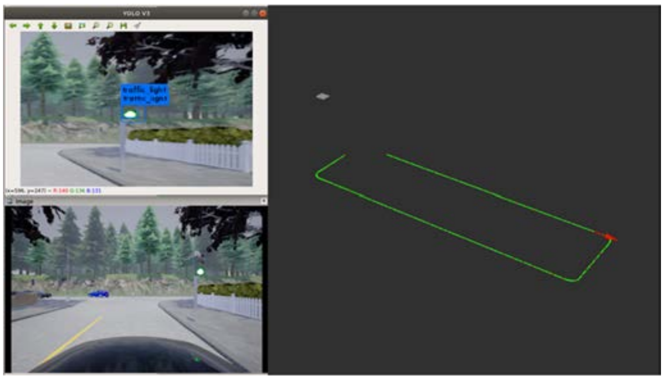

Figure 4: Autonomous agent YOLO image processing and waypoints trajectory.

The main described features can be observed in Fig. 4, showing YOLO image detection a traffic light on the upper left, front image from car dashboard on the lower left and waypoints trajectory (green line) along with car position and orientation (red arrow) on the right side.

4. RESULTS ON CARLA AD CHALLENGE

Moreover than 200 participants organized in 69 teams submitted to CARLA AD Challenge in some of its four available tracks, but only 10 of them could success. More than 5.700 hours of simulation were executed, travelling more than 6.500 km, which evidences the importance of simulation for autonomous vehicles validation.

In Track 3, Robesafe researching group achieved the 4th place over 200 participants worldwide. Furthermore, Robesafe proposal obtained the lowest penalty points among the 5 leaders of the final result, highlighting the correct behavior of the vehicle when moving in a complex urban environment.

The vehicle completed the 60% of the total route under different weather and obstacle conditions while respecting traffic rules and avoiding car crashes and pedestrian collisions.

Ranking	Route points	Infraction points	Total average
1^{st} Team	79.97	13.7	66.83
2^{nd} Team	77.48	11.87	66.05
3^{rd} Team	81.05	20.9	60.47
4^{th} Robesafe	**60.48**	**9.9**	**52.63**
5^{th} Team	48.93	13.67	35.87

Table 2: Results in CARLA AD Challenge Track 3.

4. CONCLUSIONS AND FUTURE WORKS

This paper presented the Robesafe research group approach for an autonomous vehicle navigation in CARLA AD Challenge, describing the migrating process between Smart Elderly Car project, based on V-REP and a real electric vehicle, and CARLA driving simulator. As shown, CARLA AD Challenge stablishes a benchmark to validate fully autonomous vehicles in complex urban environments by recreating hyper-realistic scenes, democratizing the accessibility to cutting edge validation technologies reducing time and cost. Robesafe proposal, based on environment perception through RGB front camera and LiDAR sensor in order to follow traffic rules and respect other dynamic objects, and pursue the provided waypoints to achieve a destination resulted the 4^{th} best of 200 submitted, obtaining the lowest penalty score of the top five.

As future works, 360 degrees object detection will be accomplished in order to acquire a higher safety degree, avoiding obstacles coming from all directions. Also, a tuned controller will be implemented to achieve better waypoint following to complete more route percentage without colliding with other obstacles, performing a safest behavior.

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¿CUÁLES SON LOS FACTORES QUE EXPLICAN LA ADOPCIÓN Y FRECUENCIA DE USO DE LOS SERVICIOS DE RIDE-HAILING? APLICACIÓN AL CASO DE MADRID

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RESUMEN

Los nuevos servicios de movilidad basados en aplicaciones están revolucionando el transporte urbano. En particular, el servicio de ride-hailing ha experimentado un auge mundial en la última década, ya que ofrece un servicio cómodo y a la carta para los desplazamientos urbanos. Paralelamente, se ha llevado a cabo un número creciente de estudios que analizan principalmente el comportamiento de los individuos hacia esta opción de transporte, los patrones de movilidad, así como los efectos del ride-hailing en la sostenibilidad urbana. Sin embargo, la mayoría de estas contribuciones se centran en ciudades estadounidenses, mientras que casi no se han dedicado esfuerzos a otras áreas geográficas, como Europa. Las ciudades de este continente presentan algunas características particulares que las convierten en un caso digno de ser investigado, como una mayor presencia de los modos de transporte público o una mayor preocupación ciudadana por las cuestiones medioambientales.

El objetivo de este trabajo es explorar el comportamiento de viaje hacia los servicios de ride-hailing en una ciudad europea. A partir de la información recogida en una campaña de encuestas en la ciudad de Madrid (España), estimamos un enfoque de Modelo de Datos Heterogéneo Generalizado para identificar los factores clave que motivan la adopción de ride-hailing y la frecuencia de uso.

El trabajo identifica una mayor adopción de los servicios de ride-hailing entre los jóvenes, con un buen nivel de estudios y ricos, que están familiarizados con las nuevas tecnologías.

Y lo que es más interesante, la investigación sugiere que la conciencia medioambiental desempeña un papel notable en la frecuencia de uso de los servicios de ride-hailing, en comparación con las ciudades estadounidenses. En particular, los individuos con menor conciencia medioambiental están más orientados al uso del coche, lo que también está relacionado con un uso más intenso del ride-hailing. Por el contrario, los individuos con una mayor conciencia medioambiental tienden a reducir el uso del transporte compartido, lo que refleja su propensión al transporte público en un entorno de tránsito intensivo.

1. INTRODUCCIÓN

El transporte urbano en todo el mundo ha experimentado cambios drásticos en los últimos años, paralelamente al desarrollo progresivo de las nuevas tecnologías. En particular, los nuevos servicios de movilidad basados en aplicaciones, como el carsharing, el scootersharing y el ride-hailing, están siendo cada vez más adoptados debido, entre otras razones, a un cambio parcial en la mentalidad del consumidor, que pasa de la propiedad a la accesibilidad (Dervojeda et al., 2013). Dentro de estos servicios de movilidad, el ride-hailing -también denominado ridesourcing en la literatura científica- ha experimentado un gran auge en los últimos tiempos, como demuestra el éxito empresarial de empresas de redes de transporte (TNC) como Lyft en Estados Unidos, Didi en China, Cabify en Latinoamérica y España, y Uber en todo el mundo. Según Statistica (2020), en septiembre de 2019, Uber alcanzó los 1.770 millones de viajes en todo el mundo, el doble de los reportados en julio de 2017 (889 millones de viajes). El atractivo de estos servicios de ride-hailing puede explicarse en parte por el hecho de que ofrecen una alternativa de transporte puerta a puerta barata, cómoda y bajo demanda en entornos urbanos (Dias et al., 2017). El servicio se ha convertido en un elemento integral del sistema de transporte urbano en muchas ciudades. Por ejemplo, en San Francisco (EE. UU.) se producen más de 170.000 viajes de ride-hailing en un día laborable típico, lo que representa alrededor del 15% de todos los viajes intravehiculares de la ciudad (SFCTA, 2017).

Como señalan Henao et al. (2017), más allá del comportamiento de los viajes, la evolución de los servicios de transporte como el ride-hailing puede tener un impacto significativo en los sistemas de transporte, la sociedad y el medio ambiente. Por ello, entender el papel que juega este nuevo actor en la movilidad urbana, así como sus efectos sobre los modos competidores y la sostenibilidad urbana, es crucial desde el punto de vista de la planificación del transporte. En este sentido, algunos autores como Calderón y Miller (2019) han indicado que las tendencias actuales sobre la creciente relevancia del ride-hailing proporcionan una justificación sustancial para considerarlo como una opción de transporte que debería incluirse en los modelos de previsión de la demanda de viajes regionales, a pesar de su proporción todavía limitada dentro de la cuota modal urbana en muchas ciudades.

Además, aparte de su tendencia creciente a corto plazo, el transporte de ida y vuelta también tiene implicaciones sustanciales para el futuro, ya que se espera que las flotas de vehículos autónomos (AV) funcionen de forma similar a los vehículos de ida y vuelta (Gerte et al., 2018).

En consonancia con la creciente adopción de los servicios de ride-hailing en todo el mundo, la literatura científica dedicada a esta opción de movilidad también ha crecido exponencialmente en los últimos años. Al igual que en el caso de otros servicios de movilidad compartida, las contribuciones anteriores sobre el servicio de transporte compartido se han dedicado principalmente a dos áreas principales: (i) la investigación de los factores asociados a su adopción y frecuencia de uso (véase, por ejemplo, Dias et al., 2017; Alemi et al., 218; Bhat & Lavieri, 2019), y (ii) la exploración de los impactos potenciales del ride-hailing en otras dimensiones relacionadas con los viajes, como la propiedad del vehículo, la elección del modo, la congestión del tráfico y la seguridad vial (véase, por ejemplo, Peck, 2017; Wenzel et al., 2019). Además, gran parte de este conjunto de investigaciones se centra en países muy concretos, sobre todo en Estados Unidos (véase Mohamed et al., 2019; Tirachini y del Río, 2019).

Por el contrario, se ha invertido poco esfuerzo en estudiar el comportamiento de ride-hailing en otras áreas geográficas del mundo que también están experimentando un crecimiento significativo en el uso de ride-hailing, como Europa. En este sentido, las ciudades europeas suelen presentar importantes diferencias relacionadas con la movilidad en comparación con las ciudades estadounidenses, incluyendo una mayor densidad de población y un mayor uso del transporte público. Estas diferencias pueden desempeñar un papel importante en la adopción y evolución de la demanda de ride-hailing y hacen de las ciudades europeas un caso interesante que merece la pena investigar.

Dentro de este contexto más amplio, el objetivo de este trabajo es identificar los factores clave que motivan la adopción y la frecuencia de uso de los servicios de ride-hailing en Madrid (España).

En particular, la investigación analiza la influencia de las características sociodemográficas, las preferencias psicológicas no observadas y los atributos relacionados con la movilidad en el uso de los servicios de ride-hailing, y compara los resultados con contribuciones anteriores centradas en ciudades estadounidenses. Para ello, analizamos la información recogida en una campaña de encuestas realizada en 2019 en la ciudad de Madrid.

Madrid es una de las áreas metropolitanas más pobladas de Europa, con una amplia oferta y demanda de transporte público, y una reciente y creciente penetración de servicios de movilidad basados en apps.

El documento se organiza como sigue. La sección 2 resume el estado actual del conocimiento científico sobre los servicios de ride-hailing, y señala algunas diferencias importantes relacionadas con la movilidad entre las ciudades americanas y europeas que motivaron la investigación. La sección 3 introduce brevemente el contexto de localización del estudio y presenta una visión general del enfoque de modelización. La sección 4 describe la encuesta que realizamos y presenta las estadísticas descriptivas de la muestra. La sección 5 describe la metodología empleada para explorar la adopción y la frecuencia de uso de los servicios de ride-hailing por parte de los individuos. La sección 6 presenta y discute los resultados de la modelización y, por último, la sección 7 resume las principales conclusiones e identifica otras áreas de investigación.

2. ESTADO DEL ARTE

Las contribuciones científicas anteriores sobre el servicio de ride-hailing se han centrado en un conjunto diverso de cuestiones de equidad y efficiencia, como el bienestar social, la congestión, la seguridad, la privacidad, el consumo de energía y los impactos ambientales relacionados (Sun y Ding, 2019). Estos esfuerzos de investigación anteriores han señalado tanto los efectos positivos como los negativos de los servicios de ride-hailing en la movilidad general del transporte. Como se menciona en Yu & Peng (2019), mientras que los partidarios han indicado el papel del ride-hailing en, por ejemplo, el fomento de estilos de vida sin coches (Jin et al., 2018) o la mejora de la seguridad vial (Peck, 2017), otras contribuciones han criticado los efectos negativos sobre la congestión del tráfico (Standing et al., 2019; Wenzel et al., 2019; Schaller, 2018) y la reducción del uso del tránsito (Gehrke et al., 2018).

En esta línea, algunos autores, como Hall et al. (2018), han señalado que las cuestiones políticas clave sobre los effectos del ride-hailing siguen sin respuesta. Para una visión general sobre el ride-hailing, incluyendo la demanda y la fijación de precios, las operaciones de la plataforma, la oferta y los incentivos, la competencia, los impactos y la regulación, se remite al lector a Wang & Yang (2019).

En el contexto de las cuestiones relacionadas con la demanda asociadas al ride-hailing, como señalan Lavieri & Bhat (2019), ha habido dos direcciones principales de investigación: contribuciones de investigación a nivel individual y contribuciones de investigación a nivel de viaje. A **nivel individual**, los trabajos de investigación han llegado a algunas conclusiones consistentes sobre la adopción y el uso de los servicios de ride-hailing. Por ejemplo, hay pruebas consensuadas de que los usuarios de ride-hailing tienden a ser más jóvenes, más educados, tienen mayores ingresos y viven en zonas urbanas (véase, por ejemplo, Chen, 2015 para Pittsburgh; Rayle et al., 2016 para San Francisco; Smith, 2016 para varias ciudades estadounidenses; Alemi et al., 2018 para California; Clewlow & Mishra, 2017 para múltiples ciudades estadounidenses; Chu et al., 2018 para seis grandes ciudades estadounidenses, Wang et al., 2019 para Hangzhou, y Lavieri & Bhat, 2019 para Dallas).

También se ha encontrado que la familiaridad con las nuevas tecnologías es un factor importante y consistente del estilo de vida que influye en la adopción del ride-hailing (véase, por ejemplo, Alemi et al., 2018; Lavieri & Bhat, 2019). La investigación también ha mostrado de manera uniforme que el ocio es el principal propósito de los viajes de ride-hailing (véase Rayle et al., 2016 para San Francisco; Zhong et al., 2018 para Shanghái; y Tirachini & del Río, 2019 para Santiago de Chile) y que esta opción de movilidad se utiliza más intensamente en las zonas más densas (Dias et al., 2017; Conway et al., 2018). Además, existe una conclusión generalizada de que el transporte público se encuentra entre las opciones de movilidad bastante afectadas por el ride-hailing. Esta conclusión se ha obtenido para los casos de San Francisco (Rayle et al., 2016; Shaheen et al., 2016), Denver (Henao, 2017), Santiago (Tirachini & del Río, 2019), Boston (Gehrke et al., 2018), así como Chicago, Los Ángeles, Nueva York, Seattle o Washington D.C. (Clewlow & Mishra, 2017), entre otros. Además, existen pruebas de que esta nueva opción de movilidad provoca un aumento de la congestión (véase, por ejemplo, Gehrke et al., 2018; Clewlow & Mishra, 2017). En cambio, algunos otros resultados presentados en la literatura científica son contradictorios.

Por ejemplo, algunos autores han establecido una relación negativa entre el uso de los servicios de ride-hailing y la propiedad del vehículo (véase, por ejemplo, Clewlow & Mishra, 2017, Gehrke et al., 2018). Sin embargo, otras investigaciones han encontrado una relación no significativa entre estas dos variables (Rayle et al., 2016; Tirachini & del Río, 2019), mientras que algunas contribuciones han llegado a la conclusión de que el ride-hailing está asociado a un aumento de la propiedad de vehículos (Schaller, 2018; Gong et al., 2017). C

abe destacar que los mencionados modelos de ride-hailing a nivel individual no han incorporado explícitamente los patrones generales de movilidad de los individuos como factores explicativos, como hacemos en nuestro presente trabajo.

A nivel de viaje, muchas contribuciones han utilizado datos de viaje obtenidos de operadores de ride-hailing para analizar la distribución espacial y temporal de la demanda, así como su relación con factores socioeconómicos y del entorno urbano. Las conclusiones de estos estudios a nivel de viaje son, de nuevo, en general, consistentes y en línea con la investigación a nivel individual.

Se ha comprobado que el Ride-hailing se utiliza más intensamente en las zonas más densas (Yu & Peng, 2019; Li et al., 2019; Goodspeed et al., 2019) y en los barrios con mayor presencia de personas jóvenes, bien educadas y adineradas (Goodspeed et al., 2019). Además, los análisis de los viajes geolocalizados han concluido en general un aumento de la congestión (Wenzel et al., 2019; Nie, 2017; Erhardt et al., 2019) y una reducción de la demanda de taxis (Nie, 2017) debido a la presencia de nuevos servicios de ride-hailing. Además, Li et al. (2019) descubrieron que el ride-hailing se utiliza con más frecuencia para los viajes que no son de ida y vuelta, mientras que Yu & Peng (2019) observaron una mayor demanda de ride-hailing para los viajes de fin de semana.

Sin embargo, algunos otros resultados no son concluyentes. Por ejemplo, Lavieri et al. (2018) señalaron un posible efecto de sustitución entre el ride-hailing y el uso del transporte público, mientras que el análisis de Hall et al. (2018) en varias zonas urbanas de Estados Unidos sugirió un efecto complementario entre el ride-hailing y el uso del transporte público.

Una observación importante de los numerosos estudios de investigación anteriores identificados anteriormente es que casi todos ellos se basan en una ciudad estadounidense, como también indican Mohamed (2019) y Tirachini & del Río (2019). En particular, hasta donde sabemos, no se ha realizado ningún estudio de este tipo en la literatura científica para analizar el ride-hailing en Europa. Mohamed (2019) exploró si las autoridades de transporte y los operadores en Londres (Reino Unido) entienden plenamente el impacto de los servicios de ride-hailing, mediante la realización de un enfoque de grupo focal. Aparte de eso, la mayoría de las contribuciones en Europa se han centrado en cuestiones de competencia y regulación relativas al funcionamiento del ride-hailing (véase, por ejemplo, Thelen, 2018; De Massi, 2018; Deighton-Smith, 2018; Geradin, 2015). Hay una escasez de investigaciones sobre el comportamiento de viaje en las ciudades europeas en el contexto del ride-hailing.

Al mismo tiempo, existen claras diferencias entre las ciudades europeas y las estadounidenses que pueden conducir a diferentes comportamientos de ride-hailing. En primer lugar, las ciudades europeas están más densamente pobladas. Según Kumar (2016), las ciudades europeas tienen una densidad media de 3.000 hab./km2, casi el doble que las norteamericanas. Este autor señala que las bajas densidades de las ciudades norteamericanas reflejan la mayor prevalencia de la vida suburbana y el predominio de los viajes en coche.

Estas variaciones en la densidad urbana pueden dar lugar a tendencias de ride-hailing bastante distintas, dado que investigaciones anteriores (véase, por ejemplo, Yu & Peng, 2019 y Goodspeed et al., 2019) han descubierto que la demanda de ride-hailing es mayor en las zonas más densamente pobladas de una ciudad. En segundo lugar, las ciudades europeas están mejor servidas por el transporte público, que funciona como columna vertebral para ayudar a apoyar otras formas de movilidad. Por lo tanto, en Europa predomina la cultura del transporte compartido, mientras que en muchas ciudades de EE.UU. se opta por el coche privado.Esto puede dar lugar a un panorama bastante diferente de competencia entre los modos de transporte en las ciudades europeas en comparación con las ciudades estadounidenses. En tercer lugar, la población de las ciudades europeas suele mostrar una mayor preocupación por las cuestiones medioambientales, como se ha señalado recientemente en una encuesta sobre el cambio climático realizada por el Banco Europeo de Inversiones (BEI, 2018). Como resultado de esta mayor preocupación medioambiental, muchos gobiernos locales de Europa han implementado numerosas medidas para reducir los atascos y las emisiones de gases de efecto invernadero de los automóviles privados, como el cobro por congestión (por ejemplo, Londres, Milán), las zonas de bajas emisiones (por ejemplo, Múnich, París) y las restricciones de aparcamiento en los centros de las ciudades.

El mayor nivel de preocupación por el medio ambiente que muestran las ciudades europeas puede dar lugar a diferentes estructuras de competencia entre los modos de transporte, especialmente entre las opciones de transporte público y los servicios de ride-hailing. Las tres diferencias entre las ciudades estadounidenses y europeas que acabamos de identificar, junto con el enfoque casi exclusivo de los estudios anteriores en un contexto estadounidense, apuntan a la necesidad de explorar la adopción y el uso de los servicios de ride-hailing en el contexto de una ciudad europea.

3. CASO DE ESTUDIO Y APROXIMACIÓN METODOLÓGICA

Madrid es la capital de España y su ciudad más poblada, con un total de 3,3 millones de habitantes (Ayuntamiento de Madrid, 2020) y una densidad media de 8.832 hab./km2. La concentración de población es especialmente intensa en los barrios interiores (24.326 hab./km2). El cuadro 1 presenta algunas estadísticas que comparan las ciudades estadounidenses con Madrid. En términos de densidad, Madrid sólo es superada por la ciudad de Nueva York en EE.UU., y está muy por encima de otras ciudades americanas investigadas anteriormente. Las dos filas siguientes de la Tabla 1 ofrecen indicaciones sobre el uso del sistema de transporte público y la infraestructura en Madrid y en las grandes ciudades de EE.UU. La cuota modal intraurbana del transporte público y de los modos activos en Madrid es sustancialmente mayor que en las ciudades estadounidenses, al igual que el número de estaciones ferroviarias en cada kilómetro cuadrado de superficie. La última fila de la Tabla 1 muestra la clara diferencia en la preocupación por el cambio climático entre los habitantes de España y los de EE.UU. (sólo se dispone de estadísticas a nivel nacional para esta dimensión).

INDICATORS		**Madrid**	**New York City**	**San Francisco**	**Boston**	**Chicago**	**Washington DC**
Population density (inhab./km^2)		8,832	11,056	7,388	5,549	4,550	4,506
Transit Use and Availability	**Modal share (intra-city trips): public transport + active modes (%)**	74.6	64.1	53.0	61.0	36.5	54.3
	Rail accessibility (stations/km^2)	0.81	0.58	0.64	0.41	0.25	0.51
Climate change perception: people concerned + alarmed (%)		87.5 (Spain)	65.6 (United States)				

Tabla 1: Indicadores comparativos de Madrid y varias ciudades estadounidenses

En el contexto de la alta densidad, la amplia oferta de transporte público y la gran preocupación por el medio ambiente, en los últimos años han empezado a funcionar en la ciudad nuevos servicios de movilidad compartida y de micromovilidad. Las operaciones de transporte en coche comenzaron a finales de 2014. Pero numerosos problemas con la legislación española sobre transporte obligaron a Uber, el principal operador de viajes compartidos en ese momento, a dejar de ofrecer viajes en el país.

Tras cumplir con todos los requisitos legales, las operaciones de Uber se reanudaron en 2016. El otro operador presente en Madrid, la empresa española Cabify, comenzó a operar en 2012, pero prestó una oferta insignificante hasta 2016. En la actualidad, más de 8.200 vehículos de ride-hailing operan en Madrid bajo las plataformas de Uber y Cabify (Ministerio de Fomento, 2020). Aunque el gobierno nacional mantiene registros de todos los viajes realizados por ride-hailing en España desde abril de 2019, no hay datos oficiales actualizados sobre estos servicios.

En la presente investigación, nuestra exploración del comportamiento de los individuos hacia la adopción y la frecuencia de uso de los servicios de ride-hailing implica la estimación de dos modelos de elección utilizando datos de encuestas recogidos en la ciudad de Madrid.

El primer modelo se estima a nivel individual basado en el Modelo Generalizado de Datos Heterogéneos (GHDM) desarrollado por Bhat (2015), mientras que el segundo modelo se estima a nivel de viaje. Los marcos de cada uno de estos modelos se analizan sucesivamente en las dos secciones siguientes.

3.1. El marco de modelización a nivel individual

3.1.1. Las variables de resultado endógenas

El primer análisis (nivel individual) modela la adopción del servicio de ride-hailing y la frecuencia de uso, junto con cuatro variables de resultado adicionales. La adopción del ride-hailing se representa como una variable binaria que indica si el individuo ha utilizado alguna vez los servicios de ride-hailing. La frecuencia de uso de los servicios de ride-hailing se representa como una variable ordinal en cinco categorías:

- (1) utilizado, pero no en los últimos seis meses,
- (2) utilizado, pero no en el último mes,
- (3) utilizado para 1-4 viajes en el último mes, y
- (4) utilizado para 5-8 viajes en el último mes, y
- (5) utilizado para más de 8 viajes en el último mes.

En comparación con estudios anteriores que solo tienen en cuenta los viajes realizados en los últimos 30 días (véanse, por ejemplo, Lavieri y Bhat, 2019; Dias et al., 2017), nosotros hemos optado por tener en cuenta un período de tiempo más largo.

Este enfoque nos permite incluir a los usuarios ocasionales y poco frecuentes de estos servicios, lo cual es importante en el caso de Madrid por dos razones principales.

En primer lugar, el ride-hailing es un servicio de movilidad relativamente nuevo en la ciudad, por lo que la familiaridad (y en consecuencia, la frecuencia de uso) observada para ciertos segmentos de la población puede ser bastante baja.

En segundo lugar, el uso intensivo del transporte público y de los modos activos en la ciudad, junto con una amplia variedad de otras nuevas opciones de movilidad (coche compartido, ciclomotores y patinetes compartidos, y bicicletas compartidas), es probable que intrínsecamente resulte en un menor número de usuarios frecuentes de ride-hailing en Madrid en relación con la mayoría de las ciudades estadounidenses.

Aparte de la adopción y la frecuencia de uso del ride-hailing, el modelo a nivel individual también tiene en cuenta cuatro variables adicionales coendógenas: la ubicación residencial, la disponibilidad de vehículos y las tasas de movilidad tanto en días laborables como en fines de semana. Estas variables se han incluido en el análisis para tener en cuenta la posibilidad de que la ubicación residencial, la disponibilidad de vehículos y las tasas de movilidad, junto con el comportamiento de ride-hailing, se determinen como un conjunto de elección, y para tener en cuenta cualquier efecto de autoselección en la influencia de la ubicación residencial y la propiedad de vehículos en el comportamiento de ride-hailing. Además, las tasas de movilidad general se han considerado como variables co-endógenas en el análisis, dado el impacto potencial del comportamiento de movilidad diaria en el uso de los servicios de ride-hailing. En este sentido, investigaciones anteriores han indicado que la mayoría de los viajes de ride-hailing se realizan durante los fines de semana (Yu & Peng, 2019) y por ocio (véase, por ejemplo, Rayle et al., 2016; Tirachini & del Río, 2019).

Por lo tanto, es importante tener en cuenta la influencia no solo del comportamiento de movilidad de los individuos durante la semana, sino también del comportamiento de movilidad durante el fin de semana, a la hora de modelar el ride-hailing.

En el cuestionario de la encuesta (que se comenta en el siguiente apartado), se pedía a los encuestados que indicaran su ubicación residencial entre las múltiples zonas de Madrid, definidas según la centralidad geográfica, la accesibilidad del transporte y la posición con respecto a las principales vías de circunvalación. Al final, teniendo en cuenta el bajo número de respuestas en algunas zonas específicas de la ciudad de Madrid y en zonas de escasa accesibilidad al transporte, la localización residencial se basó principalmente en la ubicación del hogar con respecto a las principales vías de circunvalación y en si el encuestado vivía dentro de los límites de la ciudad de Madrid o vivía más allá de los límites de la ciudad de Madrid en zonas colindantes. La ciudad de Madrid tiene dos circunvalaciones (una interior - M30 y otra exterior - M40), con una mayor densidad de individuos dentro de la primera.

En consecuencia, la localización residencial se basó en una representación nominal trinaria del espacio:

- (1) Vivía dentro de la circunvalación interior de la ciudad de Madrid,
- (2) Vivía fuera de la circunvalación interior de la ciudad de Madrid, y
- (3) Vivía fuera de la ciudad de Madrid.

La disponibilidad de vehículos se buscó en la encuesta preguntando a los encuestados si tenían frecuentemente acceso a un vehículo privado motorizado (coche/otro vehículo motorizado) en casa para uso personal. Dada la escasa presencia de vehículos motorizados distintos del coche en el hogar, creamos una variable binaria de disponibilidad de coche. En el resto de este documento, utilizaremos los términos disponibilidad de vehículos y disponibilidad de coches indistintamente para referirnos a la disponibilidad de coches motorizados. En nuestra muestra, el 69,1% de los individuos tienen un vehículo disponible para su uso personal.

El cuestionario también recogía información sobre los índices de movilidad de los individuos en días laborables y fines de semana. Los encuestados informaron del número de viajes que habían realizado en el último día laborable (de lunes a viernes) y no laborable (sábado y domingo), excluyendo los viajes a pie de menos de 15 minutos. A partir de esta información, se creó una variable ordinal para cada uno de los índices de movilidad en días laborables y fines de semana:

- (1) cero viajes,
- (2) 1-2 viajes, y
- (3) más de 2 viajes.

Se estableció un valor umbral de dos viajes al día, ya que suele indicar un patrón en el que sólo se realiza una actividad fuera del hogar en un día determinado.

Las seis variables endógenas de resultado de interés (adopción de viajes en coche de alquiler, frecuencia, elección de residencia, disponibilidad de vehículos y tasas de movilidad en días laborables y fines de semana) se modelaron conjuntamente en función de variables sociodemográficas exógenas y de un conjunto de constructos psicológicos latentes, los cuales se analizan a continuación.

3.1.2. Constructos psicológicos latentes

Las investigaciones anteriores han indicado claramente que las características relacionadas con la movilidad no sólo están determinadas por la demografía, sino también por las actitudes y las preferencias de estilo de vida. En consecuencia, el modelo incluye cuatro constructos latentes no observados que captan las preferencias psicológicas de los individuos. Estos constructos se identifican basándose en estudios anteriores sobre el transporte y en el campo de la etnografía, que reconocen que estos constructos psicosociales son importantes determinantes de los patrones de uso de la tecnología y los viajes. Los constructos latentes se introducen como determinantes de las seis variables endógenas de resultado de interés a través de variables indicadoras de los constructos recogidos en la encuesta (véase la siguiente sección para una visión general de la modelización).

El primer constructo latente se refiere a la propensión del individuo a tener un estilo de vida de búsqueda de variedad (VSL), es decir, una tendencia a comprar o probar nuevos bienes o servicios, así como una inclinación a adoptar un estilo de vida variado en términos de experiencias.

La inclusión de este constructo latente parece razonable dado que el ride-hailing puede considerarse todavía una opción de movilidad bastante nueva en Madrid, lo que lleva a ciertos individuos a percibirlos como una opción de transporte más atractiva o de moda.

Además, los individuos que siguen un estilo de vida más variado pueden tender a ser más extrovertidos, y por lo tanto pueden presentar mayores necesidades de movilidad. Este constructo latente ha sido ampliamente utilizado en el campo de la psicología para captar las diferencias en las tendencias de los individuos hacia la inercia del modo (Rieser-Schüssler & Axhausen, 2012), y también en el uso del ride-hailing (Alemi et al., 2018; Lavieri & Bhat, 2019).

Los indicadores utilizados para desarrollar el constructo VSL incluyen la apertura a los cambios en general, a las nuevas experiencias, a los nuevos productos y a los riesgos, y están adaptados de Schwartz et al. (2001).

El segundo constructo se refiere a la tecno-savviness del individuo, una variable latente ampliamente utilizada en la literatura previa cuando se explora el uso de nuevos servicios de movilidad urbana (véase, por ejemplo, Velázquez, 2019; Astroza et al., 2017). La inclusión de esta variable es clara dado que los servicios de ride-hailing solo pueden ser llamados a través de una app de smartphone. Por tanto, incluir la familiaridad del encuestado con las nuevas tecnologías y el uso de los smartphones es fundamental. Los indicadores de este constructo recogen la adopción o el uso diario de las nuevas tecnologías, en particular: las aplicaciones móviles para las tareas cotidianas, las redes sociales y la actitud para probar nuevas aplicaciones.

El tercer constructo se refiere a la conciencia ambiental del individuo, una variable latente ampliamente adoptada en la literatura científica sobre el comportamiento de viaje (véase, por ejemplo, Kamargianni et al., 2015; Davison et al., 2014; Astroza et al., 2017), y en particular el ride-hailing (Lavieri & Bhat, 2019). Este constructo es relevante en esta investigación debido a la mayor preocupación medioambiental que parecen mostrar los residentes europeos en comparación con los estadounidenses.

La variable latente tiene como objetivo capturar los comportamientos proambientales que pueden, por ejemplo, llevar a un individuo a reducir el uso del vehículo privado o mostrar una tendencia hacia las opciones respetuosas con el medio ambiente, como el transporte público, y por lo tanto potencialmente impactar en el uso de ride-hailing.

Los indicadores de este constructo recogen las preferencias por bienes y servicios respetuosos con el medio ambiente, la percepción del transporte público y el comportamiento de reciclaje en el hogar.

Por último, el cuarto constructo capta la propensión del individuo a compartir bienes y servicios en un sentido amplio. Algunos indicadores de esta variable latente también hacen referencia a la sensibilidad a la privacidad de los individuos. Se ha demostrado que tanto la propensión a compartir como la sensibilidad a la privacidad influyen en el uso de opciones de movilidad compartida como el carsharing (Velázquez, 2019). Este constructo latente pretende captar la propensión de los individuos a evitar los espacios compartidos con extraños, lo que puede influir en gran medida en que prefieran los vehículos privados en relación con el transporte público (Ripplinger et al., 2012). Además, dado que en el caso de Madrid no se dispone de viajes compartidos, una menor propensión a compartir reflejaría una mayor tendencia a los entornos privados, lo que podría fomentar el uso de los viajes compartidos en lugar del transporte público. En este sentido, mientras que en los Estados Unidos se ha observado que la sensibilidad a la privacidad puede desalentar el uso de los viajes en coche de alquiler, ya que el espacio es al menos compartido con el conductor (en relación con el uso de un vehículo privado).

La estructura de la competencia en Madrid puede ser tal que la sensibilidad a la privacidad en realidad fomenta el uso de los viajes en coche de alquiler, ya que la cantidad de compartir y estar con extraños es muy limitada en un vehículo de viaje de alquiler en comparación con los sistemas de transporte público más ampliamente disponibles en Madrid.

3.1.3. La estructura del modelo

La metodología de modelización adoptada se basa en el Modelo Generalizado de Datos Heterogéneos (GHDM) desarrollado por Bhat (2015), una metodología empleada anteriormente para analizar el comportamiento de los viajes de ride-hailing (véase, por ejemplo, Lavieri & Bhat, 2019; Vinayak et al., 2018; Lavieri et al., 2017). El GHDM representa un enfoque integral que permite analizar múltiples variables de interés y sus relaciones con otras variables relacionadas con el transporte, al tiempo que controla los factores observados y no observados que pueden afectar a las elecciones de los individuos.

Además, dada su flexibilidad, el GHDM permite la estimación conjunta de resultados continuos, nominales, ordinales, múltiples-discretos y de conteo. Para ello, el modelo establece una estructura de dependencia parsimoniosa a través de los constructos latentes estocásticos.

El modelo GHDM tiene dos componentes:

- el modelo de ecuaciones estructurales de variables latentes (SEM), y
- el modelo de ecuaciones de medición de variables latentes (MEM).

Como se ilustra en la figura 1, el componente SEM define cada constructo latente (representado como óvalos en el panel central de la figura) como una función de variables sociodemográficas exógenas (lado izquierdo de la figura) y un término de error no observado (no mostrado en la figura). Cada término de error representa el efecto de los factores individuales no observados sobre un constructo latente específico. Dejemos que estos factores no observados se denoten por η1, η2, η3 y η4 (correspondientes a uno de los cuatro constructos latentes de la figura 1) y los recojamos en un vector η.

Suponemos que η es normal estándar multivariante con un vector de media de 0 y una matriz de correlación de Γ con seis posibles elementos de correlación (debido a consideraciones de identificación, las varianzas de los elementos individuales de η deben normalizarse a 1; véase Bhat, 2015). Los constructos latentes son estocásticos debido a la presencia de los elementos aleatorios y, por definición, no se observan.

Por lo tanto, la relación del modelo SEM entre las variables sociodemográficas y los constructos latentes, así como los elementos de la matriz de correlación de Γ, no se pueden estimar directamente, sino que se estiman a través de las observaciones de los indicadores de los constructos latentes (véanse los indicadores ordinales VLS, de ahorro tecnológico, de conciencia medioambiental y de propensión a compartir que figuran en las variables endógenas del panel derecho de la figura 1; los indicadores reales se analizan en la sección 4.4) y los resultados endógenos de interés (mostrados hacia el lado derecho de la figura 1).

Los constructos latentes estocásticos, junto con las variables sociodemográficas exógenas, sirven como determinantes de las utilidades/propensidades latentes subyacentes de los resultados discretos ordinales/binomiales y nominales observados que caracterizan las variables endógenas de interés y las variables indicadoras. Esto está representado por la relación MEM en la Figura 1.

Es importante destacar que, además de captar los efectos de las preferencias de estilo de vida y de las actitudes sobre el comportamiento de transporte en coche y los patrones de movilidad, los constructos latentes estocásticos también sirven como vehículos para permitir el modelado conjunto parsimonioso de múltiples resultados en el componente MEM.

En concreto, los términos de error de la parte SEM, que definen las variables latentes, penetran en la parte MEM y establecen una estructura de dependencia parsimoniosa entre todas las variables endógenas. Por ejemplo, tal y como se desprende de nuestros resultados empíricos, si el constructo de búsqueda de variedad influye tanto en las tasas de movilidad de los días laborables como en las de los fines de semana, implica inmediatamente una covarianza de errores entre las tasas de movilidad de los días laborables y las de los fines de semana.

Del mismo modo, si el constructo de conciencia medioambiental influye tanto en la disponibilidad de vehículos como en la frecuencia de viajes en coche, genera inmediatamente una estructura de covarianza entre la disponibilidad de vehículos y la frecuencia de viajes en coche. Una descripción detallada del GHDM, así como su proceso de estimación, va más allá del alcance de este documento, pero puede encontrarse en Bhat (2015).

En resumen, las variables endógenas del modelo incluyen los indicadores de los constructos latentes y las seis principales variables de resultado de interés mencionadas anteriormente (enumeradas en el panel derecho de la Figura 1).

El GHDM controla la correlación de errores debido a la modelización conjunta de estas variables, y acomoda los efectos recursivos entre ellas. En esta investigación se han probado múltiples direccionalidades recursivas entre las variables endógenas.

El mejor ajuste de los datos se obtuvo en la especificación causal que considera que la ubicación residencial influye en las tasas de movilidad, ambas influyen en la disponibilidad de vehículos y, finalmente, estas cuatro variables influyen en la adopción y la frecuencia de uso del servicio de ride-hailing.

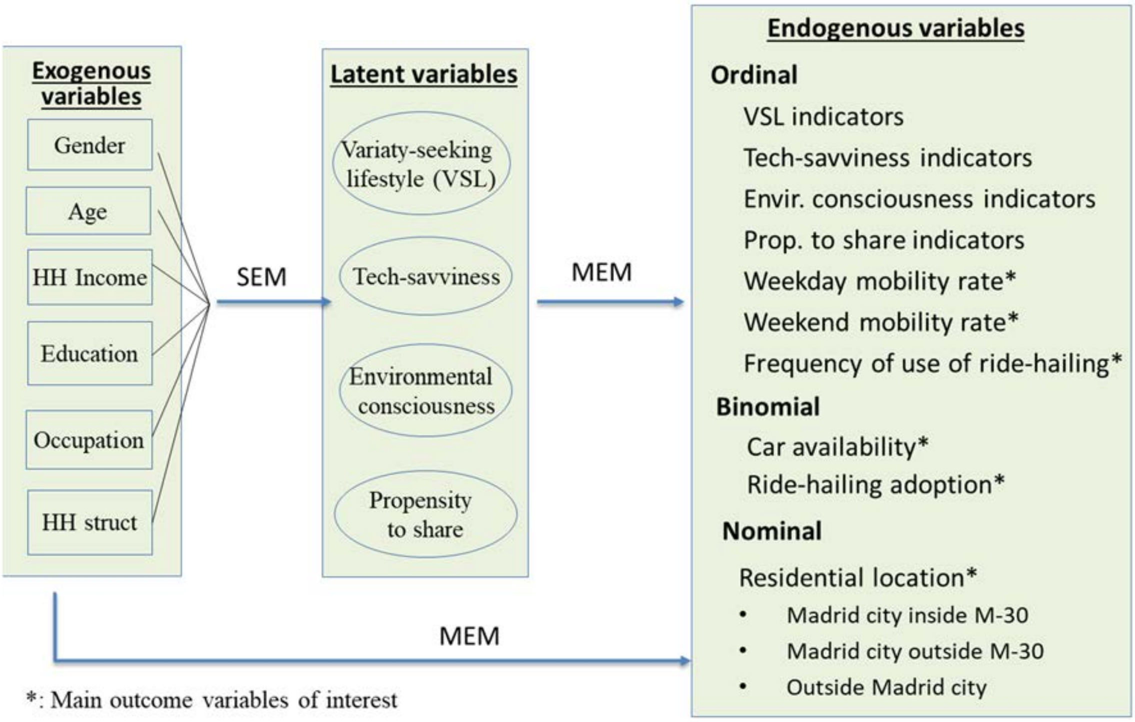

Figure 1: Visión general del modelo a nivel individual adoptado para explorar la adopción y la frecuencia de uso del ride-hailing

3.2. El marco de modelización a nivel de viaje

El segundo análisis (a nivel de viaje) caracteriza la movilidad por ride-hailing en la ciudad de Madrid, explotando la información detallada sobre el último viaje por ride-hailing proporcionada por los encuestados que habían utilizado ride-hailing en los últimos 30 días.

Se adopta un enfoque de análisis de elección para modelar múltiples características del viaje en función de las características sociodemográficas individuales, las variables psicológicas no observadas y las características relacionadas con la movilidad. En la figura 2 se presenta un esquema del modelo a nivel de viaje, que se discute a continuación.

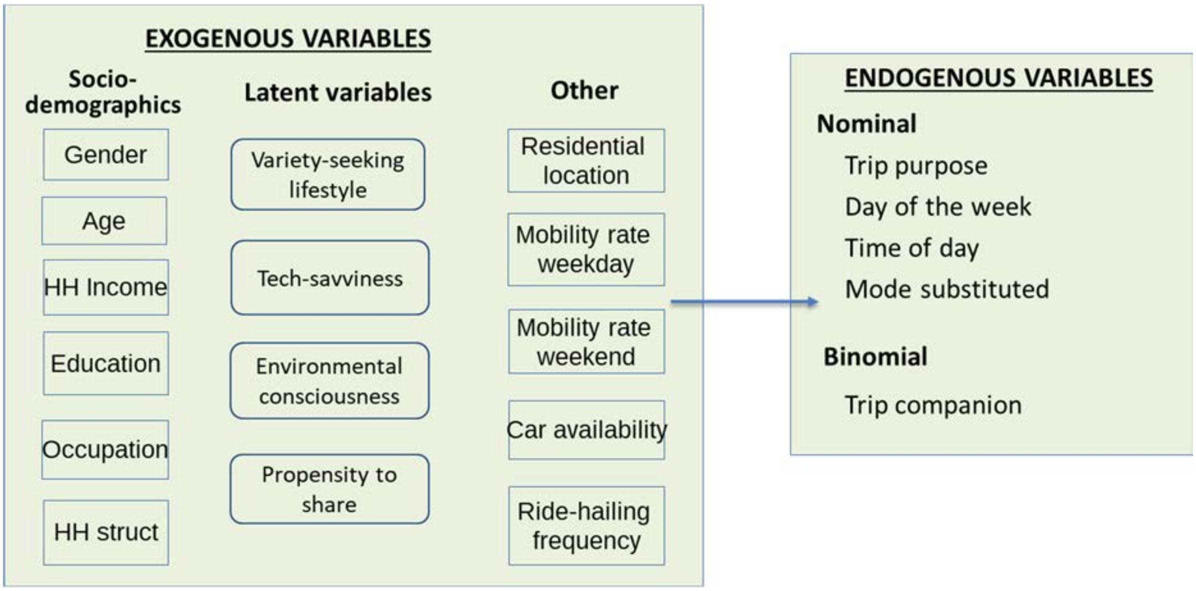

Figura 2: Visión general del modelo a nivel de viaje adoptado para explorar la movilidad en ride-hailing

Es necesario hacer una nota importante. Dado que estamos modelando viajes aislados realizados por los individuos en lugar de analizar los viajes en coche como una parte integral de los patrones de movilidad en general, los resultados de nuestro modelo a nivel de viaje deben ser interpretados con precaución.

Este segundo análisis es intrínsecamente de naturaleza exploratoria y tiene como objetivo principal complementar el primer modelo sobre la adopción y la frecuencia de uso del ride-hailing.

3.2.1. Las variables endógenas de resultado

El análisis a nivel de viaje considera cinco variables endógenas relacionadas con el último viaje de ride-hailing realizado por el encuestado, todas ellas modeladas como funciones de variables exógenas (sociodemográficas y variables latentes).

Las cinco variables endógenas son el propósito del viaje, el día de la semana, la hora del día, el acompañante del viaje y el modo de transporte sustituido para el viaje. La primera variable de resultado, el propósito del viaje, se recoge en las cuatro categorías nominales de:

- (1) viajes a la estación de autobús/tren o al aeropuerto (a/desde las estaciones de autobús/tren y los aeropuertos),
- (2) viajes de trabajo (incluyendo el viaje al trabajo o al centro educativo, y la asistencia a reuniones de trabajo/educación fuera del lugar típico de trabajo/educación),
- (3) viajes de ocio (incluyendo actividades recreativas, sociales y deportivas), y
- (4) viajes de recados (incluyendo las compras).

El segundo resultado es el día de la semana, en la categorización nominal triple de :

- (1) lunes-jueves,
- (2) viernes y
- (3) sábado-domingo.

El tercer resultado es la hora del día, que originalmente se caracterizaba por las cinco franjas horarias que se suelen seguir en España:

- (1) por la mañana (06:00 - 13:00h),
- (2) por la tarde (13:00 a 15:00h),
- (3) a primera hora de la tarde (15:00-19:00h),
- (4) a última hora de la tarde (19:00-23:30h), y
- (5) por la noche (23:30-06:00h).

Sin embargo, sólo 25 de un total de 466 personas declararon que su último viaje en coche de alquiler se había realizado por la tarde (de 13:00 a 15:00), por lo que esta categoría se combinó con la de primera hora de la tarde (de 15:00 a 19:00) para obtener un total de cuatro alternativas horarias.La cuarta es la compañía, en las dos categorías de "solo" o "con otros". La quinta dimensión es el modo sustituido por el ride-hailing (basado en la respuesta a la pregunta "si el ride-hailing no estuviera disponible, ¿qué modo habría utilizado para el viaje?"), en las cuatro categorías de:

- (1) taxi,
- (2) vehículo privado,
- (3) transporte público y
- (4) otros (incluyendo caminar, ir en bicicleta y "no habría hecho este viaje si el ride-hailing no estuviera disponible").

El número de personas que indicaron que no habrían realizado el viaje si no existiera el servicio de ride-hailing fue de sólo 7 de un total de 466 personas para el modelo a nivel de viaje (esa es la razón para combinar esta categoría con los modos de caminar y montar en bicicleta). Este resultado respalda la idea de que existen opciones de transporte público asequibles y convenientes para los madrileños, y que no hay una cantidad sustancial de supresión de viajes por falta de buenas opciones de transporte.

3.2.2. Las variables exógenas

Al igual que en el modelo a nivel individual, las características del viaje se modelan en función de los datos sociodemográficos y los constructos latentes. Además, incluimos otras variables explicativas ya presentes en el modelo anterior: ubicación residencial, disponibilidad de vehículos, patrones de movilidad (tanto en días laborables como en fines de semana), y frecuencia de uso de ride-hailing. Dado que este análisis sólo tiene en cuenta a los individuos que utilizaron el servicio de ride-hailing en los últimos 30 días, la frecuencia de uso del servicio de ride-hailing se trata como una variable binaria exógena en este análisis, diferenciando entre:

- individuos que han utilizado el servicio de ride-hailing menos de 5 veces en los últimos 30 días; y
- individuos que han utilizado los servicios de ride-hailing 5 veces o más (este último grupo se considera usuario frecuente).

Mientras que la ubicación residencial, la disponibilidad de vehículos, los patrones de movilidad y la frecuencia de uso de los servicios de ride-hailing se trataron como variables endógenas en el modelo a nivel individual, aquí se introducen como variables exógenas porque pueden considerarse como decisiones a largo plazo relativas a las características específicas de un viaje que condujeron al uso de los servicios de ride-hailing para el último viaje realizado por el modo.

Además, esto se hizo también por razones prácticas, teniendo en cuenta el tamaño limitado de la muestra para este análisis a nivel de viaje, así como la naturaleza exploratoria del análisis. Por razones similares, también incluimos los constructos latentes caracterizados a partir del modelo a nivel individual como variables exógenas desarrollando un valor esperado para cada variable latente (basado en las estimaciones del modelo SEM del modelo a nivel individual) y cada individuo de la muestra.

3.2.3. La estructura del modelo

En este análisis exploratorio, modelamos cada una de las cinco dimensiones a nivel de viaje de forma independiente utilizando modelos logit binarios y multinomiales. Se adopta la siguiente estructura secuencial: el propósito del viaje influye en el día de la semana, y estos dos influyen a su vez en la hora del día.

Además, se supone que estas tres dimensiones del viaje influyen en el acompañamiento del mismo. Por último, se considera que el modo sustituido por el transporte en coche es una función de las demás características del viaje.

4. LA ENCUESTA Y LA DESCRIPCIÓN DE LA MUESTRA

4.1. Administración de la encuesta

Realizamos una encuesta con el objetivo de captar los principales factores que podrían influir en las elecciones y comportamientos de los individuos hacia la adopción y la frecuencia de uso de los servicios de ride-hailing en Madrid (España). La población objetivo es el conjunto de individuos que viven y/o se desplazan a la ciudad de Madrid.

Se realizaron dos oleadas de encuestas para recoger los datos y obtener un conjunto heterogéneo de encuestados. La primera oleada fue gestionada por una empresa encuestadora e incluyó:

- entrevistas personales en la calle en el centro de la ciudad y en los suburbios,
- cuestionarios en línea. En esta oleada se hizo un esfuerzo especial para incluir una adecuada heterogeneidad en términos de sociodemografía individual. La segunda oleada fue gestionada por los autores e incluyó
- distribución física en la calle de volantes (en el centro de la ciudad y en los suburbios) que explicaban el propósito de la investigación e incluían un enlace para acceder al cuestionario en línea; y
- difusión del enlace de la encuesta a través de sitios web de medios sociales y aplicaciones de mensajería.

Ambas oleadas de encuestas se realizaron entre junio y octubre de 2019, los 7 días de la semana, evitando el mes de agosto, dada su menor representatividad en cuanto a patrones de movilidad en la ciudad de Madrid.

El diseño final del cuestionario buscaba respuestas sobre cuatro categorías de datos demográficos, patrones de movilidad y atributos de estilo de vida:

- Información socioeconómica y demográfica general: género, edad, ingresos anuales del hogar, nivel de educación, ocupación, estructura del hogar y ubicación residencial.
- Tendencias de movilidad diaria y variables relacionadas con los viajes: disponibilidad de coche para uso personal frecuente, posesión de permiso de conducir, patrones de movilidad urbana (número de viajes en el último día de la semana y fuera de la semana, propósito principal del viaje en el último día de la semana y fuera de la semana), percepción de la accesibilidad a la actividad en transporte público.

- Adopción y uso de los servicios de ride-hailing: uso de los servicios de ride-hailing alguna vez, uso del ride-hailing al menos una vez en los últimos 6 meses y número de viajes en los últimos 30 días. Además, se pidió a las personas que habían utilizado el servicio de transporte por cable en los últimos 30 días que informaran sobre su último viaje, incluyendo: el propósito del viaje, la hora del viaje, el día de la semana, la hora del día, el acompañante del viaje, quién hizo la reserva del viaje, las principales razones para elegir el servicio de transporte por cable y el modo de viaje que se habría utilizado si el servicio de transporte por cable no hubiera estado disponible.
- Actitudes personales y preferencias de estilo de vida: se pidió a los individuos que calificaran su nivel de acuerdo con múltiples afirmaciones utilizando una escala Likert de cinco puntos. Los temas incluían:

    - propensión a adoptar un estilo de vida que busque la variedad;
    - conocimiento de la tecnología;
    - conciencia medioambiental; y
    - propensión a utilizar bienes compartidos. Estos cuatro conjuntos de indicadores de preferencias de estilo de vida constituyeron la base para desarrollar los cuatro constructos latentes utilizados en nuestro estudio (véase la sección 5), que captan las preferencias psicológicas de los individuos.

Se recogieron un total de 1.246 respuestas válidas. Las estadísticas descriptivas básicas de los datos demográficos y los patrones de movilidad se presentan en la Tabla 2 para algunas de las variables recogidas, y se analizan brevemente en las secciones siguientes. En la Tabla 2, también proporcionamos estadísticas para variables seleccionadas que estaban fácilmente disponibles a partir de los datos del Censo de España para 2019 (Ayuntamiento de Madrid, 2020; Agencia Tributaria, 2019) para proporcionar una comparación de las características de la muestra con las características generales de la población de Madrid.

4.2. Datos sociodemográficos individuales y características del hogar

El cuadro 2 muestra una distribución bastante heterogénea de las características sociodemográficas individuales y de los hogares en la muestra. Sin embargo, en relación con los datos del censo, la muestra presenta una mayor proporción de hombres (55,2% en la muestra, frente al 46,0% de las estadísticas locales) y de individuos menores de 35 años (51,1% frente al 26,3%). Además, la muestra indica una sobrerrepresentación de individuos con un nivel educativo alto (el 69,3% de la muestra ha completado estudios universitarios en relación con el 34,5% del censo) y niveles de renta altos. Cabe destacar que alrededor del 25% de los encuestados de la muestra declaran no conocer los ingresos de su hogar, o no están dispuestos a comunicar esta información. Esta reticencia a informar sobre los ingresos está en línea con muchas encuestas anteriores relacionadas con el transporte que recogen datos sobre los ingresos en España (véase, por ejemplo, Heras-Molina et al., 2017; Cantos y Álvarez, 2009).

			Total sample		Census data	
			Individuals	%	Population/ *Households*	%
INDIVIDUAL SOCIODEMOGRAPHICS	Gender	Male	688	55.2	1,324,589	46.0
		Female	558	44.8	1,557,425	54.0
	Age	Under 25	254	20.4	313,828	10.9
		25 to 34	383	30.7	444,968	15.4
		35 to 49	356	28.6	783,569	27.2
		50 to 59	186	14.9	479,151	16.6
		Above 59	67	5.4	859,734	29.8
	Education	Has not completed University studies	383	30.7	1,630,186	65.5
		Has completed University studies	863	69.3	857,276	34.5
	Employment	Employed	863	69.3		
		Student or part/student	277	22.2		
		Other: unemployed, retired, homemaker, etc.	106	8.5		
HOUSEHOLD CHARACTERISTICS	Household Income	Below 18,000 Euro	189	15.2	*682,534*	40.6
		18,000 to 30,000 euro	277	22.2	*427,844*	25.4
		30,000 to 60,000 Euro	314	25.2	*423,694*	25.2
		Above 60,000 Euro	141	11.3	*147,135*	8.8
		DN/DWA	325	26.1	---	0.0
	Household structure	Living alone	175	14.0		
		Living with flatmates	150	12.0		
		Couple without children	237	19.0		
		Couple with children below 24	457	36.7		
		Couple with all children above 24	118	9.5		
		Other	109	8.7		
	Residential location	Madrid city (inside M-30 ring)	587	47.1		
		Madrid city (outside M-30 ring)	473	38.0		
		Outside Madrid city (outskirts)	186	14.9		
MOBILITY-RELATED	Car availability	Yes	861	69.1		
		No	385	30.9		
	Weekday mobility	0 trips	109	8.7		
		1-2 trips	681	54.7		
		> 2 trips	456	36.6		
	Weekend mobility	0 trips	248	19.9		
		1-2 trips	583	46.8		
		> 2 trips	415	33.3		
	Ride-hailing use	Never used	458	36.8		
		Used but not in the last 6 months	111	8.9		
		Used but not in the last month	207	16.6		
		Used in the last month (1-4 trips)	311	25.0		
		Used in the last month (5-8 trips)	91	7.3		
		Used in the last month (>8 trips)	68	5.5		
TOTAL			1,246	100.0		

Tabla 2: Resumen de las características de la muestra

En relación con la estructura de los hogares, hay una parte importante de familias con hijos menores de 24 años (36,7%) y de parejas sin hijos (19,0%). Las personas empleadas son mayoría en la muestra (69,3%).

Entre las características de los hogares, la ubicación residencial es una de las variables endógenas de interés en nuestro modelo (véase la sección 3.1.1). Como se indica en la Tabla 2, la mayoría de los encuestados de la muestra viven en la ciudad de Madrid (85,1%).

4.3. Variables relacionadas con la movilidad

Las variables relacionadas con la movilidad de la Tabla 2, junto con la ubicación residencial, constituyen los resultados endógenos de interés en nuestro modelo a nivel individual. La Tabla 2 muestra que el 69,1% de los individuos tienen un coche disponible con frecuencia para su uso personal.

Las estadísticas relacionadas con la movilidad en días laborables y fines de semana muestran una intensidad de actividad fuera del hogar generalmente mayor en días laborables que en fines de semana, lo que no es sorprendente debido a la contribución de los viajes al trabajo en días laborables. Lo más interesante es que la tabla indica que 788 encuestados (63,2%) han utilizado el servicio de ride-hailing al menos una vez, y una proporción no significativa de la muestra (alrededor del 13%) parece utilizarlo al menos una vez a la semana (como se obtiene sumando las dos últimas categorías de frecuencia de ride-hailing de la tabla).

VARIABLE		**Trips**	**% Sample**
Trip purpose			
	Bus/train station or airport	70	15.0%
	Work	77	16.5%
	Leisure	194	41.6%
	Errands	71	15.2%
	Other	54	11.6%
Day of week			
	Monday-Thursday	194	41.6%
	Friday	101	21.7%
	Saturday-Sunday	171	36.7%
Time of day			
	Morning (06-13:00h)	113	22.4%
	Afternoon and early evening (13:00 – 19:00h)	91	18.0%
	Late evening (19:00 – 23:30h)	159	31.5%
	Night (23:30 – 6:00h)	142	28.1%
Companion			
	I was alone	196	42.1%
	There were family members or my couple with me	140	30.0%
	There were friends with me	105	22.5%
	There were co-workers with me	25	5.4%
Mode substituted			
	Taxi	236	50.6%
	Private vehicle	42	9.0%
	Public transit: metro, bus, train, commuter rail, etc.	155	33.3%
	Other: bike,walk, not make the trip	33	7.1%
TOTAL		**466**	**100.0%**

Tabla 3: Resumen de las características del último viaje en ride-hailing

Como se ha señalado anteriormente, se pidió a los encuestados que declararon haber utilizado los servicios de ride-hailing en los últimos 30 días que proporcionaran información detallada sobre su último viaje de ride-hailing, en particular: el propósito del viaje, el día de la semana, la hora del día, el acompañante del viaje y el modo de transporte que habrían elegido en caso de que el ride-hailing no hubiera estado disponible para ese viaje específico. 466 encuestados indicaron que habían realizado al menos un viaje en coche de alquiler en los últimos 30 días, y estos son los individuos que constituyen la muestra para el análisis a nivel de viaje. Las características descriptivas de los viajes de ride-hailing declarados en la muestra, así como las categorías consideradas para cada variable, se incluyen en la Tabla 3.

Como se puede observar, los viajes de ocio son el propósito de viaje más común en la muestra (41,6%), lo que está en línea con los hallazgos anteriores en la literatura de ride-hailing. El resto de propósitos de viaje están representados de forma bastante uniforme en la muestra. En el análisis, sólo hemos tenido en cuenta los cuatro primeros propósitos enumerados en la Tabla 3: estación de autobús/tren o aeropuerto, trabajo, ocio y recados. En cuanto a los patrones de día de la semana y hora del día, está claro que la intensidad de los desplazamientos es mayor los viernes y en los períodos de tarde y noche. En cuanto a la dimensión de la compañía, hay un reparto equitativo entre los viajes en solitario y los viajes en compañía.

Finalmente, como parece razonable para el caso de Madrid, el taxi es el principal modo sustituido por el ride-hailing (50,6%), seguido del transporte público (33,3%) y, en menor medida, el coche privado (9,0%). Se obtienen resultados similares sobre la sustitución de modos debida al ride-hailing en otras zonas de tránsito intensivo como San Francisco, especialmente en lo que respecta al taxi y al transporte público (Alemi et al., 2018; Rayle et al., 2016). Por el contrario, la proporción de la demanda captada del transporte público es significativamente mayor en Madrid que en lugares dominados por el coche como Dallas (véase Lavieri y Bhat, 2019). Solo el 5,6 % de la muestra declaró que el ride-hailing sustituyó a los modos activos (caminar o ir en bicicleta) y solo el 1,5 % declaró no haber podido realizar el viaje si el ride-hailing no hubiera estado disponible (esto contrasta con el aproximadamente 6 % en el área de Dallas-Fort Worth que afirma que no podría haber realizado el viaje si no fuera por el ride-hailing).

4.4. Constructos latentes

La tabla 4 muestra los indicadores de cada constructo latente, así como sus distribuciones muestrales. Las estadísticas relativas al estilo de vida de búsqueda de variedad sugieren que la fracción más alta de individuos se encuentra en la categoría neutral. Por otro lado, los encuestados se inclinan claramente por ser conocedores de la tecnología, lo que parece razonable dada la alta proporción de adultos jóvenes con niveles de educación altos en la muestra. Como era de esperar, la conciencia medioambiental declarada es especialmente alta en la muestra.

Los encuestados se sienten sobre todo muy o totalmente identificados con los comportamientos orientados al medio ambiente relacionados con el reciclaje (73,4%), la compra de productos respetuosos con el medio ambiente (48,5%) y la elección del modo de transporte (57,3%). Asimismo, es razonable que la mayoría de los individuos crean que tienen una buena accesibilidad al transporte público. Por último, en cuanto a la propensión a compartir (introducida en una escala invertida en el análisis), se observa de nuevo que la mayoría de los individuos se sitúan en la categoría media, con proporciones aproximadamente iguales a ambos lados del centro.

		Identify very little	Identify somewhat	Neutral	Identify Strongly	Identify completely
VARIETY-SEEKING LIFESTYLE	I think it is important to have all sorts of experiences and am always trying new things	4.9%	16.1%	30.9%	30.3%	17.9%
	I love to try new products before anyone else	10.3%	25.8%	31.5%	20.4%	12.0%
	Looking for adventures and taking risks is important to me	10.3%	25.4%	29.1%	25.0%	10.4%
TECH-SAVVINESS	I frequently use online social media (e.g. Facebook, Twitter, Instagram, Snapchat, etc.)	10.4%	11.1%	18.0%	25.7%	34.9%
	I regularly use internet services or mobile applications to facilitate my daily life: banking services, online purchases, GPS navigation, email, etc.	3.5%	4.8%	14.8%	27.4%	49.6%
	Learning how to use new smartphone apps and testing them is easy for me	2.8%	6.6%	19.0%	33.3%	38.3%
	I regularly use sharing economy apps or websites: Airbnb, Wallapop, Couchsurfing, etc.	17.5%	20.7%	25.5%	21.3%	15.0%
ENVIRONMENTAL CONSCIOUSNESS	When choosing my transportation mode, I try to be environmentally friendly	3.7%	12.3%	26.7%	37.4%	19.9%
	I recycle at home	5.2%	7.7%	13.6%	28.5%	44.9%
	Generally, I am willing to spend more to buy a product that is more environmentally friendly	4.4%	13.7%	33.3%	34.5%	14.0%
	My household accessibility by public transport is good	0.7%	4.6%	11.2%	21.9%	61.6%
PROPENSITY TO SHARE	I prefer to buy a new product rather than buy it second-hand	4.0%	12.4%	30.9%	30.2%	22.6%
	I am reluctant to use / put on objects that have been used by many people before me	9.8%	27.4%	30.1%	20.5%	12.3%
	I do not like travelling with strangers	11.2%	24.0%	28.4%	21.4%	14.9%

Tabla 4: Distribución de indicadores de actitud en la muestra

5. RESULTADOS DE LA MODELIZACIÓN Y DISCUSIÓN

Esta sección resume los principales resultados del análisis realizado en esta investigación. En las estimaciones, en lugar de imputar un valor de ingresos para el 25% de la muestra que no declaró ingresos en la encuesta, creamos una categoría de variable ficticia separada para dichos individuos al probar el efecto de los ingresos.

Esto tiene como resultado el uso de individuos con valores de ingresos declarados para evaluar los efectos de los ingresos apropiados, mientras que también se utilizan todos los individuos cuando se estiman los efectos de otras variables del modelo. También quisiéramos señalar que se intentó realizar toda una serie de especificaciones diferentes, y la especificación final se obtuvo a partir de un proceso sistemático de pruebas de combinaciones alternativas de variables explicativas (y diferentes formas funcionales de las variables) y de eliminación de las que no eran estadísticamente significativas, al tiempo que se avanzaba hacia especificaciones parsimoniosas. En la especificación final del modelo, no todas las variables incluidas son estadísticamente significativas a un nivel de confianza del 95%, pero se mantuvieron algunas de ellas porque proporcionaban interpretaciones y conocimientos intuitivos.

También es importante señalar que, como se indica en la sección 3.1.3, sólo se puede estimar una estructura recursiva de influencia de los resultados endógenos de interés entre los seis resultados. En nuestras especificaciones, probamos sistemáticamente todas las combinaciones posibles de efectos recursivos entre los seis resultados, y nos decidimos por la combinación que proporcionaba el mejor ajuste de los datos. Sin embargo, hay que tener en cuenta que el modelo sigue siendo un modelo conjunto que considera todas las variables endógenas como un único proceso de elección agrupado, debido a la correlación de errores generada entre los resultados endógenos a través de las construcciones latentes estocásticas.

5.1. Modelo a nivel individual

5.1.1 Parte del SEM

Los resultados del modelo a nivel individual se presentan en la Tabla 5 (parte SEM) y en la Tabla 6 (parte MEM). De la parte SEM, podemos observar que el estilo de vida de búsqueda de variedades (VSL) varía significativamente según el género, la edad y la ocupación. Con respecto al género, la literatura sobre el comportamiento del consumidor y los valores humanos ha identificado que los hombres son más propensos a mostrar un comportamiento de búsqueda de variedad que las mujeres (McAlister & Pessemier 1982; Tscheulin, 1994) ya que están más abiertos a nuevas experiencias y cambios. Algunos autores como Stasiuk et al. (2018) indican que esto puede explicarse en parte por los roles y estereotipos de género aún existentes, en los que las mujeres siguen siendo más responsables de mantener las cosas unidas en la familia, lo que se traduce en no "agitar el barco" y, por lo tanto, evitar la novedad. Otros autores (como Croson y Gneezy (2009) y Loewenstein et al. (2001) sugieren que esta reticencia de género a la variedad se basa en la noción de "riesgo como sentimiento", que afirma que nuestras emociones instintivas e intuitivas dominan los enfoques razonados cuando nos enfrentamos a un riesgo (en nuestro caso, ver la variedad a través de un cambio constituye un riesgo). Además, dado que las mujeres experimentan sentimientos de nerviosismo y miedo más que los hombres en previsión de resultados negativos, el resultado neto puede ser una mayor aversión a la búsqueda de variedad entre las mujeres. Además, la relación que indica un estilo de vida de menor búsqueda de variedad a medida que aumenta la edad estaría en consonancia con muchos hallazgos de la literatura sobre psicología social.

Por ejemplo, autores como McCrae et al. (2000), Srivastava et al. (2003) y González-Gutiérrez et al. (2015) han indicado que la apertura de un individuo a nuevas experiencias disminuye con la edad. En particular, a medida que los adultos avanzan hacia la edad media y avanzada, los individuos están cada vez menos interesados en, por ejemplo, recopilar nueva información o conocer a nuevas personas, lo que implica una disminución de la apertura (Carstensen et al., 1999). Además, Hoyer y Ridgway (1983) y McAlister y Pessemier 1982 señalaron que la infancia y la juventud se caracterizan por un mayor nivel de curiosidad y estimulación, mientras que el deseo de cambio disminuye a medida que las personas envejecen debido a una mayor experiencia de la vida. El resultado estadísticamente significativo de una menor búsqueda de variedad en el estilo de vida de los jubilados parece estar muy relacionado con la edad. No obstante, Srivastava et al. (2003) indicaron que se pueden encontrar resultados contradictorios entre los estudios respecto a la asociación entre la apertura y ciertas características sociodemográficas.

Nuestro análisis también encuentra una fuerte conexión entre el conocimiento de la tecnología y los ingresos y la edad. Estos resultados están en consonancia con investigaciones anteriores que analizan la adopción de tecnología entre la población española (Garrido et al., 2016; Moreira, 1998), así como con estudios sobre la demanda de ride-hailing en Estados Unidos (Astroza et al., 2017). La relación entre la adopción de tecnología y el nivel de ingresos está ampliamente referenciada en la literatura (véase, por ejemplo, Kalba, 2008; DiMaggio & Cohen, 2005; Carey, 1989) y se explica normalmente por la mayor capacidad financiera de los consumidores ricos para adquirir o renovar accesorios y servicios tecnológicos (por ejemplo, teléfonos móviles).

Además, nuestros resultados relativos a una menor predisposición a la tecnología a medida que aumenta la edad están respaldados por Morris & Venkatesh (2000), que indican que los jóvenes son mucho más propensos a estar expuestos a las tecnologías de la información a una edad temprana. Investigaciones más recientes (p. ej., Rogers et al., 2017; Berjowsky et al., 2017) también han identificado el papel que desempeñan las percepciones de facilidad de uso y utilidad en la menor predisposición a la tecnología de las personas mayores. Otros resultados con respecto a la tecnociencia en la Tabla 5 se refieren a los efectos positivos de la educación y de "vivir con compañeros de piso", y a los efectos negativos de las personas que no estudian/no trabajan y de las que tienen hijos mayores.

En cuanto a la conciencia medioambiental, la única variable estadísticamente significativa está relacionada con los ingresos. Los resultados sugieren una especie de efecto en forma de U invertida de los ingresos sobre la conciencia medioambiental, alcanzando esta conciencia un pico en el rango de ingresos medios de 30.000-60.000 euros, pero disminuyendo en los ingresos más altos. La menor conciencia medioambiental entre el segmento de ingresos más bajos puede explicarse basándose en la teoría de Maslow sobre la jerarquía de las necesidades humanas, que establece que los seres humanos se centran primero en el instinto de supervivencia de satisfacer sus necesidades materiales básicas, y consideran las necesidades de mayor nivel, como la necesidad de calidad medioambiental, sólo después de satisfacer las necesidades básicas.

En el otro extremo del espectro, se ha investigado ampliamente que el consumo de lujo está asociado a las motivaciones socioculturales de señalización de riqueza, poder y estatus, y al acceso privilegiado a recursos limitados (Kastanakis y Balabanis, 2014 y Nwankwo et al., 2014), que pueden eclipsar las consideraciones de conciencia medioambiental.

VARIABLES (base category)	STRUCTURAL EQUATIONS MODEL COMPONENT RESULTS							
	VSL		TECHY		ENVIRONM		SHARER	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
Gender (male)								
Female	-0.153	-2.054					-0.177	-2.131
Income (below 18,000 Euro)								
18,000 to 30,000 euro			0.164	1.704	0.390	3.347		
30,000 to 60,000 Euro			0.149	1.462	0.451	3.957		
Above 60,000 Euro			0.248	1.885	0.206	1.431	-0.271	-2.271
DN/DWA			0.092	0.987	0.231	2.063		
Age (under 25)								
25 to 34	-0.189	-1.758	-0.300	-3.329				
35 to 49	-0.524	-4.762	-0.627	-6.219				
50 to 59	-0.717	-5.656	-1.067	-8.856			-0.296	2.634
Above 59	-0.717	-5.632	-1.067	-8.856			-0.296	2.634
Education (non-university)								
University studies			0.114	1.475				
Occupation (employed)								
Student or part/student								
Other: retired, unemp., etc	-0.616	-4.117	-0.471	-3.452				
Household structure (living alone)								
Living with flatmates			0.218	2.007				
Couple without children	-0.161	-1.742						
Couple with children below 24								
Couple with all children above 24			-0.187	-1.825				
Other								
Correlations between latent variables								
VSL	1.00	n/a						
TECHY	0.508	6.028	1.00	n/a				
ENVIRONM	0.425	8.303	0.356	3.921	1.00	n/a		
SHARER			-0.194	-2.884			1.00	n/a

Tabla 5: Resultados del modelo a nivel individual sobre el uso del transporte compartido: Parte SEM

Por último, los resultados de la propensión a compartir, que también puede considerarse como un indicador de la sensibilidad a la privacidad, son razonables. Por ejemplo, la menor actitud de compartir entre las mujeres estaría en consonancia con muchas investigaciones anteriores que concluyen, por ejemplo, que las mujeres están más preocupadas por la privacidad y, en particular, por la privacidad cuando utilizan servicios relacionados con Internet (véase, por ejemplo, Sheehan, 1999; Milne et al., 2004; Wills & Zeljkovic, 2011). Del mismo modo, el análisis SEM concluye una menor propensión a compartir entre los segmentos de población de mayor edad. Además, el modelo concluye una relación positiva entre el nivel de ingresos y la sensibilidad a la privacidad. Contribuciones anteriores como la de Chevalier & Gutsatz (2012) indican que esto puede deberse a la mayor accesibilidad de los individuos ricos a la propiedad privada, a su necesidad de sentirse seguros y preservar sus bienes materiales, y/o a su tendencia a separarse o diferenciarse de los demás como señal de exclusividad.

Cuatro de las seis correlaciones entre las variables latentes son estadísticamente significativas (véase la parte inferior de la Tabla 5). El estilo de vida que busca la variedad, la avidez por la tecnología y la conciencia medioambiental están correlacionados positivamente, mientras que existe una correlación negativa entre la propensión a compartir y la avidez por la tecnología. Las relaciones positivas entre los estilos de vida que buscan la variedad y la avidez por la tecnología han sido ampliamente referidas en la literatura sobre psicología social. Por ejemplo, Khare et al. (2010) descubrieron que los comportamientos de búsqueda de innovaciones/novedades estaban fuertemente relacionados con actividades orientadas a Internet, como las compras en línea. Además, Lee et al. (2013) han señalado que las actividades basadas en la web, como la búsqueda en línea, sirven para satisfacer las necesidades emocionales de las personas que buscan aventuras. Los conocimientos tecnológicos también se han relacionado intrínsecamente con la conciencia medioambiental de los individuos. Seçken (2005) llegó a la conclusión de que las actitudes hacia la tecnología y su utilización, así como el nivel de educación asistida por ordenador, influyen en las actitudes de conciencia medioambiental.

En cuanto a la correlación entre la conciencia medioambiental y la VSL, se ha demostrado que la búsqueda de variedad y los valores hedonistas influyen en la compra de productos ecológicos (Ceriak et al., 2010; Chen y Chang, 2012). Por último, muchas contribuciones en la literatura científica han concluido una relación positiva entre el conocimiento de la tecnología y la preocupación por la privacidad. Para el caso de España, Gómez-Barroso et al. (2019) han concluido recientemente que a medida que los usuarios se vuelven más conocedores de la tecnología, su sensibilidad a la privacidad también suele aumentar. Del mismo modo, Liao et al. (2011) concluyeron que la alfabetización en Internet tiene un impacto positivo en la preocupación por la privacidad, ya que los individuos con conocimientos tecnológicos suelen ser más conscientes de cómo se transmite y utiliza su información personal.

La estimación SEM es posible gracias a las observaciones de las variables endógenas, que incluyen los indicadores del constructo latente y los cuatro resultados endógenos de interés (véase la Figura 1). Para ahorrar espacio, y dado que estas cargas de los constructos latentes en los indicadores de constructo no son de interés primordial en este trabajo, suprimimos estos resultados de carga. Basta con mencionar aquí que estas cargas eran todas las esperadas.

5.1.2 Ubicación residencial

La parte del MEM (véase la Tabla 6) analiza la influencia tanto de los datos sociodemográficos exógenos como de los constructos latentes en las variables endógenas. En cuanto a la localización residencial, resulta interesante que nuestra mejor especificación indique que esta dimensión de la elección se ve afectada principalmente por la sociodemografía y no por los constructos latentes actitudinales. A medida que aumentan los niveles de renta, existe una tendencia a elegir vivir fuera de la ciudad de Madrid. Este resultado refleja fielmente la distribución espacial de la renta per cápita en el área metropolitana de Madrid (véase Comunidad de Madrid, 2020), ya que Madrid capital limita con siete de los 10 municipios más ricos de España (Pozuelo, Boadilla, Las Rozas, etc.). La edad también influye en la elección residencial, ya que los individuos no jóvenes (mayores de 49 años) prefieren vivir más lejos del centro de la ciudad. De forma equivalente, los adultos jóvenes parecen "acudir" más al centro de la ciudad, quizás por la mayor accesibilidad a las actividades y los deseos de mayor vitalidad social. Un resultado similar se encuentra con respecto a la educación, ya que los individuos con un alto nivel de estudios prefieren el centro de la ciudad en lugar de la periferia, mientras que lo opuesto parece ser el caso de los hogares de tipo de nido vacío.

5.1.3 Índices de movilidad y disponibilidad de vehículos

Las tasas de movilidad, incluidas explícitamente como variables endógenas en el modelo, presentan algunos resultados interesantes. En primer lugar, se observa una mayor propensión a la movilidad en días laborables y fines de semana entre los encuestados con altos niveles del constructo de estilo de vida de búsqueda de variedad (VSL).

Esto parece razonable dado que las personas con un VSL alto pueden estar más dispuestas a realizar actividades de ocio o recados (por ejemplo, ir al gimnasio, reunirse con amigos, etc.) antes o después de su turno de trabajo, o durante los fines de semana. También podemos observar que muy pocas variables exógenas resultan ser estadísticamente significativas, lo que indicaría una cierta inelasticidad en los patrones de movilidad de los individuos durante la semana y el fin de semana a través de la sociodemografía. Los individuos de hogares con ingresos medios y las parejas sin hijos tienen una propensión significativamente menor a realizar viajes durante los días laborables, mientras que los individuos de más de 50 años muestran una mayor propensión a la movilidad durante los días laborables, pero una menor propensión a la movilidad durante los fines de semana.

Este último resultado puede apuntar a una menor responsabilidad familiar entre los individuos no jóvenes, de modo que pueden realizar más actividades fuera de casa durante el día en los días laborables, mientras que, los individuos más jóvenes (especialmente los del grupo de edad más joven de "menos de 25 años"), al estar relativamente "encadenados" en los días laborables, participan en más actividades sociales/recreativas durante los días de fin de semana. Aparte de estos efectos demográficos, la ubicación residencial influye de forma muy significativa en las tasas de movilidad de los días laborables y de los fines de semana, siendo la propensión a la movilidad mucho mayor entre los individuos que residen en el centro de la ciudad que fuera de él, lo que tal vez indique las importantes oportunidades de actividad que se ofrecen a los que residen en el centro de la ciudad.

Los resultados de la modelización de la disponibilidad de vehículos indican que, salvo la conciencia medioambiental, ningún otro constructo latente influye en la disponibilidad de vehículos. La conciencia medioambiental reduce significativamente la probabilidad de disponibilidad de vehículos. Dada la fuerte conexión encontrada entre las actitudes pro-ambientales y el uso del transporte público, este resultado puede reflejar la menor propensión a tener un coche de los individuos orientados al tránsito. Este resultado contrasta con el de Lavieri y Bhat (2019), que no encontraron una relación estadísticamente significativa entre la disponibilidad de coche y la conciencia medioambiental en Dallas, una zona dominada por el coche y con escasa presencia de transporte público. Como cabe esperar, las variables sociodemográficas exógenas, como los ingresos, la edad y la educación, influyen en la disponibilidad de coches, siendo más probable que los individuos de más edad, más ricos y con mayor nivel educativo tengan un coche disponible para su uso personal. Los encuestados que viven con compañeros de piso tienen menos probabilidades de disponer de un coche, mientras que ocurre lo contrario en los hogares con niños pequeños.

En cuanto a la ubicación residencial, como parece razonable, la propensión al coche es significativamente mayor para los residentes que viven más alejados del centro de la ciudad. Además, existe una relación negativa estadísticamente significativa entre la disponibilidad de vehículos y las tasas de movilidad tanto en días laborables como en fines de semana. Este resultado debe interpretarse a la luz de los problemas que suele plantear la conducción de un vehículo privado en la ciudad de Madrid, sobre todo en los desplazamientos puramente intraurbanos. Además de los recurrentes problemas de congestión y de las restricciones al vehículo privado aplicadas recientemente por el gobierno local, el aparcamiento en la calle en Madrid es escaso, está sujeto a una tarifa por minuto y está limitado a una determinada cantidad de tiempo. Todos estos factores dificultan en gran medida el uso del vehículo privado en la ciudad de Madrid. Este resultado es realmente muy interesante, y bastante diferente de lo que cabría esperar de una ciudad típica de Estados Unidos. Indirectamente, los resultados también indican el efecto negativo del constructo VSL sobre la disponibilidad de vehículos, ya que un VSL más alto aumenta las tasas de movilidad, y las tasas de movilidad reducen la disponibilidad de vehículos.

	Residence (base: inside M30 ring)				Mobility rates weekday (ordinal)		Mobility rate weekend (ordinal)		Vehicle availability (base: no car)		Ride-hailing adoption (base: never used)		Ride-hailing frequency (ordinal)	
	Outside M30 ring		Outside Madrid city											
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
LATENT VARIABLES														
VSL					0.253	5.395	0.109	2.158						
TECHY											0.430	4.608		
ENVIRONM									-0.265	-1.752			-0.111	-1.855
SHARER														
EXOGENOUS EFFECTS														
Gender (male)														
Female											0.088	3.869		
Income (below 18,000 Euro)														
18,000 to 30,000 euro			0.298	1.834	-0.077	-0.832			0.231	4.563				
30,000 to 60,000 Euro			0.446	2.297	-0.195	-2.022			0.618	13.339	0.214	4.894		
Above 60,000 Euro			0.557	2.459					0.481	8.129	0.487	6.797		
DN/DWA	-0.115	-2.309	0.305	1.701										
Age (under 25)														
25 to 34	-0.120	-2.725					-0.254	-2.356	0.251	5.937				
35 to 49							-0.385	-3.322	0.378	8.047	-0.115	-1.667		
Above 49	0.127	1.590	0.258	1.853	0.189	1.843	-0.446	-3.336	0.686	11.542	-0.272	-2.023		
Education (non-university)														
University studies	-0.331	-4.204	-0.437	-2.992					0.623	16.549	0.224	5.596		
Occupation (employed)														
Student or part/student	-0.154	-2.577											-0.227	-2.210
Other: reitred, unemployed, etc.			-0.608	-3.332										
Household structure (living alone)														
Living with flatmates									-0.676	-14.814	0.422	5.888		
Couple without children					-0.197	-1.936								
Couple with children below 24									0.499	13.871				
Couple with all children above 24	0.475	9.694	0.360	1.789										
Other	0.211	1.973	0.501	2.000										
Residence (inside M30 ring)														
Outside M30 ring	n/a	n/a	n/a	n/a	-0.239	-2.769	-0.145	-1.849	0.244	8.322	-0.256	-9.724	-0.367	-3.496
Outside Madrid city	n/a	n/a	n/a	n/a	-0.212	-1.904	-0.488	-3.965	0.412	9.348	-0.432	-12.122	-0.217	-1.657
Weekday mobility (zero trips)														
1 to 2 trips	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	-0.270	-5.087				
3 or more trips	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	-0.503	-9.285				
Weekend mobility (zero trips)														
1 to 2 trips	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a						
3 or more trips	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	-0.097	-3.819			0.216	2.116
Car availability (no availability)														
Availability	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.315	10.539	0.259	2.276
Constant	0.107	0.851	-1.036	-2.245	1.763	19.234	1.346	13.008	-0.215	-2.766	0.228	4.942	1.103	8.542
Thresholds														
Threshold4													2.538	24.430

Tabla 2: Resultados del modelo a nivel individual sobre el uso del ride-hailing: Parte MEM

5.1.4 Adopción y frecuencia de uso del ride-hailing

El modelo presenta resultados interesantes en relación con la adopción y la frecuencia de uso de los servicios de ride-hailing cuando se compara con investigaciones anteriores sobre ciudades estadounidenses. La capacidad tecnológica es la única variable latente que influye de forma estadísticamente significativa en la adopción del servicio de ride-hailing. Este resultado parece evidente, ya que el servicio de ride-hailing sólo se puede utilizar a través de un teléfono inteligente, por lo que es razonable esperar que estos servicios sean adoptados en mayor medida por los segmentos de la población que están más familiarizados con las nuevas tecnologías (jóvenes, personas con un buen nivel educativo y adineradas). La relación entre la adopción de ride-hailing y el tech-savviness ha sido ampliamente citada en la literatura (véase, por ejemplo, Rayle et al., 2016; Alemi et al., 2018; Lavieri & Bhat, 2019).

Aparte de la influencia indirecta de las variables exógenas a través del constructo latente tech-savviness, hay efectos directos adicionales sobre la adopción de ride-hailing de los datos sociodemográficos exógenos. Como se puede observar en la Tabla 6, las mujeres muestran una mayor tendencia a adoptar el ride-hailing, lo que también es coherente con la menor tendencia de este segmento de la población a compartir bienes (indicador de sensibilidad a la privacidad). Los individuos con altos ingresos, menor edad y alta educación son más propensos a adoptar el ride-hailing que sus correspondientes compañeros, resultados que son consistentes con varios otros estudios de ride-hailing (véase, por ejemplo, Chen, 2015; Rayle et al., 2016; Smith, 2016; Clewlow & Mishra, 2017; Alemi et al., 2018; y Wang et al., 2019, entre otros). Por lo tanto, concluimos que, al igual que en otros estudios de caso ya analizados en Estados Unidos, los usuarios de ride-hailing en Madrid también tienden a ser individuos jóvenes, bien educados y ricos, que están familiarizados con las nuevas tecnologías.

Según los resultados, la ubicación residencial también juega un papel importante en la adopción de ride-hailing, siendo los individuos que viven fuera del centro de la ciudad (es decir, fuera de la primera circunvalación) menos propensos a adoptar ride-hailing que los que residen dentro de la primera circunvalación. Este hallazgo es razonable debido a la mayor oferta de servicios de ride-hailing en el centro de la ciudad y la asociación positiva entre la densidad residencial y la adopción de ride-hailing (Dias et al., 2017; Conway et al., 2018; Yu & Peng, 2019; Li et al., 2019; y Goodspeed et al., 2019). Lo más interesante es que el modelo establece una relación positiva y significativa entre la disponibilidad de coches y la adopción de ride-hailing. Este resultado contrasta con muchos hallazgos habitualmente comunicados para las ciudades estadounidenses (véase, por ejemplo, Gehrke et al., 2018 para Boston; Alemi et al., 2019 para San Francisco), que indican que el ride-hailing es utilizado con mayor frecuencia por individuos que no poseen un vehículo o que planean reemplazar o deshacerse de uno de los vehículos de su hogar. Sin embargo, en el contexto europeo, en particular para el caso de Madrid, parece razonable una relación positiva entre la disponibilidad de coches y la adopción del ride-hailing.

Los individuos que utilizan su coche privado con más frecuencia son probablemente más sensibles a los viajes cómodos de puerta a puerta, de modo que pueden encontrar una opción alternativa conveniente en los servicios de ride-hailing cuando el coche privado es menos atractivo (por ejemplo, salir a comer y beber, o acceder a zonas con restricciones para el coche privado como el centro de la ciudad). Dado que la disponibilidad de coches está correlacionada negativamente con la conciencia medioambiental, este resultado también puede indicar indirectamente que los individuos con una mayor propensión al transporte público son menos propensos a adoptar el ride-hailing.

Por último, la Tabla 6 muestra que hay relativamente pocas variables exógenas que influyan en la frecuencia de uso del ride-hailing, una vez que se ha controlado la adopción del mismo. El resultado más notable es que la conciencia medioambiental reduce la frecuencia de uso del transporte compartido. Esto es coherente con la noción de que los individuos con actitudes pro-ambientales probablemente tienen una mayor propensión a preferir seguir utilizando el transporte incluso en presencia de una amplia disponibilidad de oferta de ride-hailing, particularmente en un entorno con una oferta intensiva de transporte público. La relación negativa entre la conciencia medioambiental y la frecuencia de uso contrasta directamente con otros resultados de ciudades estadounidenses.

Para el caso de San Francisco, un área metropolitana con una alta presencia de transporte público, Alemi et al. (2019) encontraron una relación positiva entre la conciencia ambiental y la frecuencia de uso de ride-hailing, pero no proporcionaron una interpretación para ello. La única variable sociodemográfica con un impacto estadísticamente significativo en la frecuencia de uso de ride-hailing es la ocupación; concretamente, los estudiantes presentan una menor propensión a utilizar frecuentemente el ride-hailing.

El lugar de residencia también influye en la frecuencia de uso del ride-hailing, además de su impacto en la adopción del ride-hailing. Los individuos que residen en el centro de la ciudad muestran un uso más intensivo de los servicios de ride-hailing en comparación con las personas que viven en otras zonas. Una vez más, este resultado confirma la relación entre la frecuencia de uso y la densidad de población encontrada en la literatura.

Según los resultados correspondientes a los efectos de las tasas de movilidad, los encuestados que realizan más de dos viajes durante el fin de semana tienen una propensión estadísticamente significativa a utilizar el servicio de ride-hailing con frecuencia. Este resultado subraya la importancia de incluir explícitamente los índices de movilidad general como variables explicativas en los modelos de frecuencia de uso del transporte compartido. La disponibilidad de vehículos presenta efectos similares en la propensión a la frecuencia de viajes en coche de alquiler, así como en la propensión a la adopción de viajes en coche de alquiler, ya que una mayor disponibilidad conduce a una mayor propensión al uso de viajes en coche de alquiler. En este contexto, las observaciones de Henao (2017) son especialmente relevantes.

Henao subraya el punto de que una persona que normalmente considera el coche como el principal modo de transporte puede ser más propensa a tomar ride-hailing para viajes de ocio (porque el ride-hailing se percibe como relativamente similar a los viajes en vehículo privado). Pero, en el caso de San Francisco, Alemi et al. (2019) observaron una relación negativa entre el uso de ride-hailing y la disponibilidad de vehículo propio. En la zona de Dallas, dominada por los coches, Lavieri y Bhat (2019) también observaron que la disponibilidad de vehículos reducía significativamente la frecuencia de ride-hailing.

5.1.5 Comparación del ajuste del modelo

La metodología GHDM utilizada en este modelo a nivel individual considera las seis variables endógenas de interés como una elección conjunta. La mejora en el ajuste de los datos a partir de la modelización conjunta de estas seis dimensiones de elección puede evaluarse comparando el modelo GHDM con un Modelo de Datos Heterogéneos Independientes (IHDM) que no considera la unión de las seis dimensiones (es decir, se ignoran las covarianzas generadas por los constructos latentes estocásticos en el modelo GHDM). En este modelo IHDM, introducimos las variables exógenas (variables sociodemográficas) utilizadas para explicar los constructos latentes como variables exógenas en las ecuaciones de la dimensión de elección. De este modo, la contribución a la parte observada de la utilidad debida a las variables sociodemográficas se mantiene (y se permite que varíe en relación con el GHDM para absorber, en la medida de lo posible, las covarianzas del GHDM debidas a los efectos no observados). El IHDM resultante puede compararse con el GHDM utilizando el criterio de información de probabilidad compuesta (CLIC) introducido por Varin y Vidoni (2005). El CLIC adopta la siguiente forma (tras sustituir la probabilidad marginal compuesta (CML) por la CML máxima aproximada (MACML)):

$$\log L^{*}_{MACML}(\overleftrightarrow{\widehat{\boldsymbol{\theta}}}) = \log L_{MACML}(\overleftrightarrow{\widehat{\boldsymbol{\theta}}}) - tr[\hat{J}(\overleftrightarrow{\widehat{\boldsymbol{\theta}}})\hat{H}(\overleftrightarrow{\widehat{\boldsymbol{\theta}}})^{-1}] \quad (1)$$

Se prefiere el modelo que proporciona un valor más alto de CLIC. Los valores del log $L_{MACML}(\overleftrightarrow{\widehat{\boldsymbol{\theta}}})$ para los modelos GHDM e IHDM se estimaron en -585.985 y -593.563, respectivamente, con los correspondientes valores del estadístico CLIC de -588.973,57 y -594.555,84. Estos estadísticos CLIC favorecen claramente al GHDM sobre el IHDM. Las variables indicadoras ordinales utilizadas en la ecuación de medición se incluyen únicamente con el fin de identificar el modelo y no sirven para predecir el conjunto de elecciones endógenas de interés una vez estimado el modelo. Por lo tanto, también podemos utilizar la conocida prueba de razón de verosimilitud no anidada para comparar informalmente los dos modelos. Para ello, evaluamos un valor de log-verosimilitud predictiva $L(\hat{\hat{\boldsymbol{\theta}}})$ de los modelos GHDM e IHDM utilizando los valores de los parámetros en los valores convergentes de GHDM, excluyendo las variables indicadoras y centrándose sólo en las cuatro variables endógenas de interés. Entonces, se puede calcular el índice de relación de verosimilitud ajustado de cada modelo con respecto a la log-verosimilitud con sólo las constantes:

$$\bar{\rho}^2 = 1 - (L(\hat{\boldsymbol{\theta}}) - M)/L(c) \quad (2)$$

donde $L(\hat{\boldsymbol{\theta}})$ y $L(c)$ son las funciones de log-verosimilitud predictiva en la convergencia y en las constantes, respectivamente, y M es el número de parámetros (sin incluir la(s) constante(s) para cada dimensión y sin incluir los indicadores ordinales) estimados en el modelo. Si la diferencia en los índices es $(\bar{\rho}_2^2 - \bar{\rho}_1^2) = \tau$, entonces la probabilidad de que esta diferencia pueda haber ocurrido por azar no es mayor que $\Phi\left\{-[-2\tau L(c) + (M_2 - M_1)]^{0.5}\right\}$ en el límite asintótico (sin embargo, esto es sólo una prueba informal, porque el uso del enfoque de inferencia MACML en lugar del enfoque tradicional de máxima verosimilitud cambia las propiedades asintóticas). Un valor pequeño de la probabilidad de ocurrencia del azar sugiere que la diferencia es estadísticamente significativa y que se debe preferir el modelo con el valor más alto del índice de relación de verosimilitud ajustado.

Los valores $L(\hat{\boldsymbol{\theta}})$ (número de parámetros) para los modelos GHDM y IHDM se calcularon en -2.657,58 (número de parámetros= 103) y -2.707,24 (número de parámetros= 95), respectivamente. El valor fue de -2.989,93. La prueba de razón de verosimilitud ajustada no anidada (en su versión informal utilizada aquí) devuelve un valor de Φ(-8,67), que es literalmente cero, lo que refuerza el resultado del estadístico CLIC más formal al rechazar el modelo IHDM en favor del modelo GHDM y subraya la importancia de considerar los constructos latentes estocásticos que generan covariación entre las dimensiones de elección.

5.2. Modelo a nivel de viaje

En esta sección se analizan los resultados del modelo correspondientes a las cinco dimensiones del último viaje en coche de alquiler del individuo: propósito, día de la semana, hora del día, compañía y modo sustituido. Los resultados de estas cinco dimensiones se presentan en la Tabla 7 y la Tabla 8, y se discuten a continuación. Estas tablas también proporcionan la log-verosimilitud en la convergencia de cada modelo individual, la log-verosimilitud sólo con constantes y el valor de la barra rho al cuadrado calculado como en la ecuación (2).

Todos los modelos muestran una clara mejora del valor de la log-verosimilitud en la convergencia con respecto a la log-verosimilitud con constantes solamente, por lo que no discutiremos los problemas de ajuste del modelo en el resto de esta sección.

5.2.1 Propósito de viaje

Los resultados del componente del modelo que representa el propósito del viaje se presentan en la Tabla 7. En la primera categoría de constructos latentes, sólo la variable VSL influye en el propósito del viaje, ya que los individuos con un VSL más alto están más inclinados a participar en el ocio en relación con otros propósitos.

Este resultado confirma la fuerte relación observada en el modelo a nivel individual entre el VSL, la movilidad de fin de semana, las actividades de ocio y el uso del transporte compartido.

Además, la propensión a compartir tiene un impacto positivo en la probabilidad de que el anterior viaje en coche compartido se realizara con fines de ocio. Las mujeres y las personas que no son estudiantes ni están empleadas parecen tener más probabilidades de haber utilizado el servicio de ride-hailing en su último viaje con fines de ocio. Este último resultado puede ser simplemente una manifestación del hecho de que aquellos que no están empleados y no son estudiantes son propensos a hacer más viajes de ocio en general que los que están empleados y/o son estudiantes. Por último, los viajes por encargo parecen ser menos probables entre los encuestados con un buen nivel de estudios, mientras que los viajes por encargo de los residentes que viven fuera de la ciudad de Madrid parecen realizarse más por motivos de trabajo que por otros motivos de viaje.

Variables (base category)	**Trip Purpose (base: airport or train/bus station)**						**Day of week (base: Monday-Thursday)**			
	Work-related		Leisure		Errands		Friday		Saturday-Sunday	
	Coeff.	p-value	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat
Latent variables										
ariety-seeking lifestyle			1.447	4.712						
ech-savviness										
nvironmental consciousness										
ropensity to share			0.953	1.896						
Gender (male)										
emale			0.479	2.054						
Age (under 25)										
5 to 34									0.460	1.812
5 to 49										
0 to 59										
bove 59										
Education (non-university)										
niversity studies					-0.890	-3.101				
Employment (employed)										
tudent or part/student										
ther: retired, unemployed, etc.			1.041	1.412						
Household structure (living alone)										
iving with flatmates										
ouple without children							-0.847	-2.196		
ouple with children below 24										
ouple with all children above 24										
ther									1.138	2.575
Residence (inside M30 ring)										
utside M30 ring										
utside Madrid city	1.024	3.096								
Trip purpose (airport or bus/train station)										
Vork-related									-2.564	-4.498
eisure							0.970	4.395	1.192	5.122
rrands										
Constant			1.895	4.761	0.640	4.867	-0.839	-4.672	-0.631	-4.996
Log-likelihood at convergence						-455.238				-279.532
Log-likelihood at constants						-566.400				-495.874
Rho-bar squared value						0.186				0.424

Tabla 7: Caracterización de la movilidad del ride-hailing en Madrid: resultados a nivel de viaje (Parte 1)

5.2.2 Día de la semana y hora del día

En cuanto al día de la semana en que se realizó el último viaje en coche de alquiler, la edad y la estructura del hogar parecen tener cierto impacto. Las personas de entre 24 y 35 años parecen ser más propensas a utilizar el servicio de ride-hailing durante los fines de semana, tal vez como resultado de que las actividades de ocio se concentran en los fines de semana y, en consecuencia, se incrementa el uso del servicio de ride-hailing durante los fines de semana.

El hallazgo más interesante es la fuerte relación entre los viajes de ocio por medio de ride-hailing y un uso más intensivo durante los últimos viernes o los días de fin de semana. Esto refuerza el fuerte vínculo entre los viajes de ride-hailing, el ocio y la movilidad de fin de semana. Por el contrario, los resultados indican un menor número de viajes relacionados con el trabajo por ride-hailing durante los fines de semana, de nuevo simplemente un reflejo de un menor número de viajes de trabajo realizados durante los días de fin de semana.

Los resultados relativos a la hora del día son coherentes con algunas de las observaciones ya realizadas, con:

- (1) menos viajes de ride-hailing por motivos de trabajo durante el período nocturno,
- (2) un mayor nivel de viajes orientados al ocio realizados por ride-hailing durante los períodos de tarde/noche y un menor nivel de viajes de ocio y recados en el período de la mañana, y
- (3) menos viajes de ride-hailing los viernes durante el período de la mañana, y mucho más viajes de ride-hailing durante los períodos de tarde/noche durante los fines de semana.

5.2.3 Acompañamiento y sustitución de modo

Los resultados de la compañía en los viajes indican que los encuestados con una menor propensión a compartir tienden a viajar solos. Como era de esperar, los individuos en hogares con pareja muestran una mayor probabilidad de no viajar solos, mientras que los viajes de ride-hailing para el ocio y los recados (en relación con los viajes al aeropuerto y al trabajo) son más propensos a realizarse en compañía. Asimismo, es más probable que los viajes de fin de semana se realicen en compañía.

Por último, presentamos los resultados para el modo sustituido por el ride-hailing. Curiosamente, los individuos con una mayor propensión a un estilo de vida de búsqueda de variedad habrían elegido el transporte público o la opción "otros modos", que incluye caminar, ir en bicicleta o "no habría hecho este viaje" (aunque esta categoría de "otros modos" está dominada por los modos activos). Este resultado implicaría que, dado que los hombres y los individuos más jóvenes tienen un VSL más alto, estos individuos tenderían a reducir su uso del transporte público o de los modos potencialmente activos en presencia del ride-hailing.

Este resultado también es coherente con el hecho de que, según el modelo a nivel individual, los encuestados con un estilo de vida más variado estarían menos orientados al coche en términos de propiedad/disponibilidad de vehículos privados, lo que llevaría a mayores niveles de sustitución entre el ride-hailing y el transporte público/los modos activos.

No obstante, este efecto puede anularse en parte en el caso de los individuos con mayor conciencia medioambiental, que son menos propensos a sustituir la "otra" opción por el ride-hailing. Además de los efectos latentes del constructo, las mujeres son menos propensas a abandonar el vehículo privado en presencia de los servicios de ride-hailing, mientras que las parejas sustituyen los viajes anteriores en vehículo privado por el ride-hailing.

La relación positiva entre vivir en un hogar con compañeros de piso y sustituir el transporte público refuerza el hallazgo de que los jóvenes perciben el ride-hailing como una opción atractiva frente al transporte público siempre que el coste del viaje pueda compartirse.

Variables (base category)	Time of day (base: afternoon and early evening)						Trip companion (base: alone)		Mode substituted (base: taxi)					
	Morning		Late evening		Night		Not alone		Private vehicle		Public transpor		Other	
	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat	Coeff.	t-Stat	Coeff	t-Stat
Latent variables														
Variety-seeking lifestyle											0.869	1.881	1.967	2.196
Tech-savviness														
Environmental consciousness													-0.603	-1.645
Propensity to share							-0.980	-1.866						
Gender (male)														
Female									-0.696	-1.675				
Household structure (living alone)														
Living with flatmates											0.657	1.943		
Couple without children							0.757	2.457						
Couple with children below 24							0.660	2.511	0.755	1.799				
Couple with all children above 24									1.165	1.881				
Other														
Trip purpose (airport or bus/train station)														
Work-related					-1.170	-1.530								
Leisure	-0.909	-2.053	1.009	3.098	2.043	5.103	1.228	5.654			0.553	1.911		
Errands	-0.928	-1.645					0.624	1.825	0.792	1.514	0.788	2.410		
Day of week (weekday)														
Friday	-0.826	-2.455												
Weekend			1.159	4.975	1.611	4.999	0.623	2.513			-0.591	-2.258	1.208	-2.458
Time of day (afternoon & early evening)														
Morning														
Late evening														
Night									-1.438	-2.650	-0.880	-3.100		
Trip companion (alone)														
Not alone											-0.419	-1.616		
Constant	0.725	5.122	-0.401	-1.812	-1.092	-5.267	-1.863	-5.321	-1.538	-5.197			-0.694	-1.812
Log-likelihood at convergence						-345.71		-396.545						-308.903
Log-likelihood at constants						-640.28		-631.852						-519.628
Rho-bar squared value						0.448		0.363						0.377

Tabla 8 –Caracterización de la movilidad del ride-hailing en Madrid: resultados a nivel de viaje (Parte 2)

Los resultados también muestran que el transporte de ida y vuelta ha sustituido al transporte público principalmente para los viajes de ocio y de recados, mientras que el transporte de ida y vuelta ha sustituido al coche privado para los viajes de recados.

Esto parece razonable porque las opciones de transporte de puerta a puerta son más convenientes cuando los viajes están encadenados (como es el caso típico de los recados) o cuando el individuo tiene que llevar mercancías pesadas (por ejemplo, los viajes relacionados con las compras). También podemos observar que el transporte público o los modos activos serían altamente sustituidos durante los fines de semana, lo que sugiere una alta demanda de viajes en coche durante el sábado y el domingo que puede aumentar la congestión del tráfico en los días de fin de semana. Por último, los resultados para el periodo "nocturno" indican que es menos probable que el "ride-hailing" reste opciones al vehículo privado y al transporte público, pero más probable que reste opciones al taxi y al modo activo durante el periodo nocturno. Esto puede ser el resultado de la percepción de una mayor seguridad asociada a los viajes en coche en comparación con los taxis y los desplazamientos a pie o en bicicleta por la noche. Por supuesto, aunque se puede explicar este resultado y todos los anteriores de más de una manera, existe una clara necesidad de investigar estos efectos con mucho más detalle en futuros estudios dentro del contexto de los patrones generales de actividad-viaje. Como se ha indicado en múltiples ocasiones, este análisis a nivel de viaje no es más que de carácter exploratorio.

5.3. Implicaciones de política

De los resultados del análisis a nivel individual y de viaje se pueden extraer algunas implicaciones políticas. Debemos señalar que se basan en los resultados de un contexto muy específico, en particular: una ciudad compacta con una presencia intensiva de transporte público, que ha implementado restricciones al uso de vehículos privados en algunas partes de la misma, y cuyos residentes presentan una notable conciencia medioambiental.

5.4 Transporte en coche y alternativas orientadas al automóvil

Según el modelo a nivel individual, el ride-hailing es adoptado y utilizado con mayor frecuencia por individuos con alta disponibilidad de vehículo privado. Henao (2017) se refirió a este comportamiento como bi-estilo, según el cual los conductores frecuentes utilizarían los servicios de ride-hailing más a menudo para viajes de ocio, pero no necesariamente para otros propósitos de viaje. De hecho, el análisis a nivel de viaje mostró que alrededor del 60% de los viajes de ride-hailing fueron captados desde alternativas orientadas al automóvil (es decir, vehículo propio y taxi; ver Tabla 3).

El efecto neto de esto sobre la demanda de tráfico y la congestión todavía necesita una evaluación adicional. Por un lado, el servicio de ride-hailing puede tener efectos positivos en caso de que los vehículos privados se mantengan fuera de las calles. En particular, se reduce la congestión relacionada con la búsqueda de aparcamiento por parte de los vehículos privados. Se estima que la búsqueda de aparcamiento contribuye a alrededor del 15-30% del total de los desplazamientos en el núcleo central de Madrid, por lo que su reducción sería muy beneficiosa para la congestión vial y la sostenibilidad urbana.

En caso de que el uso del ride-hailing crezca drásticamente y capte gran parte de los actuales viajes en vehículo privado, también se producirá un aumento de los viajes en vehículos vacíos (es decir, que viajan vacíos para recoger a un pasajero), lo que podría provocar por sí mismo graves problemas de congestión (véase Nair et al., 2020). Este hecho se ha observado en muchas ciudades como San Francisco (Rayle et al., 2016), NYC (Schaller, 2017), Denver (Henao & Marshall, 2019) o Shenzen en China (Nie, 2017), entre otras. Por otro lado, la sustitución del taxi por vehículos de ride-hailing es relativamente neutral desde el punto de vista de la sostenibilidad urbana.

5.5 El ride-hailing y el transporte público

Parece que el servicio de ride-hailing llena un vacío de servicio bastante importante al proporcionar oportunidades para participar en actividades de ocio durante los fines de semana y las noches. Durante los fines de semana y las noches, la oferta de transporte público es significativamente menor en Madrid, y por lo tanto el ride-hailing proporcionaría más oportunidades de movilidad en escenarios de baja accesibilidad. Por supuesto, el impacto sobre las empresas de taxis y los conductores sigue siendo un problema, y, como en los EE.UU. y otros países, las consideraciones de regulación justa y equitativa deben ser continuamente pensadas en este sentido.

A pesar de este efecto positivo de la accesibilidad, una parte bastante importante de la demanda de ride-hailing se capta del transporte público tanto en los días laborables como en los fines de semana, lo que contrasta con los valores más bajos de sustitución del transporte público por el servicio de ride-hailing en contextos dominados por el coche dentro de los Estados Unidos (Lavieri y Bhat, 2019). Por lo tanto, mientras que algunos usuarios del transporte público (especialmente los que tienen una alta conciencia ambiental) pueden no alejarse del transporte público, los usuarios previamente raros/ocasionales del transporte público podrían alejarse aún más de estos servicios, y potencialmente podrían dejar de considerar el tránsito como una opción para moverse por la ciudad después de la llegada de una alternativa cómoda de puerta a puerta. Esto también puede tener un impacto, aunque limitado, en los ingresos del tránsito. En cualquier caso, mientras los viajes en transporte público (e incluso los modos activos) sean sustituidos por el "ride-hailing", se producirá un aumento del kilometraje, la congestión y la contaminación atmosférica en los contextos urbanos. Una cuestión especialmente preocupante a este respecto es que, según nuestros resultados, el servicio de ride-hailing no sólo restará viajes al transporte público, sino también a los modos activos, especialmente durante los fines de semana.

Esto tiene la doble desventaja de aumentar la demanda de tráfico, así como de tener impactos potenciales relacionados con la salud debido a la reducción del modo activo (caminar y montar en bicicleta) de los viajes.

Una estrategia para reducir el uso del transporte público durante los fines de semana puede ser rediseñar el sistema de transporte público durante los fines de semana para complementar el sistema de transporte fijo reducido (desde los días laborables) con un patrón de servicio limitado que responda a la demanda para un mejor servicio puerta a puerta durante el fin de semana.

Una estrategia para desalentar la sustitución de los viajes de corta distancia "a pie" por el ride-hailing puede consistir en diseñar un sistema de precios para el ride-hailing que ponga un precio bastante elevado al primer kilómetro (excepto si el usuario tiene problemas de movilidad).

5.6 Consideraciones sobre la accesibilidad a la actividad y el ride-hailing

Una de las consecuencias de nuestros resultados es que, en Madrid, los servicios de ride-hailing parecen especialmente atractivos para realizar recados (como compras y otros asuntos personales). En concreto, los viajes de recados realizados en vehículos privados o en transporte público parecen ser sustituidos por el ride-hailing.

El cambio de los vehículos privados a los viajes a domicilio puede explicarse por una experiencia sin complicaciones y sin necesidad de conducir, mientras que el cambio del transporte público a los viajes a domicilio puede explicarse por la comodidad de llevar la compra. Pero otra de las razones de este cambio hacia el ride-hailing para los recados es que hacer recados suele implicar el encadenamiento de múltiples actividades en la misma salida de casa y/o implica llevar y almacenar alimentos y otros productos perecederos durante el viaje.

El servicio de transporte compartido no es el más conveniente para este tipo de encadenamiento porque es más un servicio de consumo basado en el viaje que una opción de transporte más amplia que permite un servicio de consumo rentable basado en el tiempo (en el que el mismo vehículo está disponible para llevar a cabo múltiples actividades y durante un período de tiempo prolongado).

Tal vez los proveedores de servicios de ride-hailing deban pensar en ofrecer también una opción basada en el tiempo, que combinaría efectivamente los actuales servicios de ride-hailing y de coche compartido en un solo servicio. Esto también puede tener la ventaja de reducir la congestión al hacer que un solo vehículo recorra la ruta de varias paradas deseada por un solo cliente en lugar de que varios vehículos hagan lo mismo. Con múltiples vehículos, los kilómetros de viaje en vacío aumentan a medida que cada vehículo se desplaza hasta el cliente en cada punto de parada.

Nuestros resultados también apuntan al hecho de que las personas mayores tienden a tener un menor conocimiento de la tecnología, así como a utilizar los servicios de transporte en coche mucho menos que sus compañeros más jóvenes.

Al mismo tiempo, la posible exclusión social debida a la disminución de la accesibilidad física de los mayores es una preocupación importante, ya que los países desarrollados, incluida España, se enfrentan al envejecimiento de la población (véase, por ejemplo, Walsh et al., 2016 y King, 2016). Dado que no parece probable que este segmento de edad avanzada se beneficie sustancialmente de los servicios de ride-hailing como una mejora general de la accesibilidad con el statu-quo, pueden ser beneficiosas las campañas de información y las acciones para aumentar sus niveles de conocimiento de la tecnología y la aceptación del ride-hailing como un nuevo servicio que puede abrir nuevas posibilidades de socialización para ellos.

5.7 El ride-hailing y la sostenibilidad urbana

En general, el ride-hailing puede mejorar la accesibilidad de determinados segmentos de la sociedad y la seguridad en las carreteras. Sin embargo, las posibles consecuencias del ride-hailing en la futura sostenibilidad urbana siguen siendo motivo de gran preocupación y requieren un análisis más detallado para diseñar una vía sostenible que permita integrar estos servicios en el panorama de la movilidad urbana. Al fin y al cabo, es probable que la adopción y la frecuencia de uso de los servicios de ride-hailing aumenten en los próximos años con el aumento de los conocimientos tecnológicos de la población. Además, la evolución del cambio climático aumentará la conciencia medioambiental de los residentes, lo que llevará a una mayor implantación de las restricciones al uso del coche en los centros urbanos y a un menor uso del vehículo privado. Además, el parque automovilístico tenderá a ser más limpio con el paso de los años.

En este escenario futuro, el ride-hailing se convertiría en una alternativa más atractiva y podría aumentar sustancialmente su demanda respecto a su nivel actual. Por esta razón, buscar la coordinación o integración con los servicios de taxi será esencial para evitar el exceso de flotas y limitar el impacto en la congestión debido a los viajes en vacío. Además, es necesario regular la evolución del ride-hailing en entornos de tránsito intensivo para evitar que se produzcan desplazamientos masivos de las alternativas de transporte público; al fin y al cabo, el transporte público representa en última instancia la columna vertebral de la movilidad general en las ciudades grandes y densas.

6. CONCLUSIONES Y FUTURAS INVESTIGACIONES

En este trabajo se han estimado dos modelos de elección para explorar la adopción y la frecuencia de uso del ride-hailing en una ciudad europea, tomando como caso de estudio Madrid (España). A partir de la investigación, hemos podido obtener algunas conclusiones interesantes.

En primer lugar, al igual que en otras partes del mundo, los usuarios de ride-hailing de Madrid también tienden a ser individuos jóvenes, bien educados y ricos, que están familiarizados con las nuevas tecnologías.

Además, el análisis reveló la importancia de separar los patrones de los días de la semana y de los fines de semana al modelar la demanda de ride-hailing. Esto se debe a la fuerte relación que existe entre el uso del ride-hailing y las actividades de ocio, especialmente en las sociedades extrovertidas como la mediterránea.

En segundo lugar, la investigación mostró el papel clave de la conciencia medioambiental y la propensión al uso del coche en las ciudades de tránsito intensivo. Ambos presentan efectos significativos en relación con el uso del ride-hailing. En comparación con las ciudades estadounidenses, las actitudes favorables al medio ambiente reducen el uso de las opciones orientadas al coche (tanto el vehículo privado como el ride-hailing) en favor de modos respetuosos con el medio ambiente como el transporte público. En consecuencia, la adopción y la frecuencia de uso del servicio de "ride-hailing" fueron significativamente mayores entre las personas propensas al uso del coche, para las que la comodidad ofrecida por los servicios de puerta a puerta es crucial, y que pueden adoptar el servicio de "ride-hailing" para viajes relacionados con el ocio. Estos resultados se encuentran en un contexto con una oferta intensiva de transporte público y restricciones al vehículo privado en el centro de la ciudad, lo que difiere de los anteriores estudios de casos estadounidenses analizados en la literatura.

En tercer lugar, la mayoría de los viajes de ride-hailing de la muestra sustituyeron a las opciones orientadas al coche (vehículo privado y taxi), aunque también se capta una parte importante de los modos respetuosos con el medio ambiente, como el transporte público y los modos activos. Esta conclusión pone de manifiesto que, junto con los aspectos positivos del ride-hailing (aumento de la accesibilidad para algunos segmentos vulnerables de la población o mantenimiento de los vehículos privados fuera de las calles), pueden surgir algunos efectos negativos, como una disminución de los ingresos de los operadores de transporte público o un aumento de los viajes en vacío realizados por los vehículos de ride-hailing, como se ha observado en muchas ciudades de todo el mundo. Por lo tanto, las compensaciones también deben ser evaluadas cuidadosamente. Aunque el ride-hailing parece elegirse actualmente en situaciones muy específicas, el atractivo de estos servicios frente al transporte público debería reconsiderar el futuro papel de este nuevo actor dentro de la movilidad urbana y la sostenibilidad.

Nuestras conclusiones sugieren varias direcciones futuras de investigación. Son necesarias futuras contribuciones para ampliar la investigación actual a otros países europeos en los que las dinámicas sociales y de movilidad difieren de las del Mediterráneo, como en Europa Central o del Este. Además, habría que estudiar cómo cambian las percepciones y el uso de los servicios de ride-hailing en escenarios con mayores restricciones al vehículo privado (por ejemplo, las políticas de tarificación de la congestión en Londres o Singapur) en comparación con los estudios de caso ya analizados. Por último, la competencia entre el servicio de ride-hailing y los principales modos de transporte sustituidos (el taxi y el transporte público) debería explorarse más a fondo, dada su importancia para comprender el papel actual y futuro del servicio de ride-hailing en la sostenibilidad urbana.

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NEW URBAN MOBILITY OPTIONS: ALTERNATIVE FUTURES AND THEIR IMPACT IN TRANSPORT PLANNING TECHNIQUES

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ABSTRACT

The acceleration of technology evolution is changing urban mobility at a much faster pace than we have seen in previous decades, leading to an increasingly uncertain future within this field. It is very likely that current transport planning tools and techniques will have to be adapted to the increasing number of innovative mobility forms in order to maintain their usefulness in the urban policy cycle. In this paper, we present a series of explorative scenarios for European urban mobility and the consequent challenges that they imply for such tools and techniques. Two groups of scenarios have been developed for assessing two different uncertain relations. First, a set of exogeneous scenarios has been defined for studying how different urban mobility socioeconomic contexts could affect the evolution of emerging mobility solutions. These scenarios are adaptations of the IPCC's Shared Socioeconomic Pathways. Second, a set of pathways that these mobility innovations may follow has been shaped in order to determine to what extent each innovation will potentially pose new requirements on transport data sources, models and decision support tools. The methodology used for developing the scenarios started by a literature review covering the most prominent urban mobility trends.

Then, policy-makers and modellers were engaged in the process through a series of workshops and a Delphi poll. This served to gather inputs from a wide range of end-users and practitioners. The paper covers the results from these methodologies, unveils the resultant scenarios, and outlines the conclusions in terms of future plausible requirements for transport planning tools and techniques.

1. INTRODUCTION

Urban mobility is a dynamic field that is subject to continuous innovation. Different technologies and business models arise to meet the increasing demand for transportation in cities. In recent years, the rapid development of automation and digitalization technologies together with the expansion of shared economy has fuelled the emergence of new mobility solutions. Smartphone connectivity and advanced fleet management strategies based on GPS positioning have boosted the potential of vehicle sharing, either by providing users with a vehicle to drive (e.g., car sharing, bike sharing, e-scooter sharing) or by attending a trip request providing a car with a driver (e.g., ride hailing). In parallel, Mobility-as-a-Service (MaaS) platforms provide travellers with access to a unified gateway to plan, book and pay for a full multimodal door-to-door journey, so the user does not have to worry about who operates each service. All these innovations will face further transformations due to vehicle automation. CAVs are expected to revolutionise bus operation and boost services such as ride hailing, which is likely to become cheaper than current taxi-like services once no driver will be needed.

It has been recently acknowledged that the data analysis techniques, modelling frameworks and decision support tools used by transport planners require major adaptations to properly address emerging mobility solutions (Franco et al., 2020). The requirements guiding these adaptations depend on which will be the indicators and analyses most demanded in the future. Some prominent challenges that are highly likely to arise in any case have been already identified, such as the supply-demand interaction mechanisms in shared mobility services (Li et al., 2018) or the empty trips modelling in the context of vehicle automation (Friedrich et al., 2019).

However, any attempt to improve transport planning tools and techniques in this direction would benefit from more knowledge on the plausible future needs of transport stakeholders. This encompasses two main questions. First, it is highly uncertain how the societal and technological trends surrounding transport systems will evolve. Hence, it is not possible to anticipate a narrow development path for emerging mobility solutions. Second, it is highly uncertain which are the impacts and challenges that cities will face due to the expansion of mobility innovations. This implies that it is difficult to establish requirements for the tools and techniques that will assist transport planners in the implementation and management of new mobility solutions.

Given the importance of anticipation when evaluating the impacts of their decisions, transport stakeholders have usually resorted to scenario-making techniques. The provision of transport infrastructures and services has been traditionally based in deterministic estimations of future demands (Owens, 1995). These forecasts rely on the observed relation between historic travel demand trends and external socioeconomic variables. This approach has been criticized for failing to account for the inherent uncertainties of future travel behaviour (Lyons & Davidson, 2016). In the case of emerging mobility solutions this critique becomes more evident, as there is simply no enough historical data to infer how the demand for the new services will respond to different contexts. As a consequence, deterministic forecasting is ill-suited for anticipating the requirements that transport planning tools and techniques will face as a consequence of the expansion of mobility innovations. Instead, the development of alternative plausible futures seems to provide richer requirements that will lead to more resilient tools and techniques. In line with the two questions mentioned above, two types of scenarios have been developed:

- Exogeneous scenarios, which propose different alternative futures for a series of relevant external factors that shape transport systems (e.g., demographics, economics, etc.). These scenarios can be used to reflect upon the evolution of new mobility solutions in relation to those variables (e.g., for a given socio-demographic situation, what is the expected penetration of vehicle automation?).
- Endogenous mobility-related scenarios, which set up a range of different possible futures for emerging mobility solutions themselves (e.g., business models, levels of adoption, etc.). These scenarios can be used to reflect upon the adaptations that transport planning tools and techniques require depending on the role of these solutions in cities (e.g., for a given modal share of micromobility services, which improvements in transport models are needed?).

The use of these scenarios in stakeholder involvement opportunities facilitates the anticipation to the plausible range of demands that transport stakeholders will pose on data analysis techniques, modelling frameworks and decision support tools.

This paper explains how these future images can be created, describes the scenarios developed and shows how they can be used for exploring the future impact of mobility innovations in transport planning tools and techniques, taking shared mobility services as an example. The document is organised as follows: Section 2 provides the theoretical background for the scenario-making process, Section 3 explains the methodology followed for developing the scenarios, Section 4 presents the exogeneous scenarios for European urban mobility, Section 5 presents the endogenous scenarios related to shared mobility services, Section 6 shows how the scenarios were used to explore the uncertainties associated to shared mobility and its impacts on transport planning tools and techniques, and Section 7 summarises the research conclusions.

2. MOBILITY FUTURES AND SCENARIO-MAKING TECHNIQUES

The acceleration of societal and technological transformations during the 20th century led to a growing interest in the development of rigorous methods for foresighting (Masini, 2006). Future reflections have evolved from individual practices, linked to instinct and survival, to research approaches able to make meaningful contributions to humankind development (Slaughter, 1996). The scientific foundations of this task have been developed by the field called 'futures studies' (Bell, 1997), where the plural 'futures' is emphasized to acknowledge that is hardly ever possible to anticipate a deterministic future (Sardar, 2010).

Scenarios are the main product of futures studies. The notion of scenario is not free from polysemy. Although it clearly resembles the idea of reflecting upon the future, there is no consensus on whether it includes any image of the future or only images drafted under certain conditions or for certain purposes. One of the most common approaches is to embrace a broad definition that includes any 'possible, probable or preferable future' (Amara, 1981; Bell, 1997). This conceptualisation is often accompanied by taxonomies that help to interpret existing scenarios or guide the processes towards new scenarios. Börjeson et al., (2006) provides a synthetic classification that is suitable to many contexts, based on what is the underlying question that motivates the use of scenarios (Table 1).

Predictive scenarios *What will happen…?*	Forecasts	*…if the most likely development unfolds.*
	What-if	*…on the condition of near future events.*
Explorative scenarios *What can happen if…?*	External	*…if an external factor develops.*
	Strategic	*…we act in a certain way.*
Normative scenarios *How can a desired future be reached…?*	Preserving	*…by adjusting the current situation.*
	Transforming (or 'backcasting')	*…by changing current structures.*

Table 1: Scenario types (Börjeson et al., 2006).

The scenarios developed in this paper fall under the category 'explorative scenarios'. They provide a range of possible alternative futures. First, there are no prior assumptions about their likelihood. All of them must be plausible, to pose meaningful questions to transport practitioners, but none is developed to accurately predict the future. Second, there are no prior assumptions about their desirability. There is no prescription of a certain future associated to certain policies, since the goal is to test how transport planning tools and techniques would respond to different future mobility contexts and situations.

More specifically, all the alternative futures addressed in this paper can be classified as 'explorative external scenarios', given that the images are not based on decisions made by the target agents -those who develop transport planning tools and techniques-. Rather, the images are a result of complex societal changes and policy trends that provide a framework for action.

3. SCENARIO-MAKING METHODOLOGY

The scenario-making process conducted to generate the futures presented in this paper involved three steps:

- a desk research phase, which consisted of a literature review of previous initiatives that provide referential scenarios
- a generation phase, which produced an initial version of the scenarios by tailoring the ideas and concepts selected from the referential scenarios; and
- an stakeholder involvement phase, which included a Delphi poll aimed at refining the initial version of the scenarios with target agents.

3.1 First phase: referential scenarios from desk research

A total of 22 references were selected as a basis for the scenario-making process (Table 1). The selection of documents prioritised those focusing on transport sector, as well as those having Europe as geographical scope. As a result, a large number of different types of scenarios were reviewed.

Normative scenarios and R&D roadmaps	(Dotter et al., 2019; Eckhardt et al., 2017; ERTRAC, 2011a, 2011b, 2013, 2017; ERTRAC-ERRAC-Waterborne-ACARE-ECTP Task Force, 2013; European Commission, 2011; Lindsay, 2016; MaaS Alliance, 2017, 2019; Mobility4EU, 2019)
Explorative scenarios	(de Stasio et al., 2013; European Commission, 2017; Hill & Bates, 2018; Lutz et al., 2019; POSSUM, 1998; Seibt et al., 2012; Transport for NSW, 2016; TRANS-TOOLS, 2009)
Predictive scenarios	(de Stasio et al., 2013; Holden & Goel, 2016)
Mobility indicators	(WBCSD, 2015)

Table 1: References used as a basis for the scenario-making process.

The literature review was not restricted to the above selected references. In some cases, the documents led to discover other initiatives that have also worked with scenarios. Thus, a 'snowball sampling' technique was followed to ensure that a wide range of relevant scenario-making processes were reviewed. For each scenario contained in these documents, the following aspects were explored:

- the factors and elements that inform each scenario
- the temporal scope of the scenario and the criteria employed for its selection; and
- the links established between mobility futures and the evolution of socioeconomic variables.

3.2 Second phase: generation of the scenarios

The generation of the scenarios involves three tasks. First, certain factors identified in the referential futures are selected as candidates for their inclusion in the scenarios, together with predefined factors that may not be part of previous studies. In the case of exogeneous scenarios, the criteria that drives the selection is the impact of each factor on urban mobility. In the case of the endogenous scenarios, the criteria focus on how the factors contribute to a complete description of alternative mobility futures.

Second, all the factors that are expressed in global terms in the referential scenarios have to be geographically downscaled to the European urban context. Most of the quantitative factors are already segmented by continent in the original source (e.g., demographic figures) and others have been previously analysed either at European or at urban level by additional studies. Moreover, most of the qualitative trends refer to common situations in the well-developed countries, so no particular adjustments are needed (e.g., digitalisation). The factors that are not appearing in previous sources can be derived from the evolution of other dependent factors.

Finally, the resultant evolution of the factors is put together into narratives that provide a short description of the alternative future. In the case of the exogeneous scenarios the narratives are complemented with some basic quantitative figures.

3.2 Third phase: stakeholder involvement

The involvement of target agents is crucial for achieving robust scenarios (Larsen & Gunnarsson-Östling, 2009). In this case, the scenarios were contrasted with transport experts through a two-round Delphi poll conducted during Autumn 2019. This process engaged 16 respondents from transport administrations (50%), transport consulting firms (25%) and academia (25%). The feedback got from the participants in the first round was taken into account to provide a final version of the narratives.

4. EXOGENEOUS SCENARIOS FOR EUROPEAN URBAN MOBILITY

4.1 Socio-shared Socioeconomic Pathways (SSPs) and urban mobility

The desk research phase revealed that climate change research is a valuable source of exogeneous scenarios for transport applications. Anthropogenic climate change research deals with complex systems with a high degree of uncertainty. This implies that these researchers often rely on future scenarios to pose alternative evolutions of the systems involved in climate change (Moss et al., 2010). The production of climate change scenarios has been coordinated by the International Panel on Climate Change (IPCC). This organisation promotes and certifies a set of official scenarios that can be used as a common language by the climate change research community. It is possible to identify two strategies in the production of scenarios along the history of climate change research.

Until 2008, IPCC worked with sequential cause-effect scenarios, which posed certain assumptions on socioeconomical factors to justify different emission levels, which in turn produce different effects and impacts in climate. In 2008, IPCC decided to decouple socioeconomical scenarios from emission scenarios. Two reasons are behind this move (Moss et al. 2010):

- shorten the long process required by the sequential approach; and
- explore with more detail certain relations that were demanded by scenario users, such as adaptation measures effects (van Vuuren et al., 2011).

Therefore, there are currently two groups of climate change scenarios:

- Shared Socio-economic Pathways (SSPs), which focus on population, GDP and urbanization rate. They provide five alternative narratives describing how the societal, political, cultural and economic context may develop, in order to represent five levels of mitigation and adaptation challenges towards climate change (O'Neill et al., 2014).
- Representative Concentration Pathways (RCPs), which focus on the concept of radiative forcing, an indicator of the changes of energy flows into the Earth system caused by greenhouse gases (IPCC, 2014). These scenarios integrate the research conclusions about the possible evolutions of greenhouse gases concentrations and land uses (van Vuuren et al. 2011), which are the main components of radiative forcing.

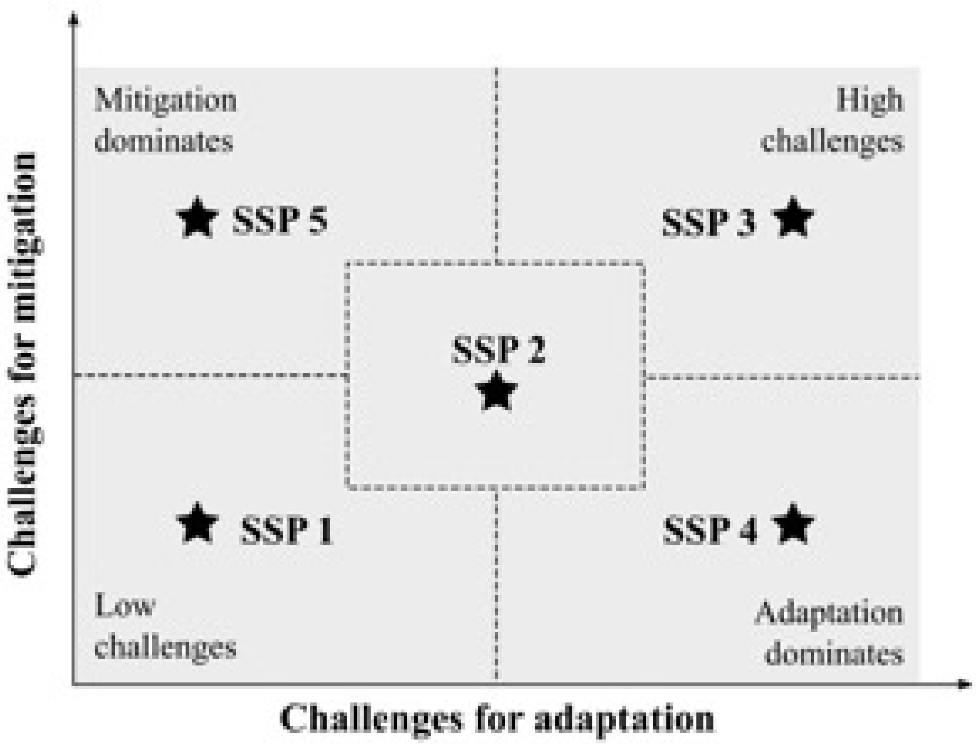

Figure 1: SSPs in the 'adaptation-mitigation challenges space' (O'Neill et al., 2014)

In this context, it is clear that the SSPs developed by the climate change research community have a great potential for inspiring exogeneous scenarios that provide several alternative contexts where urban mobility will have to operate.

There are five SSPs. Each of them produces different challenges for adaptation and mitigation of climate change (Figure).

A complete description of the narrative and the quantitative figures associated to each scenario is available in O'Neill et al. (2017). Each scenario can be summarised as follows:

- SSP1 represents low challenges both for mitigation and adaptation, since society embraces Sustainable Development Goals (SDG) which facilitates an environmental and social sustainable growth.
- SSP3 represents high challenges both for mitigation and adaptation, since the high rivalry among worldwide regions would limit growth and governance capacity for achieving robust agreements.
- SSP4 implies high challenges for adaptation but low challenges for mitigation. This represents a two-speed society, where an upper class would be able to adopt sustainable life-styles helping to mitigate climate change, but the material restrictions suffered by the lower class would limit their capacity to adopt mitigation measures.
- SSP5 implies high challenges for mitigation but low challenges for adaptation. It assumes that technology will be ready to adapt society to climate change, but also that there are no incentives for mitigation.
- Finally, SSP2 is an intermediate scenario where neither mitigation nor adaptation challenges dominate.

It is possible to identify a set of advantages for the application of SSPs in the generation of exogeneous scenarios for European urban mobility:

- There are many studies that already make references to SSPs as a source for further scenario-making processes, providing values for indicators that are relevant to urban mobility.
- IPCC is a very well-known institution and the reports they produce using SSPs as a basis are highly disseminated among research communities and public opinion.
- Many climate change adaptation and mitigation factors are also relevant for the future of transport (Banister, 2011).

There are also some limitations that need to be taken into account when using SSPs for the purposes stated in this paper:

- Given that SSPs have been produced for the specific field of climate change research, there might be mismatches between the needed contents for the scenarios (Kok et al., 2019). However, it is expected that the aforementioned relation between climate change impacts and the transport sector will limit this effect.
- The spatial scope of SSPs is global, while the application seeked in this paper is European. Therefore, SSPs contributions need to be downscaled to European urban areas for being relevant to urban mobility. Downscaling can be problematic, since it assumes that the resulting local scenario will not deviate significantly from the original scenario (Absar & Preston, 2015; Pedde et al., 2019). The consistency during the downscaling process can be ensured by adopting similar approaches to previous research. In this case, there are examples of both European (Kok et al., 2019) and urban (Rohat et al., 2019; Terama et al., 2019) downscaling processes. In addition, the stakeholder involvement phase represents an additional opportunity to improve the adjustment of the alternative futures to the European urban context.

4.2 Adapting SSPs to European urban mobility drivers

The literature about SSPs and their applications provide a set of factors that can be included in the exogeneous scenarios. Each factor selected has specific needs in terms of geographical downscaling and sectoral application, as mentioned in the Methodology section. The following factors are selected to take part of the exogeneous scenarios:

4.2.1 Population growth, urbanisation rate and ageing

These quantitative factors are included in the global SSPs. The models from the International Institute for Applied Systems Analysis (IIASA) provide population forecasts for each SSP at continental level, and a detailed discussion of the results can be found in Kc & Lutz (2017). The US National Center for Atmospheric Research model has produced indicators related to urbanisation rates for each SSP. A discussion of the results can be found in Jiang & O’Neill (2017).

4.2.2 Education levels.

The proportion of citizens with tertiary education is provided also by IIASA models and discussed by Kc & Lutz, (2017) and Kok et al., (2019).

4.2.3 Gross Domestic Product (GDP)

This economic indicator is forecasted for each scenario by IIASA model, and discussed by Crespo Cuaresma (2017). Economic development is also part of European SSPs (Kok et al., 2019).

4.2.4 Technological development

The levels of technology advancements associated to each scenario are included in the SSPs global narratives (O'Neill et al., 2014) and in the European version by Kok et al. (2019).

4.2.5 Environmental consciousness

Each SSP implies a level of environmental consciousness among society. This is described in the global narratives (O'Neill et al., 2014) as well as in the European version (Kok et al., 2019).

4.2.6 Consumption levels

Depending on the economic trends, each SSP is linked to certain consumption trends, which are described in the narratives (Kok et al., 2019; O'Neill et al., 2014).

4.2.7 National income inequality

Income distribution is included in the global SSPs narratives (O'Neill et al., 2014) and is part of the definition of each European scenario in Kok et al. (2019). The role of inequality has been further analysed by Rao et al. (2019), leading to the following conclusions:

- SSP1: low inequality
- SSP2: medium inequality
- SSP3: medium-high inequality
- SSP4: high inequality
- SSP5: low inequality

4.2.8 Land use in cities and urban form

Land uses interact with transport supply and demand features. SSPs include urbanisation rates but they do not address how population is allocated in urban areas. However, the narratives and quantitative features of SSPs suggest correlative trends in urban form evolution.

The evolution of consumption preferences and the population pyramid can be related to preferred residential settlements and availability of land for other purposes (Rohat et al., 2019; Terama et al., 2019):

- SSP1: urban + suburban preference / overall increasing density
- SSP2: not addressed
- SSP3: suburban preference / decreasing density in suburban areas
- SSP4: urban preference / increasing density in urban areas
- SSP5: rural + suburban preference / decreasing density in suburban areas

4.2.9 Pride of ownership vs. shared economy

A contextual factor that is perceived as relevant for emerging mobility solutions is to what extent shared economy is going to challenge (vehicle) ownership models.

This aspect is not addressed by studies based on SSPs, but it is possible to look at the factors behind the intensity of the adoption of shared economy (Hawlitschek et al., 2016): there is a motivation for saving money (Böckmann, 2013) and it is driven by a trust-based collaborative lifestyle (Heinrichs, 2013).

Since economic prosperity and incentives to collaboration are central elements to SSPs, there is an opportunity for formulating an evolution of the pride of ownership in contrast to adoption of shared economies for each scenario:

- SSP1: much higher trust + higher growth → lower pride of ownership
- SSP2: medium trust + medium growth → medium pride of ownership
- SSP3: much lower trust + stagnated growth → high pride of ownership
- SSP4: lower trust + medium growth → medium pride of ownership among higher class, high pride among lower class
- SSP5: medium trust + much higher growth → high pride of ownership

4.2.10 Digital divide

Many emerging mobility solutions depend on the use of smartphones and Internet for the interaction of the end users with the services providers. Hence, the evolution of the digital divide plays a role in the spread of the new mobility options.

While SSPs do not address the evolution of the digital divide, it is clear that this is related not only to age but to income distribution (Haight et al. 2014). Economic indicators related to each SSPs and ageing can be associated with the intensity of the digital divide in each scenario:

- SSP1: high ageing + low inequality → medium divide
- SSP2: medium ageing + medium inequality → medium divide
- SSP3: low ageing + medium-high inequality → medium divide
- SSP4: limited ageing + high inequality → high divide
- SSP5: medium ageing + low inequality → low divide

4.2.11 E-commerce

Shopping trips generation rates might be lower due to the generalisation of e-commerce (Shi et al., 2019). While e-commerce is not directly addressed by SSPs, there are many factors included in these scenarios that have an impact in the potential evolution of e-commerce.

Societal trust, technology advances, urbanisation rate, education, consumerism, interest in diverse products and availability of a wide range of payment methods has been linked to e-commerce adoption (Chaparro-Peláez et al., 2016; Markus & Soh, 2003):

- SSP1: low consumption + high-tech advances + high trust → moderate expansion of e-commerce
- SSP2: medium consumption + medium tech advances + medium trust → moderate expansion of e-commerce
- SSP3: medium consumption + stagnated tech advances + much lower trust → limited expansion of e-commerce
- SSP4: unequal consumption + high-tech advances + lower trust → moderate expansion of e-commerce
- SSP5: very high consumption + high-tech advances + high trust → wide expansion of e-commerce

4.2.12 Teleworking

Work trips generation rates can change if teleworking gains popularity (Alonso et al., 2017; Larson & Zhao, 2017). Telework is feasible in job positions that are largely based in ICT.

The technological development achieved by future societies may ease telework or expand its application to other sectors (Messenger, 2017). Furthermore, it has been observed that telework is more frequent in households with children (Vilhelmson & Thulin, 2016), so a link with fertility can be established as well. Fertility rates are part of the demographic forecasts of each SSPs (Kc & Lutz, 2017).

It has to be noted that this research was conducted before the COVID-19 pandemic, that has boosted teleworking at a much faster pace than expected. Regardless of the expansion driven by the pandemic consequences, the following can be expected:

- SSP1: high-tech advances + high rate of tertiary educated + low-medium fertility → moderate expansion of telework
- SSP2: medium tech advances + medium rate of tertiary educated + medium fertility → moderate expansion of telework
- SSP3: stagnated tech advances + low rate of tertiary educated + low fertility → limited expansion of telework
- SSP4: high-tech advances + low rate of tertiary educated + low-medium fertility → moderate expansion of telework
- SSP5: high-tech advances + high rate of tertiary educated + high fertility → wide expansion of telework

Apart from the downscaling and application process behind the conceptualisation of the factors, two additional aspects have to be defined:

- The scenarios have to be related to a specific time horizon. A SSPs-based approach provide flexibility given that the models for quantitative figures are publicly available and can be used up to 2100. In this case 2050 was used, according to the European urban mobility policies furthest horizon.
- The convenience of a middle-of-the-road scenario. SSPs do include an intermediate scenario (SSP2). In this case only extreme scenarios have been used: by developing an even number of scenarios there is no central future that can be confounded with a predictive scenario (Moss et al., 2010).

4.3 A set of exogeneous scenarios for European urban mobility

The result of the generation phase is a set of four narratives for alternative future context of urban mobility in Europe, together with quantitative figures coming from the corresponding SSP model (Table 2).

Indicator	Sc. 1	Sc. 2	Sc. 3	Sc. 4
EU GDP/PPP annual average growth	+3.0%	+0.9%	+2.5%	+4.9%
EU population total growth	+6.9%	-9.1%	-1.1%	+18.1%
EU urban population growth	+20.7%	-4.4%	+9.3%	+33.4%
EU population over 65 years (2018: 19.7%)	33.8%	31.3%	32.9%	30.7%
EU population aged 30-34 years with tertiary education (2018: 40.7%)	70.5%	31.9%	26.5%	70.6%

Table 2: Quantitative figures associated to each exogeneous scenario (2050).

4.3.1 Scenario 1 – Mixed compact cities in a sustainable Europe (SSP1)

“European society shifts towards sustainability driven by the generalisation of environmental concerns and the popularity of sustainable development goals in public opinion. Changes are reflected both in urban daily life, with lower consumption and higher trust among citizens, and in urban governance, with higher cooperation between authorities. Access to public services is generalised limiting urban segregation and inequalities. The strong efforts for completing the energy transition have boosted European economy, with cities demanding many qualified workers for the green industry. Renewable energies and small-scale storage solutions provide relatively cheap and versatile energy to European cities. The benefits generated by high-tech green industry are reinvested in improving public services, increasing social equality across urban areas. Improvements in life expectancy of all population layers result in an elder population, but with a limited digital divide thanks to the integration measures. Specialty products are delivered by green e-commerce but convenience products are based on proximity and purchased through local consumer communities. Telework is a feasible tool for improving work-life balance, but it is not highly demanded.

Pride of ownership is declining and urban citizens seek collective solutions to daily-life problems. Urban sustainable life-styles are popular and accessible, attracting people to densified urban cores. The high demand for residential areas impacts suburban rings, that become much denser, and are also attractive for certain people given the proximity to natural parks. There are almost no greenfield developments. Mixed compact developments within urban cores host offices and high-tech industry."

4.3.2 Scenario 2 – Stagnant individualist cities in a nationalist Europe (SSP3)

"European society becomes dominated by a climate of distrust where individual and national interests have priority over collective and global targets. Environmental concerns are a residual driver for citizens, so people consume as much as their limited economic resources enable. Few households have managed to improve their living conditions, even in the upper classes. Clean energy research programs suffered from a lack of funding, so fossil fuel dependency remains stable. Tensions between global regions have an extraordinary impact on energy prices in Europe given the lack of own resources. E-commerce becomes standard for specialty products but the limited growth is a barrier for a definite expansion. Telework is only used by qualified workers. Elderly people have limited access to the latest technological developments. Ownership is not only related to a certain social status but also key for feeling safe given the successive economic crises and the security concerns in cities.

The degradation of urban cores intensifies and there is limited demand for living in dense areas, which are associated with high crime levels and high pollution. Urbanisation rate slows down in Europe and the increasing need of national supply of food and energy have reactivated rural areas and the suburban ring of small cities, where low density developments become more and more extensive. Industries remain in current locations and do not need more space due to the economic stagnation. However, offices and institutions tend to move from urban cores to suburban areas."

4.3.3 Scenario 3 – Segregated green cities in an unequal Europe (SSP4)

"European society is unable to limit the growth of inequality in the continent. On the one hand, a highly educated cohort achieves high incomes thanks to the flourishing green economy. Business and political power are concentrated in this exclusive population layer, which is worried about climate change. On the other hand, large sectors of the society fail to improve their conditions due to limited public education investments. They struggle to access a European labour market where old low-tech industry is not generating as many jobs as in the past. There is progress in the energy transition towards renewable sources, but these are still not accessible to everyone due to high prices. Elites rely on e-commerce for almost all products but face-to-face trade still holds for the rest of the population. Similarly, upper classes are familiar with telework, while unemployment and precariousness are the rule among lower income communities. The limited fertility rates lead to an ageing population.

Retirees from higher-income classes have much better access to technology than those from lower-income groups. While ownership is not trendy among urban upper-class, larger lower-income population perceives ownership as positive for achieving social status. The taste of upper classes for creative environments have fuelled the completion of gentrification processes in European urban city centres, limiting suburban growth and low-density developments both in large and small cities. Lower-income groups tend to live in high-density neighbourhoods with stretched social services. Leading high-tech industry settles in the renovated industrial areas within the urban cores, since proximity to the workplace is highly valued by qualified workers."

4.3.4 Scenario 4 – Sprawling technological cities in a vibrant Europe (SSP5)

"European society experiences a period of prolonged growth thanks to the development of climate change adaptation technologies and the cheap energy prices. There is no special consciousness on the effect of the lifestyle on the environment, since technology keeps most people away from the consequences of the nature degradation. As a result, consumption trends move towards resource intensive lifestyles. Fossil fuels are still the main energy source since the exploitation of new deposits is now possible and much cheaper than before, opening the room for the large-scale extraction of shale gas. This benefits European countries and cheapens energy.

There is extensive and promising research related to adaptation measures to issues such as sea level rise or extreme weather effects, with big investments in new smart infrastructures.

E-commerce and teleworking boost allow people to live in small cities and work for companies based in big cities, causing small cities to grow above average. Face-to-face commerce is residual. The high fertility rates spurred by good economy perspectives limit European population ageing. The efforts to enhance human and social capital limit digital divide, although rapid changes in technology make it hard to keep the pace for some elder people. Given societal convergence, pride of ownership is not related to social status but to a strong sense of freedom in cities and their surroundings. Suburban areas become attractive and host the major part of the urban population growth in large cities. Larger properties are highly demanded and therefore many rural municipalities become suburban."

5. ENDOGENEOUS SCENARIOS FOR EUROPEAN URBAN MOBILITY

5.1 'Plausible yet challenging' scenarios

The purpose of endogenous scenarios is to depict different implementation levels and business models of the mobility innovations. As it is the case with exogeneous scenarios, these are explorative alternative futures that have to be plausible but challenging, in order to stimulate creative thinking among the target agents (Banister & Hickman, 2013). The factors analysed for the development of the endogenous scenarios are discussed in detail in Burrieza-Galán et al. (2021).

Three elements were crucial:

- *Particular coverage of each innovation*. In order to emphasize the particularities of each solution, it was decided to separate them and prepare tailored groups of scenarios. Hence each of the following innovations are associated to a group of scenarios: carsharing services, micromobility services, Demand Responsive Transport services, Connected Autonomous Vehicles, Urban Air Mobility and Mobility-as-a-Service.
- *Number of scenarios for each innovation*. In order to keep the number of scenarios manageable but cover alternative evolutions, the approach selected was to provide two opposite scenarios for each innovation. This allows the target agents to better perceive the full range of effects that the development of emerging mobility solutions may entail for the tools and techniques under evaluation (Schwartz, 2012).
- *Temporal scope*. Some developments can take decades to materialize while others may require less time. This implies that the richness of the set of scenarios can benefit from using two different temporal scopes. Following the same criteria than for the exogeneous scenarios, 2050 was set as a limit and 2030 was used as an intermediate milestone, in line with European policy targets.

5.2 Endogeneous scenarios for shared mobility service in Europe.

As mentioned above, the endogeneous scenarios cover up to six different mobility innovations. The complete set is reported in (Burrieza Galán et al., 2021). Here, the two pair of scenarios most closely related to shared mobility services are presented (carsharing and micromobility).

5.2.1 Alternative scenarios for carsharing services

5.2.1.1 Medium term

The electric carsharing operates as an additional transport mode in the cities. The implementation of stricter urban vehicle access regulations and parking management policies in the metropolitan areas imposes limitations in the use of the private cars.

The transport sector is characterized by multimodality, combining mass transport for long-haul trips and individual transport for last-mile. This situation combined with the high acquisition cost of the electric cars benefits the integration of sharing schemes in the transport sector increasing its modal share up to 20-25%.

Electric vehicle infrastructure has also been developed at certain urban areas in order to serves the increasing use of electric vehicles sharing schemes. Electric carsharing is fully integrated with public transport modes and the new mobility services offer more flexibility and better quality of combined transport options.

5.2.1.2 Long term

A holistic housing solution has been developed, which integrates aspects such as mobility, housing, energy distribution and ICT networks. In this scenario the electric sharing vehicle schemes are included in the modern collective housing policies. The different urban electricity needs throughout the day are balanced through smart energy grids. Thus, the holistic housing-mobility approach leads to an easily accessible community-based electric vehicle scheme are developed with low parking requirements. The large-scale implementation of this approach contributes to the homogeneous modal share of electric vehicle solutions.

5.2.2 Alternative scenarios for micromobility services

5.2.2.1 Medium term

Micromobility mainly substitutes other transport modes in short distance trips. The safety regulatory framework for micromobility has been defined in most cities and dedicated lanes for e-scooters and similar vehicles are provided to road users.

Thus, they are used for daily short distance trips instead of car and taxi rides since car ownership appears a decline especially in young people who prefer new transport modes based on pay-per-use rather than a car purchase mode. In addition, and once the policy framework has become mature, operators will be able to explore new business schemes openly pursuing pilot projects and market’s needs, since all of the competitors in the field are subjected to the same regulation.

5.2.2.2 Long term

Micromobility becomes a part of a longer combined trip providing most flexible, efficient, and sustainable transport options. It is combined with public mass transport and following a strict regulatory framework it is completely integrated in the transport system. The mobility packages provided to travelers through MaaS platforms include the micromobility option mainly as a mode to reach or leave the transition stations or combined with the private car in Park&Ride solutions. The design has evolved to be more user friendly for people suffering from motor impairment such as those with injuries, disabilities, or even just old age.

6. MAKING USE OF THE SCENARIOS: RESILIENT TOOLS AND TECHNIQUES FOR TRANSPORT PLANNING

6.1 Basic mobility indicators under different exogeneous scenarios

There are some transport-related factors that are very much linked to the variables that characterise each exogeneous scenario. Hence, the Delphi poll started by exploring how car ownership, trip rates and average trip distances would change under each scenario. **Table 3** shows the average estimations among respondents and **Table 4** shows the variability across the panel.

The main results are the following:

- Sustainable futures are perceived by the experts as linked to decreases in car ownership, average trip distance and even trip generation rates. The remaining scenarios would lead to increases in the three indicators.
- The variable that produces more diverging opinions and also more differences between the four scenarios is car ownership.
- Scenario 4 is associated to a higher relative dispersion, where somewhat contradictory drivers (e.g., telework versus income growth) may introduce additional uncertainties. This suggests that further research on the mobility impacts of the interaction between digitalisation effects and increased purchase power is likely to be welcomed.

These conclusions were already clear after the 1st Round of the poll, but the dispersion of the opinions decreased in the 2nd Round, in particular for the responses to the average trip distance estimation (-25% in the standard deviation).

Exogeneous scenario	Car ownership	Trips / person	Avg. trip distance
1 - Mixed compact cities in a sustainable Europe	Moderate to large decrease	Slight decrease	Slight to moderate decrease
2 - Stagnant individualist cities in a nationalist Europe	Slight to moderate increase	Slight increase	Slight increase
3 - Segregated green cities in an unequal Europe	Unchanged	Slight increase	Slight increase
4 - Sprawling technological cities in a vibrant Europe	Slight to moderate increase	Slight increase	Moderate to large increase

Table 3: Average estimation of the evolution of basic mobility indicators

Exogeneous scenario	Car ownership	Trips / person	Avg. trip distance
1 - Mixed compact cities in a sustainable Europe	Low dispersion	High dispersion	Medium dispersion
2 - Stagnant individualist cities in a nationalist Europe	High dispersion	Medium dispersion	Low dispersion
3 - Segregated green cities in an unequal Europe	Very high dispersion	Very low dispersion	Low dispersion
4 - Sprawling technological cities in a vibrant Europe	Very high dispersion	Very high dispersion	Very low dispersion

Table 4: Relative dispersion among estimations of the evolution of basic mobility indicators

6.2 Shared mobility services under different exogeneous scenarios

The participants in the poll were asked about the expected modal share for these services. More than 70% of participants convey that it will raise above 10% in large cities, regardless of the scenario considered. The average estimation for this figure ranges from 15% in Scenario 2 to 30-35% in Scenario 1, although opinions appeared to be dispersed for most scenarios. Interestingly, there are no major differences in the estimations with regard to city size, as they were are only slightly lower for smaller cities. The 2nd Round produced less disperse results, but converging in the average estimations already obtained in the 1st Round (Figure 1 and Figure 2).

Assuming that not all shared mobility trips are induced demand, part of these trips were based on different transport modes prior to the implementation of the services. According to the participants, the impacts of shared mobility services on other modes would not be the same under all alternative futures. Participants consider that Scenario 1 opens the room for shared mobility services that compete with car instead of with public transport, which would not be the case for the remaining scenarios (Figure 3). Trip induction rates would be low (Figure 4). The results with regard to these impacts did not change from the 1st Round to the 2nd Round.

Figure 1: Shared mobility modal share in large cities across scenarios

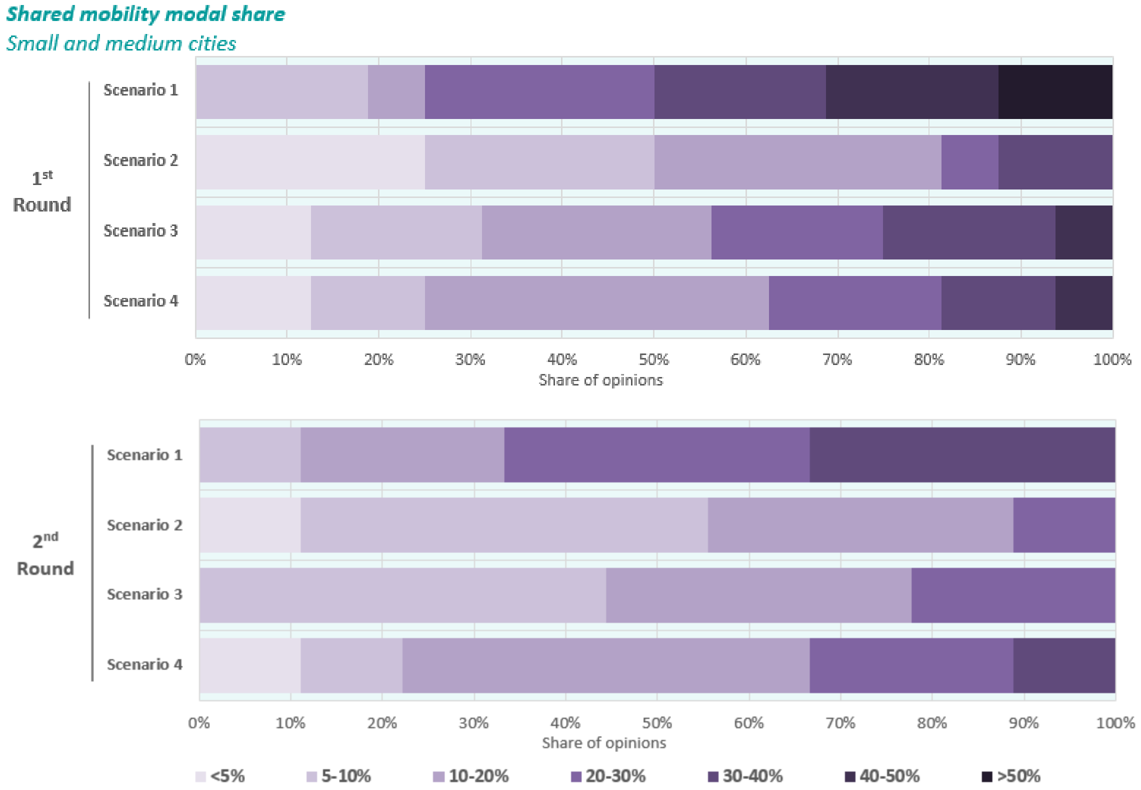

Figure 2: Shared mobility modal share in small and medium cities across scenarios

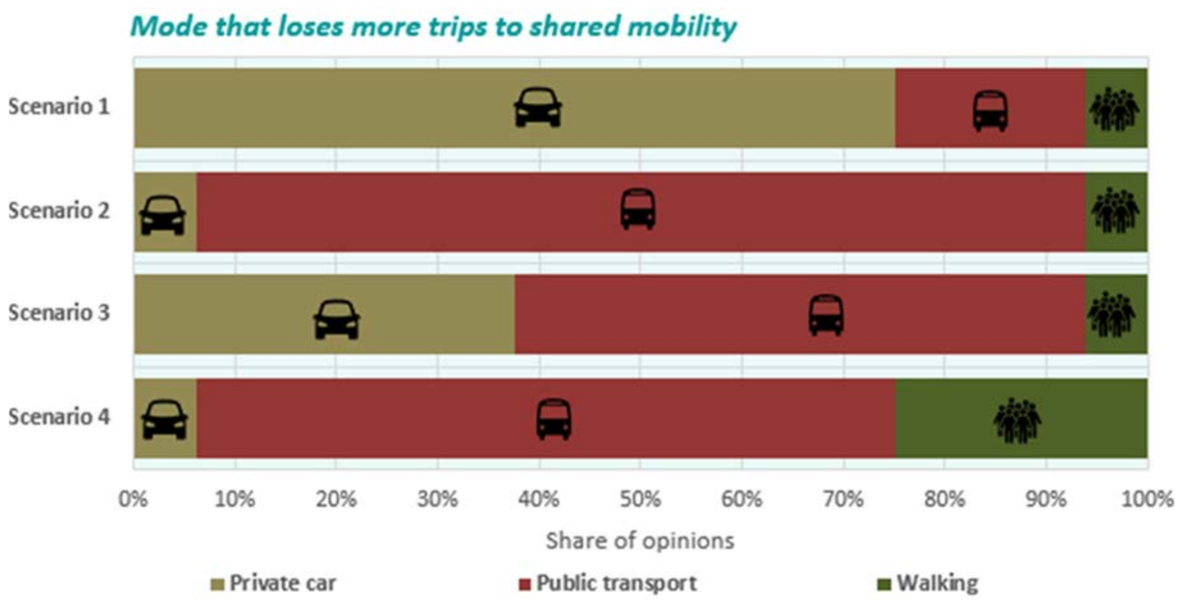

Figure 3: Relative modal shifts to shared mobility across scenarios (1st Round)

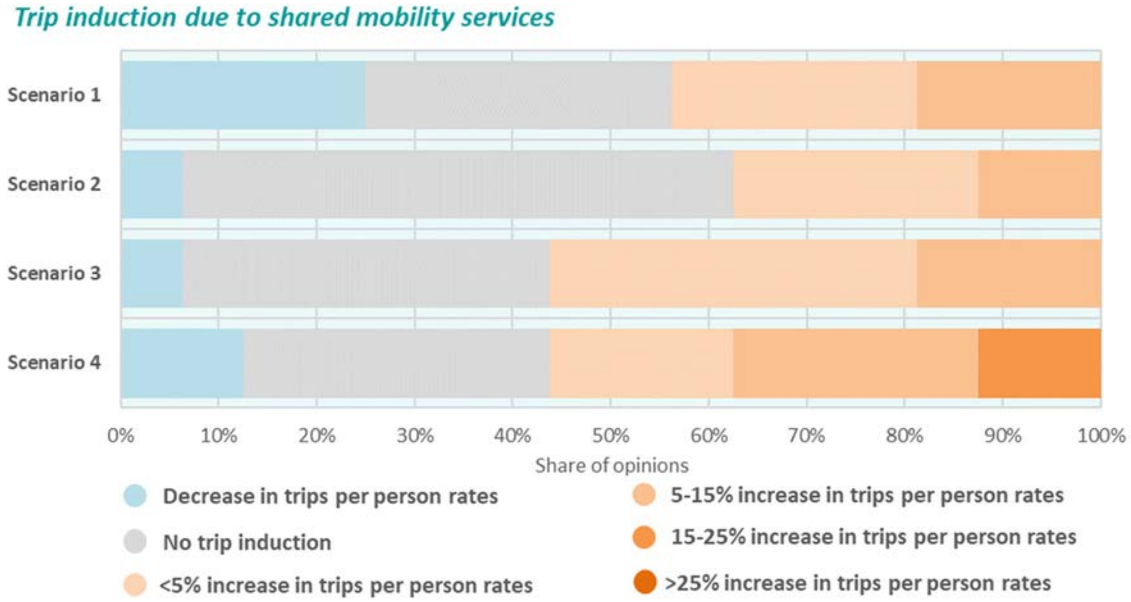

Figure 4: Trip induction estimations due to shared mobility services (1st Round)

The participants were asked also about the likelihood of some trends in how shared mobility systems are provided:

- the achievement of stable agreements between cities and operators,
- the public operation of the services,
- the integration in MaaS platforms,
- the convergence between car sharing and ride sharing due to vehicle automation an
- a general increase in prices to meet profitability targets.

The integration of the services in MaaS platforms is the trend regarded as most probable (Table 5), with low dispersion of opinions within and among scenarios already in the 1st Round (Table 6).

The evolution of the remaining trends seems to be more uncertain, since the dispersion was higher and did not decrease significantly after the 2nd Round. Some trends would depend a lot on the future scenario or present higher dispersion among opinions, such as the agreements between operators and cities to complement public transport.

All scenarios would lead to an increase in prices of these services in order to reach profitability, but the dispersion is higher for this trend than for the ones related to MaaS integration and public transport complementarity.

Exogeneous scenario	Agreements operator-city	Cities as operators	Integration in MaaS	Carsharing = Ridesharing	Increase in prices
1 - Mixed compact cities in a sustainable Europe	Likely to very likely	Likely	Likely to very likely	Slightly likely	Slightly likely
2 - Stagnant individualist cities in a nationalist Europe	Slightly unlikely to unlikely	Slightly likely	Likely	Slightly unlikely	Slightly likely to likely
3 - Segregated green cities in an unequal Europe	Slightly likely	Slightly unlikely to unlikely	Likely to very likely	Slightly unlikely	Slightly likely to likely
4 - Sprawling technological cities in a vibrant Europe	Slightly likely to likely	Slightly unlikely	Likely to very likely	Slightly unlikely	Slightly likely

Table 5: Likelihood average estimation of trends in shared mobility systems (1st Round)

Exogeneous scenario	Agreements operator-city	Cities as operators	Integration in MaaS	Carsharing = Ridesharing	Increase in prices
1 - Mixed compact cities in a sustainable Europe	Very low dispersion	Medium dispersion	Very low dispersion	High dispersion	Medium dispersion
2 - Stagnant individualist cities in a nationalist Europe	Low dispersion	High dispersion	Medium dispersion	Low dispersion	High dispersion
3 - Segregated green cities in an unequal Europe	Medium dispersion	High dispersion	Very low dispersion	Low dispersion	Medium dispersion
4 - Sprawling technological cities in a vibrant Europe	High dispersion	Very high dispersion	High dispersion	Medium dispersion	High dispersion

Table 6: Relative dispersion among the estimated likelihood of trends in shared mobility systems (1st Round)

6.3 The impacts of shared mobility services in cities

Once the participants had reflected about how the exogeneous scenarios will have an influence on the evolution of shared mobility services, they evaluate which impacts these services have on cities. The scenarios are not directly used in the questions of this section of the poll, but had served to put the participants in a creative mode of thinking that allows them to be aware of all plausible impacts. In the 1st Round the opinions were gathered through two open questions addressing current and future impacts, and in the 2nd Round rankings of adverse and positive impacts were requested. Table 7 summarises the answers to the open questions, Figure 5 shows the importance of adverse impacts and Figure 6 shows the importance of positive impacts.

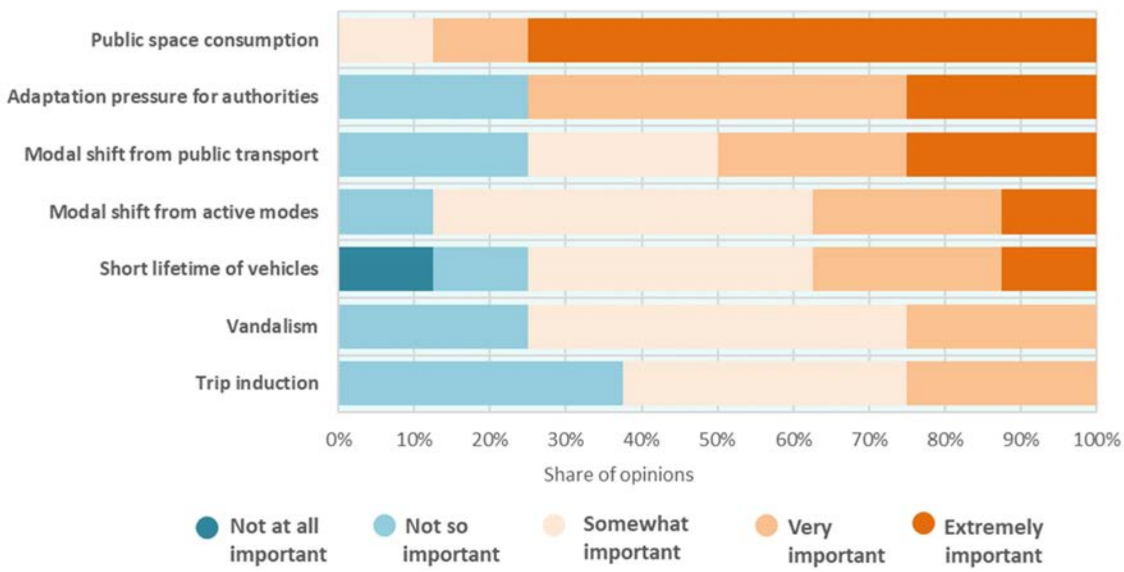

Figure 5: Importance of adverse impacts of new mobility options for cities

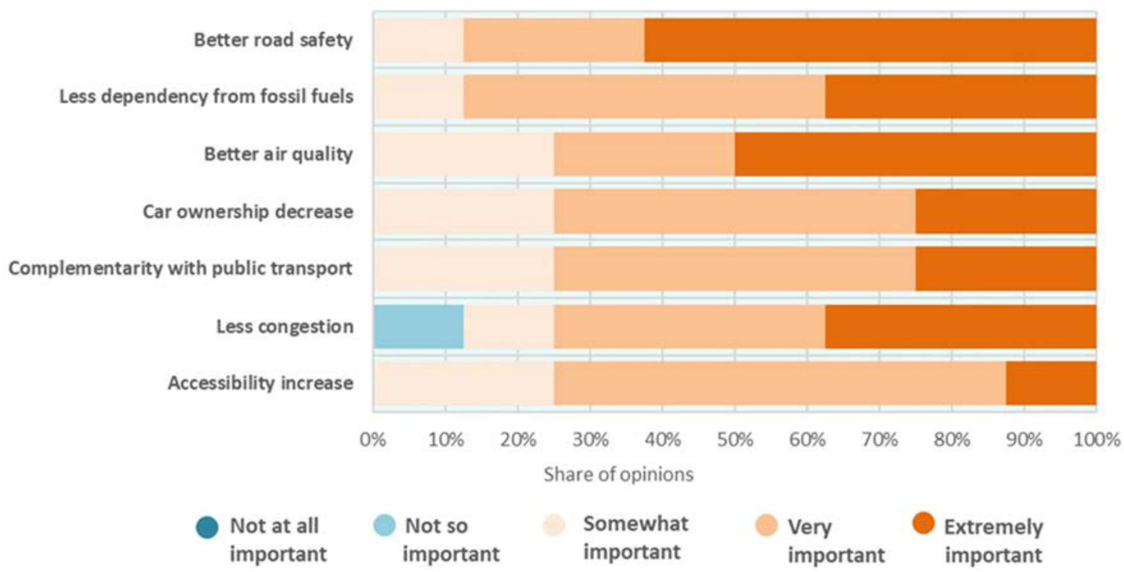

Figure 6: Importance of benefits of new mobility options for cities

Current impacts	Future impacts
Modal shift from public transport services.	A reduction in private car use and ownership. This would lead to an increase in walkability of inner-city areas, less need for parking space, less congestion and better air quality.
Modal shift from active mobility modes (i.e., walking and cycling).	An improvement of accessibility, especially in suburban areas.
Public space consumption, leading to conflicts with pedestrians in sidewalks and with other traditional modes	A replacement of scheduled public transport services, especially in low-density areas.
Short life time of micromobility vehicles drive cities away from sustainable mobility principles.	A reduction in the dependency of urban mobility in fossil fuels.
Increased pressure to public authorities for adaptation to new solutions.	An improvement in road safety.
Vandalism	An improvement of the overall economic performance of the city.
Trip induction.	A series of regulatory challenges for public authorities.
Increase of accessibility.	Modal shifts from traditional modes to emergent modes.
Car ownership decrease.	

Table 7: Potential impacts of shared mobility services in European cities according to participants, from most to least mentioned.

In the 1st Round, a quarter of them reported no current impacts but were aware that they may have impacts in the future. Among those that cited effects of these solutions that are already in place, negative aspects prevailed. Modal shifts from sustainable modes were the ones most mentioned. Interestingly, the answers to the future impacts of emerging mobility solutions were by far more positive, with few exceptions that report that no positive impacts are to be seen. The role of emerging mobility options as a potent alternative to private car use stand out as the most mentioned future impact. The 2nd Round positioned the pressure on public spaces as the most relevant negative impact and safety and energy improvements as the most relevant positive impacts.

6.4 Consequences for transport planning tools and techniques

The final section of the Delphi poll addressed the consequences of emerging mobility options for the transport planning tools and techniques. This subsection reports the results for shared mobility services. First, the participants were asked to evaluate when do they consider that shared mobility services are challenging for data analysis techniques, modelling frameworks and decision support tools. Table 8 shows the results of the analysis. Two thirds of the participants conveyed that shared mobility is already posing significant challenges. About

43% of the respondents consider that a 4% modal share is enough to consider adaptations in the tools and techniques used in transport planning. This percentage climbs up to 68% if the threshold is situated at 6%. This question was also presented as a temporal matter. All respondents considered that shared mobility should be included in supply models before 2040, and a majority of respondents considered that this should have happened before 2020 (the Delphi poll was conducted in late 2018).

Question	Options	% respondents
1. At current implementation levels in your city, do you think that shared mobility is already challenging transport planning tools and techniques?	Yes	66,7
	No	33,3
2. From which implementation level (in terms of modal share) do you expect that the following mobility solutions will require major changes in transport planning tools and techniques?	>2%	25,0
	>4%	18,8
	>6%	25,0
	>8%	6,3
	>10%	25,0
3. When do you think that shared mobility services should be added as a mode option in the transport models with a suitable treatment of the provision of their level of service (supply model)?	Now	43,8
	Before 2020	56,3
	Before 2030	93,8
	Before 2040	100

Table 8: Consequences of shared mobility for transport planning tools and techniques

Second, the participants were asked about the research gaps they find in the area. Data sharing between operators and policy-makers was highlighted by many respondents. Apart from this repeated issue, the following gaps seem to be relevant according to the 1st Round:

- The lack of solid and stable agreements with operators introduces uncertainties to the approaches needed for coping with these solutions. There is a lack of monitoring tools and normative models that would be valuable for policy-makers and regulators.
- The limited cooperation of urban planning and transport planning is also perceived as a gap in relation to this particular issue of emerging shared mobility services.
- The nature of the new options requires disaggregated demand modelling approaches taking into account improved behavioural models and the household context, e.g., in terms of car availability.
- The dynamism of shared mobility supply requires improvements in supply modelling techniques to be useful for the management of these systems.
- The lack of models for assessing specific impacts of these solutions, such as empty trips modelling or car type choice in shared mobility systems.
- The lack of strategies for data fusion, e.g., generation of synthetic populations from mobile phone data and household survey data.
- The limited real-life data available for performing analyses.
- The lack of skills by transport planners to deal with the advances in transport modelling tools.

The 2nd Round served to prioritize these gaps in terms of importance for the accurate modelling of the new mobility options. Figure 7 shows the results for the aspects related to the context of modelling practices, Figure 8 shows the results for data analysis techniques, and Figure 9 reports the results for modelling approaches. Technical skills, data sharing agreements and disaggregated modelling are perceived as most relevant factors.

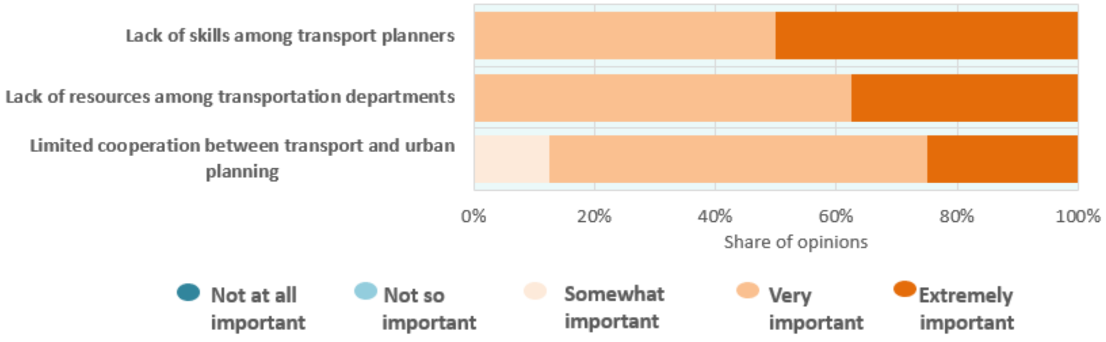

Figure 7: Importance of urban mobility planning cycle barriers

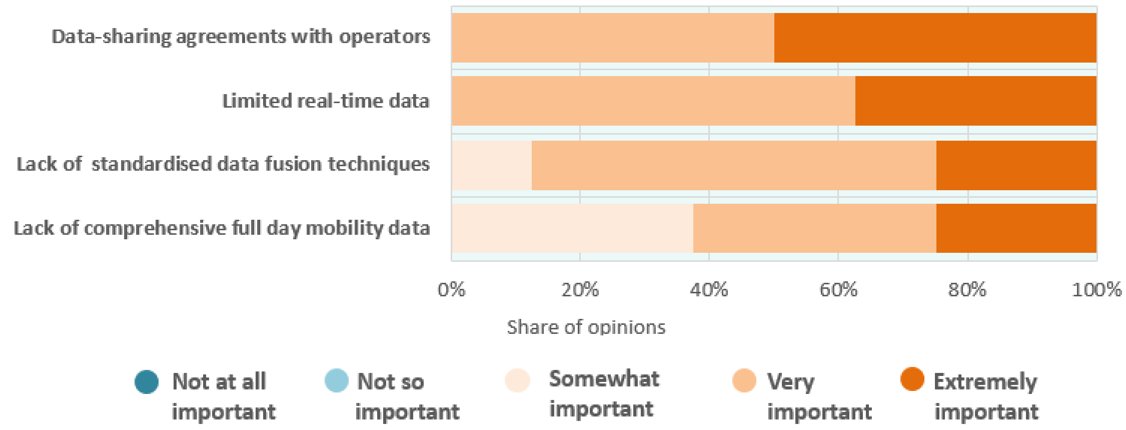

Figure 8: Importance of transport data sources gaps

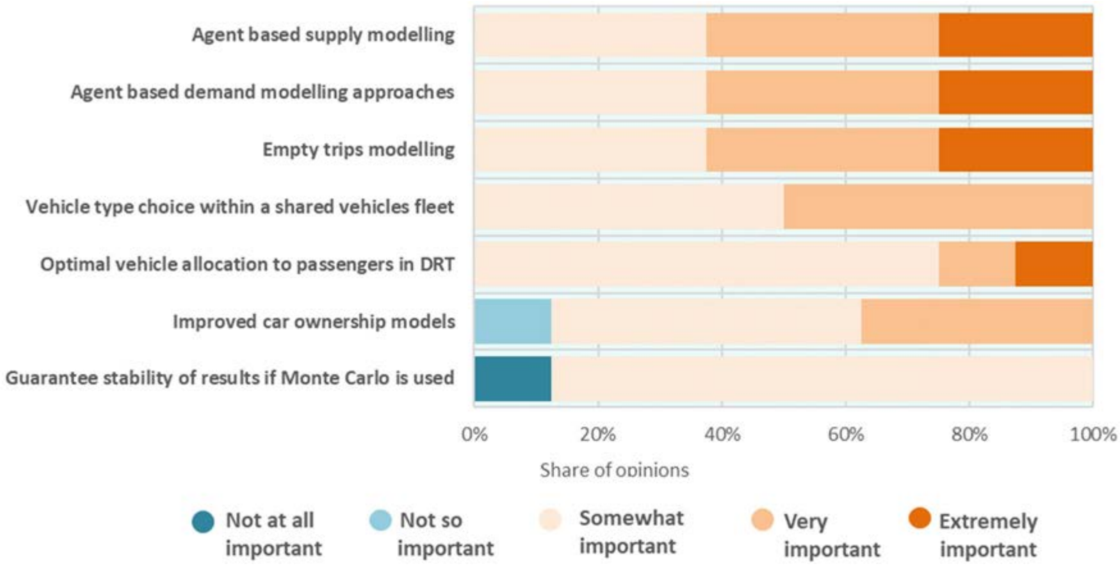

Figure 9: Importance of transport modelling gaps

7. CONCLUSIONS

The rapid development of new technologies and solutions in the transport sector calls for a continuous update of our data analysis techniques, modelling frameworks and decision support tools. This paper shows how the development of explorative scenarios for European urban mobility can facilitate a discussion about the impacts that emerging mobility options have on transport planning tools and techniques. The extensive literature on climate change research provides a good starting point for defining exogenous scenarios that cover the relevant variables that have an influence on how the emerging mobility options will develop in the following decades. The exogeneous scenarios can be complemented with endogenous scenarios that set different implementation levels for the different innovations.

In order to identify which are the requirements that future transport planning tools and techniques will have to meet in order to effectively support cities in the implementation of shared mobility services, a Delphi poll was organised. The poll engaged 16 transport experts and used the exogeneous scenarios as a tool for creative thinking among the participants. The results show that shared mobility is likely to reach modal shares above 10% before 2050 in any scenario.

The societal progress towards sustainability goals and the associated measures will define if the captured demand will come from private cars or from public transport and active mobility. Indeed, a potential modal shift from sustainable modes was the adverse impact most highlighted by the experts. At the same time, the role of shared mobility as an attractive alternative to private car use is seen as the most relevant potential positive aspect.

In order to assess these impacts, the experts claimed that shared mobility services should be included in the transport modelling tools in the next years. The majority agreed that this should happen before they reach modal shares above 4-6%.

Finally, the participants in the poll noted that the main gaps for achieving the integration of the new modes in transport models are the difficulties for reaching data sharing agreements with service providers, the availability of fine-grained data about the demand of the services and the challenges associated to disaggregated modelling. This will require not only technical adaptations but also new skills among practitioners.

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OPTIMIZATION OF THE POWERTRAIN OF ELECTRIC VEHICLES FOR A GIVEN ROUTE

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ABSTRACT

The global challenge to reduce emissions of polluting gases and greenhouse gases has forced the development of alternatives to the traditional internal combustion engine vehicles, such as electric or hybrid vehicles.

The electric powertrain are the most efficient for delivery trucks or urban buses, due to acceleration and deceleration patterns make them inefficient for using internal combustion engines. Despite this, its range and purchase cost are the main factors limiting the use of electric vehicles in these applications.

Range and purchase cost of an electric vehicles are mainly related to the energy storage system. Therefore, the optimum size of the battery pack should be considered as the design goal of a vehicle when its application is known.

This paper presents a methodology to optimize the battery pack of an electric vehicle according to a given route run in a target time. Therefore, it would be applicable to delivery vehicles, buses and any vehicle whose route and travel time are known in advance. The proposed methodology allows minimizing the energy consumption by determining the optimal powertrain ratio for a given track, setting the travel time as an objective. A full vehicle model and a multi-objective genetic algorithms are used for this matter.

1. INTRODUCTION

Vehicle manufacturers, R&D centers, Universities and so on have started projects about electric vehicles to reduce carbon emission and the dependence to fossil fuel energy. Many configurations of electric vehicles are designed to attain these objectives (Bayindir, 2001). There are many of applications where an electric vehicle can be use in a very efficient way.

For example, in delivery trucks, acceleration and deceleration patterns makes them inefficient for using internal combustion engines, it can be optimized using electric trucks (Zhao, 2016). Other optimal use can be urban buses, in which the zero tail pipe emissions make them the best actual option (Qin, 2016). Something similar happened in racing electric vehicles, where the track is known and a reference time for the lap is set.

Already knowing the route and an estimated time, gives the chance of designing the vehicle especially for it proposes. In what concerns to electric vehicles, one of the most relevant decisions is made during the powertrain design. A regular approach to the design of the powertrain in electric vehicles, start with selecting the proper motor power and transmission parameters requirements (Yu, 2017). This approach can be a simple solution to this problem, but for many other scenarios, it does not achieve an optimal configuration.

Hand in hand with the lack of transmission, clutch or gears, the electric vehicle needs to be extremely efficient, in order to minimize the consumption of energy. For this matter, the influence of including a gearbox with a gear ratio can be determinant on its efficiency (Ren, 2009). This is highly related to the range and performance of the vehicle (Abdelrahman, 2017).

In some studies, (Basso, 2019) the authors focus the effort on planning the most efficient route, in order to minimize the energy, consume. Other papers establish the necessity of designing an efficient gearbox for the powertrain, which play a key role in the design of electric and hybrid electric vehicles (Dagci, 2018). In Kulik (2018), they pose the option of estimating the requirements for a hybrid electric powertrain base on analysis of the city vehicle GPS track together with accelerometer data.

In relation with the techniques use for the optimization of the powertrain, some studies have explored the option of using genetic algorithm as a strategy for optimization the parameters of the powertrain of a hybrid vehicle. Among that, the use of multi-objective design for different systems of vehicles, it is widely use (Callejo, 2015) for optimization a response.
This multi-objective genetic algorithm can also be used to define operational strategies of, for example, fleets of trucks, reducing its operational cost, for an early amortization of the expensive hybrid electric vehicles (Fries, 2017).

It can be seen the appropriateness of developing an optimization method, that defines the optimal powertrain for an electric vehicle and a determined route. An already defined path and time, allows the designer to find a solution adapted to the specific need of the vehicle. The use of multi-objective genetic algorithms for this matter, would serve as a reliable generic method of finding the optimal configuration for the powertrain, for a case given the particularities of the route.

In this paper a methodology is proposed that allows to calculate the optimal transmission for a given route, setting the travel time as a target. This would allow the transmission ratio to be adapted to the route, being applicable to transport vehicles in one or more given routes. It would allow the design of optimal powertrains or gearboxes for each route or the definition of an automatic change strategy based on the selected path.

2. METHODOLOGY

This work proposes an optimization methodology for powertrain design. The minimization of the weight of the battery pack is established as design objective. Problem constraints are a given route and the travel time. The proposed flowchart is the one shown in figure 1.

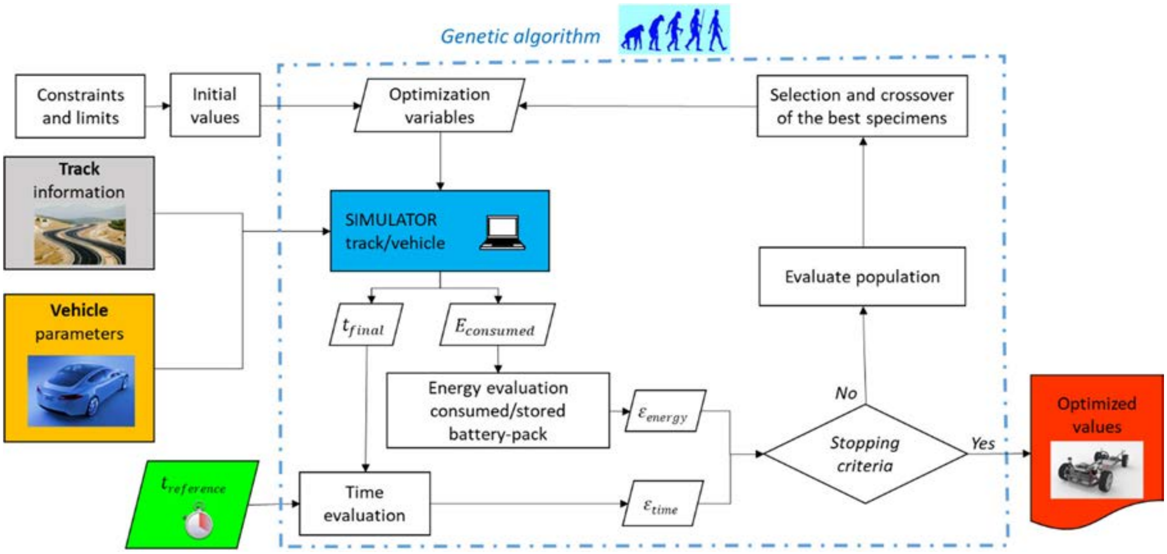

Figure 1: Flowchart of proposed methodology

The characterization of the route, the vehicle to be optimized and the reference time are established as a starting point. With all this in mind the possible design constraints and limitations, a first set of initial values of the parameters to be optimized is proposed. These values include aspects of the powertrain design, such as transmission ratio or engine characteristics. In addition, the mass of the battery is another parameter to optimize.

These parameters allow to obtain, after calculation with the module "simulator", the results of time (t_{final}) and consumed energy ($E_{consumed}$). These obtained values are evaluated with the time set as a reference ($t_{reference}$) and the stored energy, obtaining the values error of time (ε_{time}) and energy (ε_{energy}). By using a multi-target genetic algorithm, the modification of the design parameters is proposed in order to minimize the errors obtained. When the stopping criteria have been reached, the optimization process stops.

3. ANALYSIS OF ELECTRIC VEHICLE DYNAMICS

The electric vehicle under study has a powertrain that can be characterized by the following parameters:

- Maximum torque (T_{max})
- Maximum power (p_{max})
- Maximum engine speed
- Total transmission ratio (i_t)

These values are supposed to be optimized according to the needs of the study. It may be that some of these values are set at the beginning of the study, having, for example, restrictions on the type of motor to be used. Another characteristic parameter of the motor is the cut-off speed ($v_{cut-off}$). This speed sets the limit between maximum torque and constant power traction. Various yields and efficiencies will also be taken into account in the powertrain design. The powertrain design allows to obtain, in every location of the route, the traction force (F_T), including the effect of all drive axles.

$$F_T = F_f + F_r \tag{1}$$

In addition, the mass in running order of the vehicle is known and the load status. Regarding the battery pack, the type and therefore the voltage of each cell, cell unit weight and energy density are taken as initial information. The full weight of the battery pack (m_b) is considered a design variable that is intended to minimize for the given route.

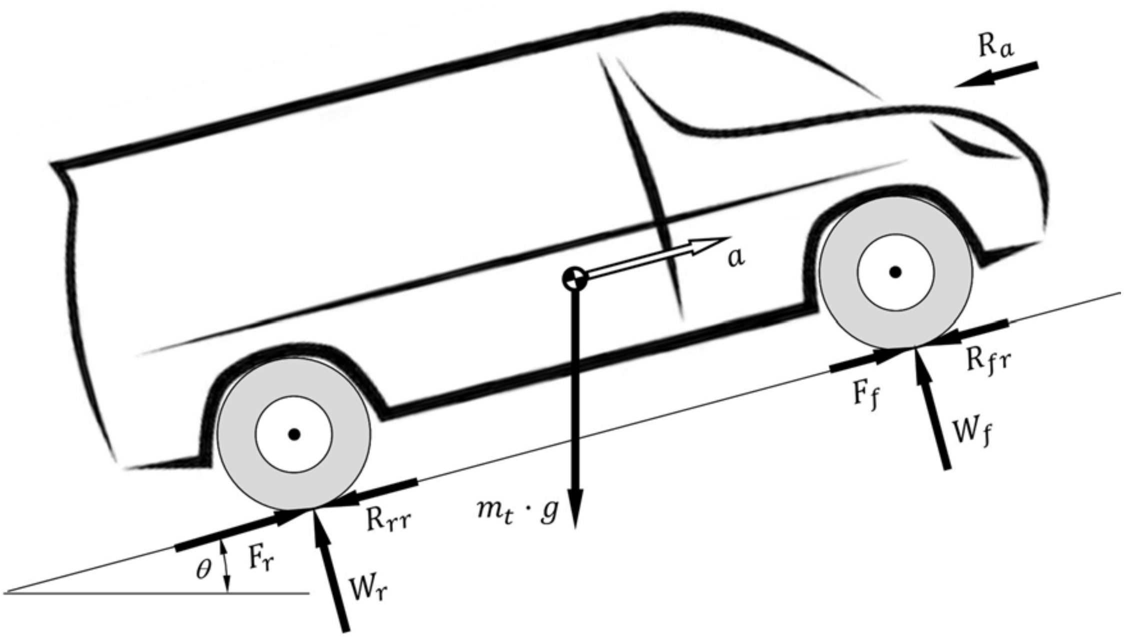

Figure 2: Vehicle dynamics

On the other hand, the dynamics of the vehicle, according to Figure 2, is characterized by resistances or drag forces that include both the rolling resistances on the axles (R_{fr}, R_{rr}), as well as the aerodynamic resistances (R_a), other mechanical losses, and the grade resistance (Allonca, 2019). The over-all drag forces are characterized by the following expression:

$$R = A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta \quad (2)$$

The total mass of the vehicle (m_t) can be expressed as the sum of the mass of energy storage systems (m_b), such as batteries and auxiliary systems and the rest of the vehicle's masses (m_v).

$$m_t = m_v + m_b \quad (3)$$

Depending on the powertrain design, drive shaft position, wheelbase, weights in every shaft (W_f, W_r) and center of gravity position, the vehicle's traction capacity may be limited by the adhesion of the drive wheels to the rolling surface. It should therefore be checked, both the performance of the powertrain and the limitations of the environment.

4. ROUTE ANALYSIS

As already mentioned, the method proposed on this paper has the objective of defining an optimization method for designing the powertrain of an electric vehicle, knowing its final propose. This includes knowing a reference time for the route and the route itself. A route, can be a complex consecution of different sections like strait lines, open curves, closed curves, uphill or downhill. This makes the study of the route quite complex, taking in mind the necessity of apply the equations to the entire track.

To simplify this problem, a solution is proposed. If we can find a method to typify every section of a route, and then apply the calculation process to it summing up all the sections at the end, will be easier, more precise and more efficient.

The general methodology implies that the complete route for which you want to optimize the vehicle must be divided into sections that are characterized by having the constant values of the section parameters. The parameters that characterize each section are:

- Start point
- End point
- Ramp/slope
- Radius of curvature. In the case of a straight section, the radius is considered to be infinite (∞).
- Adhesion

If a change of ramp/slope or adhesion occurs on the same constant radius curve, it must be divided into as many sections as there are different values.

After the analysis of the route, there is a division of sections characterized by its starting and ending point. If distances to the origin are taken, it is clear that the endpoint of a section (n) coincides with the start of the next one (n+1).

Each section must be characterized by a maximum speed (v_{max}) which is function of the vehicle and the road. The vehicle has a circulation limit according to the powertrain. The road imposes a limit that is a function of the maximum lateral acceleration radius of curvature and the posted speed. Once the route partition has been defined, the behaviour of the vehicle within each section must be analyzed.

The simulator considers that the initial speed of the section (n) is the final speed of the stretch $(n-1)$, so when it reaches that section, the speed is assumed to be known. In general, it is established as a condition that when it under traction force, the powertrain will be considered the maximum tractive effect (considering both the limit of the powertrain and the adhesion). The maximum speed in every section cannot be exceed. At the end of the section (n) cannot be exceed the starting limit speed of the next section $(n+1)$, which will be taken by default the maximum speed.

If the vehicle is driving at a speed higher than the final speed, a braking procedure must be established. The point from which braking must start must be determined to reach the end of the run at the defined speed.

As a conclusion, a complex and long track can be automatically segmented into an undefined number sub-tracks or sections, each one also defined by its parameters that can be its length l, its slope θ, its initial speed $v_{initial}$, its maximal speed v_{max} and its final speed v_{final}.

In general, each section can be defined by its maximal speed v_{max}, that restrict the circulation throw that section. For example, if the maximal speed of the section is greater than the cutoff speed of the motor of the vehicle, it can be defined four different dynamic behaviors:

- The vehicle accelerates from $v_{initial}$ to v_{cut_off} at constant torque. The acceleration in this subsection is:

$$a_{Tmax}(t) = ((T_{max}i_t/r) - (A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta))/(m_t\gamma) \tag{4}$$

- The vehicle accelerates from v_{cut_off} to v_{max} at constant power. The acceleration in this subsection is:

$$a_{pmax}(t) = ((P_{max}/v) - (A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta))/(m_t\gamma) \tag{5}$$

- The vehicle circulates at constant speed v_{max}. The acceleration in this subsection is 0. In this case the tractive force must be such that it equals the drag resistances, resulting in zero acceleration
- The vehicle breaks from v_{max} to v_{final}. The acceleration of this subsection is:

$$a_b(t) = (-F_b - (A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta))/(m_t\gamma) \tag{6}$$

A general sequence of speed variation is shown in figure 3.

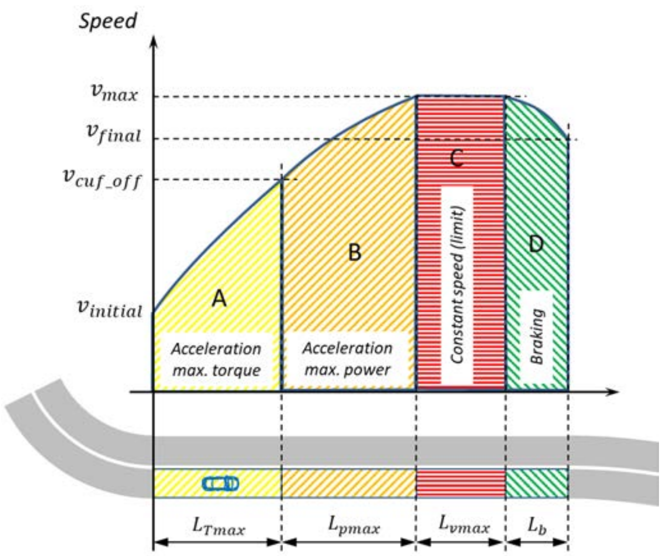

Figure 3: Speed variation in a general section.

The simulation module analyzes the dynamic response of the vehicle in every section of the given track. The calculation procedure include la classification of the different subsections, according to the vehicle response. The total length of a section, is described by 4 subsections, having each one its own length:

- L_{Tmax}: Subsection length associated to the maximal torque.
- L_{pmax}: Subsection length associated to the maximal power.
- L_{vmax}: Subsection length associated to the maximal speed.
- L_b: Subsection length associated to the braking phase.

At the end, the total length of a i-section $L(i)$ is the sum of the length of this 4 subsections:

$$L(i) = L_{Tmax}(i) + L_{pmax}(i) + L_{vmax}(i) + L_b(i) \tag{7}$$

These lengths can be calculated based on the dynamic behaviour of the vehicle.

$$L(i) = \int_{v_{initial}}^{v_{cut\_off}} (v \cdot dv/a_{Tmax}(v)) + \int_{v_{cut\_off}}^{v_{max}} (v \cdot dv/a_{pmax}(v)) + v_{max} \cdot t_{vmax} + \int_{v_{max}}^{v_{final}} (v \cdot dv/a_b(v)) \tag{8}$$

The total time spend in go across a section is describe by 4 subsections, having each one its own time:

- t_{Tmax}: Time spend going throw the section of maximum torque.
- t_{pmax}: Time spend going throw the section of maximum power.
- t_{vmax}: Time spend going throw the section of maximum speed.
- t_b: Time spend going throw the breaking section.

At the end, the total time spend going throw a section is the sum of the time needed for the 4 subsections:

$$t_{total} = t_{Tmax} + t_{pmax} + t_{vmax} + t_b \tag{9}$$

The total time (t_{total}) to travel the section will be:

$$t_{total} = \int_{v_i}^{v_c} (dv/a_{Tmax}(v)) + \int_{v_c}^{v_{max}} (dv/a_{pmax}(v)) + t_{vmax} + \int_{v_{max}}^{v_f} (dv/a_b(v)) \tag{10}$$

As it can be seen, a general section of the route or track, can be composed by the combination of this 4 types of subsections. In case of vehicle and route limitations, in each study section in which the route has been divided, one or more subsections may disappear. Some special cases could appear, as follows:

- The maximum speed is not reached: This implies that the maximum speed phase (C) disappears. In that case $t_{vmax} = 0$. It can be expressed mathematically as:

$$v < v_{max}, \forall t \tag{11}$$

- The maximum speed acceleration of the run is not reached (B): This implies that the maximum speed phase disappears. Speed (v) never exceeds the change rate (v_{cut_off}). It can be expressed as:
-

$$v < v_c, \forall t \tag{12}$$

This can occur with or without maximum speed phase. If you the maximum speed phase is not reached, an additional constraint should be considered:

$$v_{max} < v_c \tag{13}$$

- No braking phase: This implies that the braking phase (B) disappears. In that case the speed does not reach the final speed.

$$v < v_{final}, \forall t \tag{14}$$

This can be achieved in three different ways:

  - Finishing the section in maximum speed
  - Finishing the section at maximum power
  - Finishing the section at maximum torque

- It starts from acceleration at constant power: This implies that the acceleration phase at maximum torque (A) disappears. In that case the initial speed exceeds the cut-off speed.

$$v_{cut\_off} < v_{initial} \tag{15}$$

- The run starts at constant speed and equal to the maximum: This implies that the acceleration phase disappears. In that case, the initial speed is equal to the maximum speed.

$$v_{max} = v_{initial} \tag{16}$$

All this logic is implemented in the simulator. Initially the simulator has the information that characterizes each section. This information is relative to the length of each section, slope, maximum speed and braking deceleration. The simulation module starts from an initial speed of the first section. Every simulation step the vehicle is located in a section (i).

This allows you to know the maximum section speed, the maximum permissible final speed and the braking acceleration. If the speed is less than the maximum speed, it accelerates. If the speed is lower than the cut-off speed, acceleration with constant maximum torque is assumed. Otherwise, the engine is considered to drive at constant power. In this case the torque is a function of the power and engine speed.

At each point of the section it is necessary to check that the speed does not exceed the maximum, so in that case, the torque will be necessary to counteract the losses due to the resistance forces when driving at constant speed.

In parallel, it should be noted, depending on the final speed, that the braking distance required is no less than the distance to the end of the run.

With these conditions, a simulation of the route of each vehicle configuration is obtained based on the design variables. Differences between the times obtained and the reference time are evaluated. It is also checked that the energy consumed is at least equal to that stored in the battery pack. With all this, a set of new vehicle configurations is proposed, using a genetic algorithm. The ultimate goal is to get a weight-optimized solution.

4. RESULTS AND CONCLUSIONS

As an example of application of the proposed methodology, the analysis of a given route is shown in Figure 4.

Figure 4: Given track used to methodology implementation.

After entering all the characteristic parameters of the vehicle and the sections of the route the genetic algorithm is run. The different powertrain configurations of the vehicle are iteratively simulated. Finally, a configuration with a minimized weight of the battery pack is obtained. Figure 4 shows the different points at which a change of status occurs in the dynamics of the vehicle.

As conclusions, can be stated that a new methodology is proposed to optimize the chassis of electric vehicles. This methodology focuses on minimizing the energy consumption for a given track and travel time.

A simulated model of an electric vehicle behavior on a certain track, to use on a multi-objective genetic algorithm, has successfully accomplished in order to optimize the powertrain of an electric vehicle. This method is reliable and can be used in many applications, in where the time and the route are already known.

The design variables are composed by the battery pack mass and the transmission ratio, both optimized to guaranty the best performance in the track. The multi-objective model is validated with the use of a real-life case that confirms its functionality.

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OPTIMIZACIÓN DE UNA MANIOBRA DE ADELANTAMIENTO APLICADA A VEHÍCULOS AUTÓNOMOS

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RESUMEN

El grado de autonomía en los vehículos ha crecido significativamente en la última década debido a la aparición de nuevas tecnologías, que permiten conocer en cada instante de tiempo, tanto las condiciones del entorno, como las del vehículo, dejando en un segundo plano el factor humano.

Ya son una realidad en los vehículos que circulan por nuestras carreteras, el sistema de mantenimiento de carril (LKAS – Lane Keeping Assistance System), el sistema de ayuda de permanencia en la carretera (RDM – Road Departure Mitigation) o el control de crucero adaptativo inteligente (ACC – Adaptative Cruise Control), aunque la idea, es ir más allá, a vehículos totalmente autónomos capaces de transportar con seguridad a personas entre dos localizaciones sin la implicación de éstas.

En el presente artículo, se desarrolla la optimización del tiempo de ejecución de una maniobra de adelantamiento, utilizando campos potenciales para el cálculo de la trayectoria y las regiones de estabilidad (velocidad de guiñada – ángulo de deriva) para determinar el nivel de seguridad.

Los campos potenciales, son una herramienta utilizada en la generación de trayectorias, permiten conocer en cada instante de tiempo, el entorno y las situaciones que rodean al vehículo, adaptando así sus movimientos. Por otro lado, con las regiones ($\dot{r} - \beta$) es posible conocer los límites de estabilidad de los vehículos, además de detectar situaciones comprometidas durante la conducción.

La combinación de ambas herramientas permite realizar maniobras de adelantamiento, no solo rápidas, sino seguras. Para el desarrollo, se realizan simulaciones con un modelo 3D complejo en el software de simulación dinámica multicuerpo MSC Adams® y se implementa el control en Matlab Simulink®.

1. INTRODUCCIÓN

En los últimos años, los vehículos autónomos y sus tecnologías han sufrido un gran desarrollo (Kuramoto, 2018; Somogyi, 2018; Park, 2016). La utilización de este tipo de vehículos supone muchos beneficios para la circulación vial (European Commission, 2016), desde la reducción del número de accidentes/incidentes en la carretera (de factor humano) (National Highway Traffic Sfety Administration, 2015; Rowley, 2018), pasando por la reducción de los atascos o la aparición de nuevos servicios de transporte.

A la hora de hablar de conducción autónoma, es necesario distinguir entre 6 niveles de autonomía (SAE International, 2018), según el grado de intervención del ser humano (Figura 1).

Nivel de Automatización	Denominación	Control de los actuadores	Monitorización del entorno	Capacidad del sistema
0	Sin automatización	Conductor humano	Humano	n/a
1	Asistencia del conductor	Sistema + Humano	Humano	Algún modo
2	Automatización parcial	Sistema	Humano	Algún modo
3	Automatización condicionada	Sistema	Sistema	Algún modo
4	Automatización alta	Sistema	Sistema	Algún modo
5	Automatización total	Sistema	Sistema	Todos modos

Figura 1: Niveles de automatización para vehículos (SAE)

A pesar de los claros beneficios que tienen hoy en día los vehículos autónomos, su uso en la actualidad, está reducido a entornos controlados, aunque cada día incrementan sus posibilidades (Jiménez, 2018). Un ejemplo de esto, de aplicación en el transporte de mercancías, es la agrupación de vehículos en un pelotón, siendo el primero del grupo el que controla a los demás (Jia, 2017; Santini, 2017). Además, surgen nuevas opciones de negocio, car-sharing o taxis autónomos (Bischoff, 2016), vehículos militares (Naranjo, 2019) y nuevas posibilidades para gente de avanzada edad o con discapacidades (Harper, 2016).

En un vehículo autónomo, se distinguen tres etapas durante la conducción, que se desarrollarán cíclicamente, percepción (del entorno), toma de decisión y acción (Figura 2).

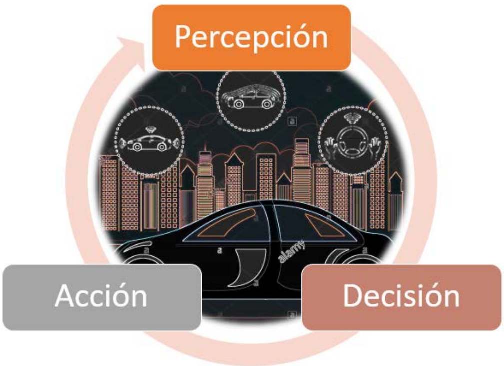

Figura 2: Etapas vehículo autónomo

De las tres etapas que se distinguen, la que más desarrollo está sufriendo en la actualidad es la percepción. Son múltiples las tecnologías utilizadas para el reconocimiento del entorno o del tráfico, visión artificial (Bertozzi, 2000), ultrasonidos (Alonso, 2011), radar (Eltrass, 2018) o/y LiDar (Kidono, 2019; Baras, 2019).

Como se ha visto, el vehículo autónomo, lleva asociado, una red de telefonía (redes 4G-5G, WiFi) (Wang, 2019) y periféricos (sensores, microcontroladores) (Faouzi, 2016; Khaleghi, 2013) e infraestructura (posicionamiento por satélite) (Milanés, 2008), que hacen posible su funcionamiento (Brown, 2014).

A la hora de abordar la toma de decisiones, intervienen varios factores, planificación de trayectorias, tipo de carretera y geometría, obstáculos en la vía, peatones, entre otros, por lo que se trata también de una etapa de gran complejidad. (Jiménez, 2018; Rasekhipour, 2017; Aldibaja, 2018).

Lo que se pretende en este trabajo, es combinar los campos potenciales (técnica para la toma de decisiones) con las regiones de estabilidad del vehículo ($\dot{r} - \beta$) (definidas por la velocidad de guiñada y el ángulo de deriva) de forma que se consigan maniobras, en este caso de adelantamiento, más rápidas y seguras. Por un lado, los campos potenciales posicionan el vehículo en la vía e inducen cambios en el movimiento de este, mientras que las regiones de estabilidad condicionan la velocidad con la que se realiza la maniobra, de forma que nunca se superen los límites asociados a cada vehículo y condición operativa.

2. METODOLOGÍA

El uso de modelos tridimensionales y simulaciones virtuales son ampliamente utilizados tanto para la comprobación de las capacidades técnicas de los vehículos, como para la modelización de escenarios de tráfico.

2.1 Modelo virtual de vehículo

En la Figura 3 se muestra el modelo 3D complejo, definido en el programa de simulación dinámica multicuerpo MSC Adams View® y utilizado para la modelización del vehículo.

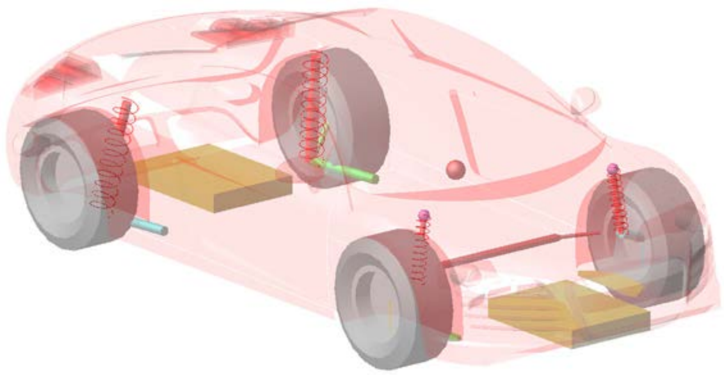

Figura 3: Modelo virtual utilizado para los ensayos

Se trata de un modelo con 16 grados de libertad y 21 partes móviles, capaz de reproducir fidedignamente el comportamiento dinámico del vehículo real. El vehículo tiene una suspensión delantera de tipo McPherson y trasera de brazos arrastrados. En este caso, el modelo de neumático utilizado es un Pacejka 2002 (Pacejka, 2002).

El modelo virtual utilizado para las simulaciones se exporta desde el software de simulación hacía el software en el que se realiza el control Simulink®. El bloque generado en la exportación (planta), es el que se muestra en la Figura 4.

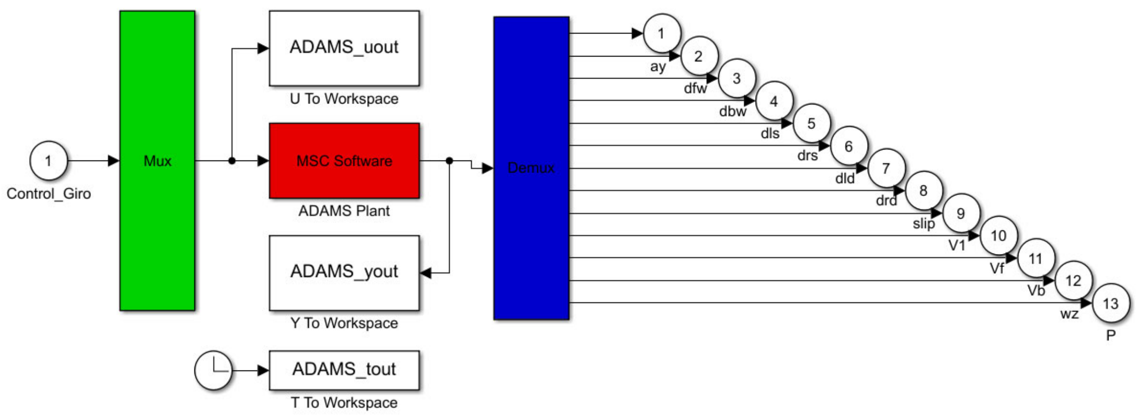

Figura 4: Planta del modelo 3D de simulación

De la simulación se obtienen datos de distancias entre vehículos, distancia a los límites de la carretera, datos sobre la dinámica vehicular, como pueden ser la velocidad de guiñada y el ángulo de deriva, datos de la geometría del vehículo como la posición del centro de gravedad (cdg) o la masa de este.

2.2 Diseño del sistema de control

Para la realización de las simulaciones se ha considerado una velocidad de circulación constante, por lo que la variable de control del modelo es el giro de volante durante la maniobra de adelantamiento. El modelo de control se divide en tres partes, Figura 5:

- Control en base a la sobreaceleración lateral
- Control aplicando campos potenciales (Martínez, 2019)
- Control aplicando regiones de estabilidad (Beal, 2013; Bobier, 2013; Bobier, 2012, Erlien, 2015)

Una vez se tiene definido un ensayo para un modelo dado, se exporta la planta desde Adams View® a Matlab Simulink® para realizar el control, Figura 5, ya que es más flexible para trabajar y da más opciones.

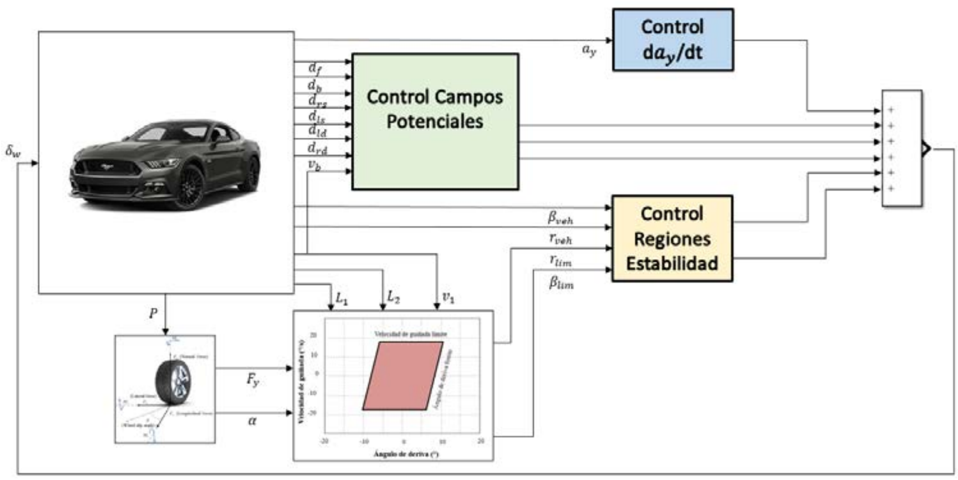

Figura 5: Control para el adelantamiento del vehículo

Mediante los campos potenciales, se define el giro de volante necesario que hace posible la maniobra de adelantamiento, mientras que el control de a_y y las regiones de estabilidad, determinan que ésta, se haga con total seguridad.

2.3 Control en base a la sobreaceleración

Para el control en base a la sobreaceleración lateral, se toman como referencia los límites que se establecen en la Norma 3.1 – IC Trazado sobre la sobreaceleración que sufren los pasajeros durante la circulación. En la Figura 6, se muestran los diagramas de bloques que llevan a cabo el control.

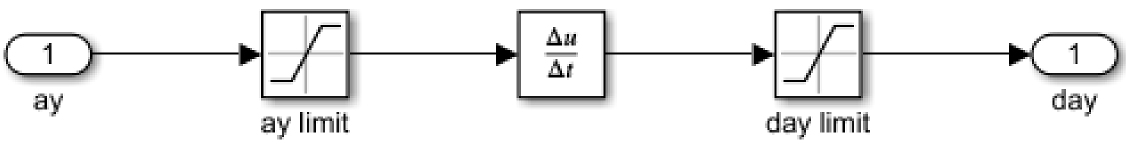

Figura 6: Diagrama de bloques para el control a partir de a_y

Al tratarse de una maniobra de adelantamiento, en la que el cambio de carril se realiza de forma brusca, se limita esta sobreaceleración a ±2 (m/s^3). En la Figura 7 se muestran los valores de aceleración lateral y sobreaceleración para el vehículo utilizado durante una maniobra de adelantamiento.

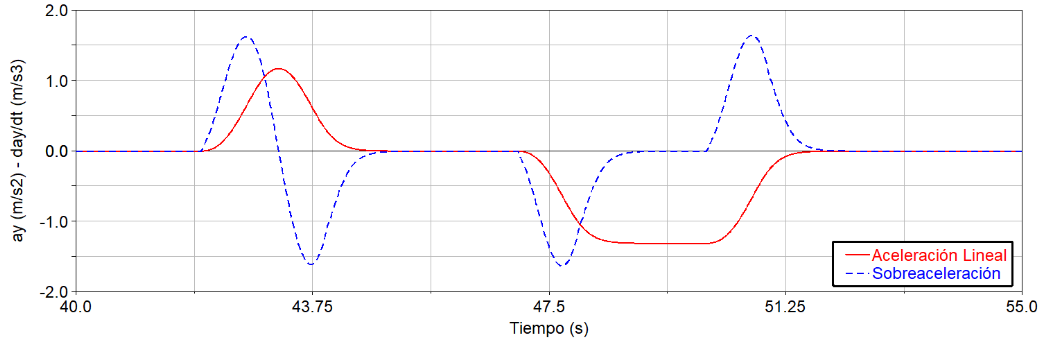

Figura 7: Aceleración y sobreaceleración para un vehículo

La aceleración lateral límite, para que sea común en todos los vehículos, se considerará un valor de ±5 (m/s^2).

2.4 Control aplicando campos potenciales

A la hora de abordar la toma de decisiones en la conducción autónoma, se puede recurrir a varias técnicas, tele-operación, navegación por waypoints o control difuso entre otras. Para este análisis se ha optado por utilizar técnicas reactivas, campos potenciales, donde el vehículo responde en todo momento a la situación actual generando el movimiento adecuado.

Como se puede ver en la Figura 8, cada elemento del entorno (carriles, otros vehículos o los propios límites de la vía) produce un campo potencial con el vehículo. Según el tipo de potencial, el vehículo modificará su comportamiento.

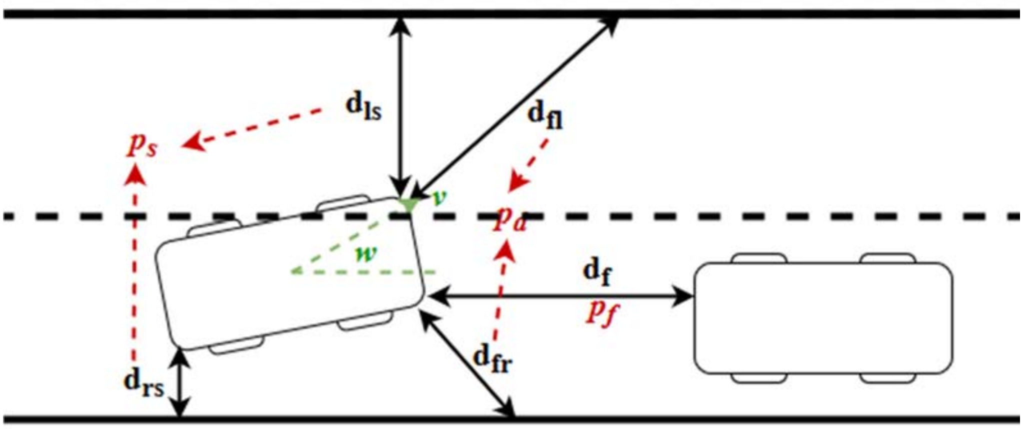

Figura 8: Distancias que definen los potenciales entre el vehículo y el entorno

En la Figura 9, se representan sobre el vehículo los potenciales frontales/traseros, laterales y diagonales, que permiten posicionar el vehículo en la vía y respecto al resto de usuarios.

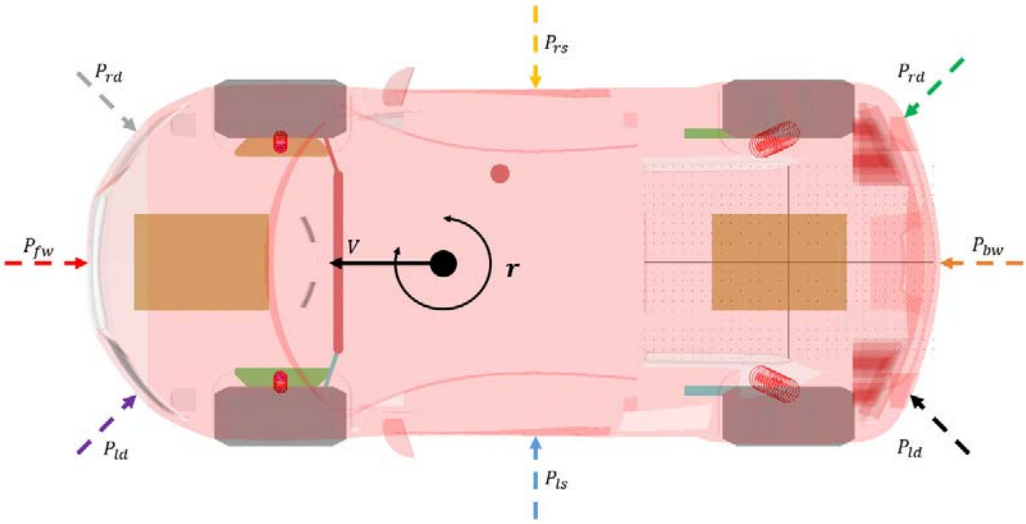

Figura 9: Diagrama de campos potenciales sobre el vehículo

Para el cálculo de los potenciales, se utilizan las siguientes expresiones.

2.4.1 Potencial respecto al vehículo a adelantar:

$$P_{fw} = \{[0\ si\ v_{B1} \geq v_{max}], [(v_{max} - v_1)/d_f \ \ si\ v_{B1} < v_{max}]\} \quad (1)$$

donde:

- v_{max} – velocidad máxima de la vía
- v_1 – velocidad del vehículo que va a ser adelantado
- d_f – distancia frontal entre los vehículos

2.4.2 Potencial respecto al vehículo que se tiene detrás:

$$P_{bw} = \{[0\ si\ v_A \geq v_{B2}], [v_2 - v_A)/d_{bw} \ \ si\ v_A < v_{B2}]\} \quad (2)$$

donde:

- v_2 – velocidad del vehículo que ejecuta la maniobra de adelantamiento
- v_A – velocidad del vehículo que le sigue
- d_{bw} – distancia trasera con el vehículo que le sigue

2.4.3 Potenciales respecto a los límites de la vía:

$$P_s = P_{rs} + P_{ls} = 1/d_{rs}^2 - 1/d_{ls}^2 \quad (3)$$

donde:

- d_{rs} – distancia lateral derecha
- d_{ls} – distancia lateral izquierda

2.4.4 Potenciales diagonales:

$$P_d = P_{rd} + P_{ld} = 1/d_{fr}^2 - 1/d_{fl}^2 \quad (4)$$

donde:

- d_{fr} – distancia diagonal derecha
- d_{fl} – distancia diagonal izquierda

2.4.5 Potencial total:
El potencial total es la suma de cada potencial, multiplicado por el valor de su ganancia:

$$P_T = \sum K_i \cdot P_i = K_s \cdot P_s + K_d \cdot P_d + K_{fw} \cdot P_{fw} + K_{bw} \cdot P_{bw} \quad (5)$$

Siendo K_i la constante de proporcionalidad.

Del modelo virtual se obtienen las distancias entre los vehículos, las cuales son las entradas del control de giro con potenciales. En la Figura 10, se muestra el diagrama de bloques para el control según los campos potenciales. Si la propuesta se llevase a cabo en un vehículo real, sería necesario la instrumentación de este, con LiDAR, visión artificial, u otras tecnologías que permitan medir distancias. La salida del control es directamente el giro de volante.

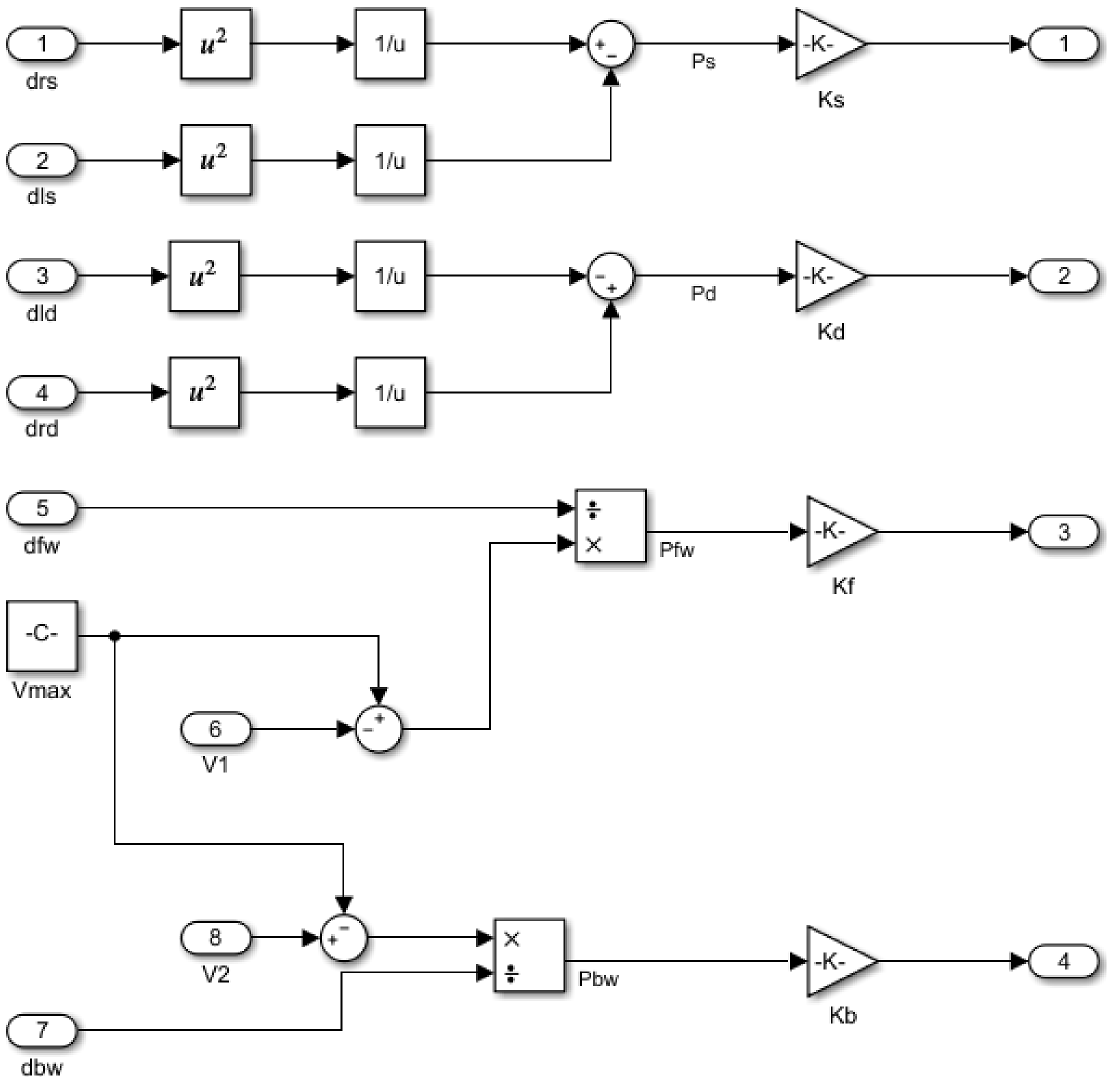

Figura 10: Diagrama de bloques para el control según los potenciales

2.5 Control aplicando regiones de estabilidad

El control de la dinámica vehicular se realiza a través de las denominadas regiones de estabilidad, determinadas por los valores límite de velocidad de guiñada y ángulo de deriva del neumático ($\dot{r} - \beta$), cuya representación se puede apreciar en la Figura 11.

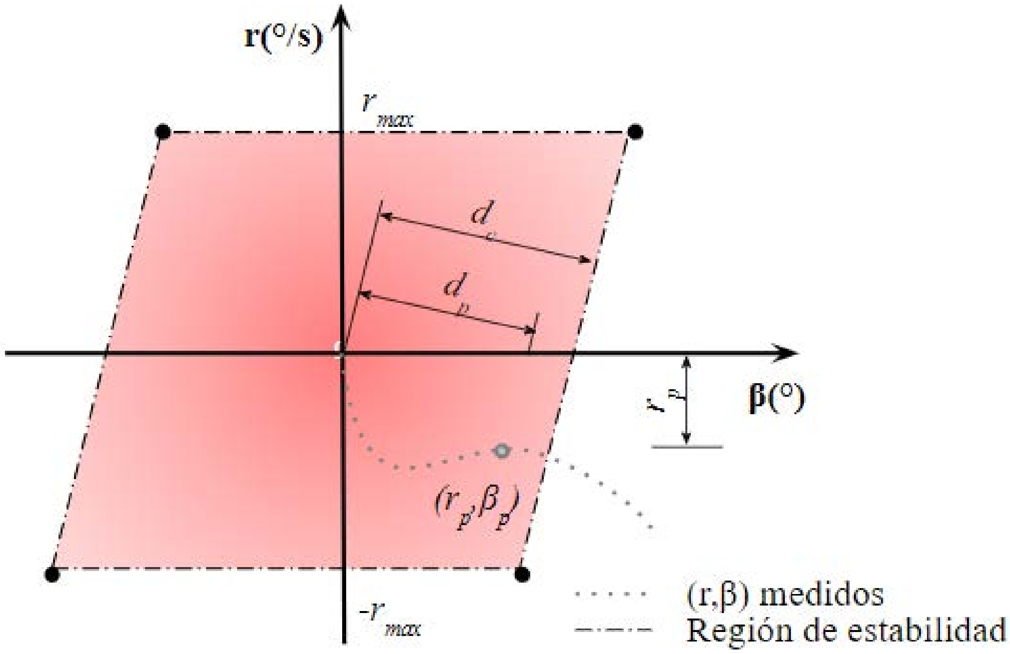

Figura 11: Parámetros para definir la seguridad disponible en cada caso

El uso de estas regiones, en conjunto con el control de la sobreaceleración, evita que el vehículo alcance situaciones comprometidas, como derrapes o pérdida de la dirección en casos más graves (Alonso, 2019).

$$\beta_{demandada}(\%) = d_p/d_c \cdot 100 \quad (6)$$

$$\dot{r}_{demandada}(\%) = r_p/r_{max} \cdot 100 \quad (7)$$

donde:

- d_p – deriva del vehículo parar una condición e instante determinado
- d_c – deriva máximo parar una condición e instante determinado
- r_p – guiñada del vehículo parar una condición e instante determinado
- r_{max} – guiñada máxima

3. RESULTADOS

En el desarrollo de la metodología, se ha considerado un adelantamiento a alta velocidad en una autopista, Figura 12. Para simplificar el caso, se han considerado velocidades constantes de todos los vehículos implicados en la maniobra.

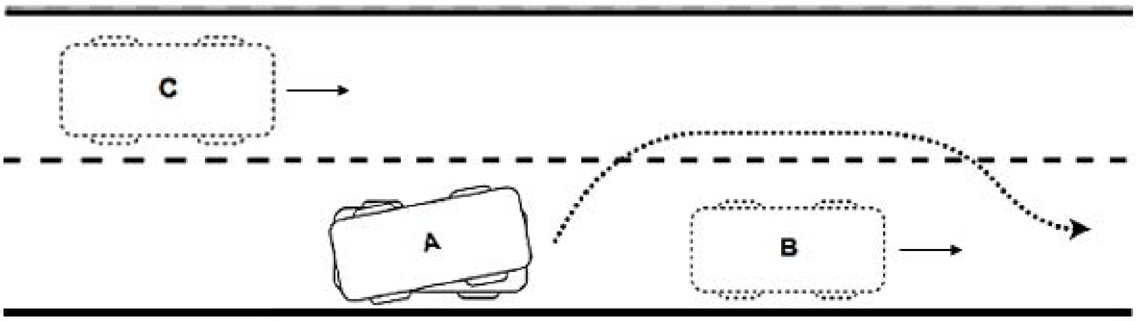

Figura 12: Adelantamiento a alta velocidad

En la Figura 13, se muestran los valores de los potenciales sobre el vehículo, frontal/trasero, laterales y diagonales. Se puede apreciar, que cuando se produce el adelantamiento el potencial frontal cambia de signo, pasa de ser positivo a negativo, también, el efecto en el potencial lateral de la maniobra de cambio de carril.

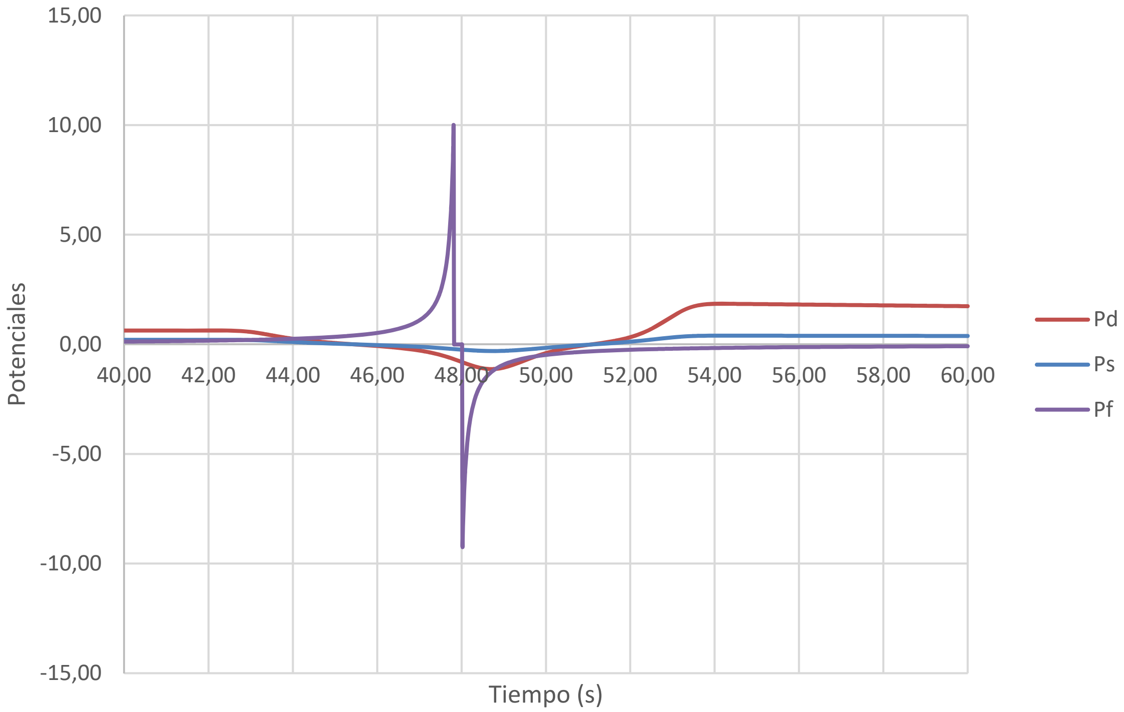

Figura 13: Potenciales sobre el vehículo

Los potenciales, no son indicativos de la seguridad con la que se realiza la maniobra, por lo que es necesario analizar los parámetros que si la determinan. La aceleración lateral y la sobreaceleración representadas en la Figura 14, alcanzan el valor definido como límite para la sobreaceleración, mientras que la aceleración lateral se mantiene por debajo de $1 m/s^2$.

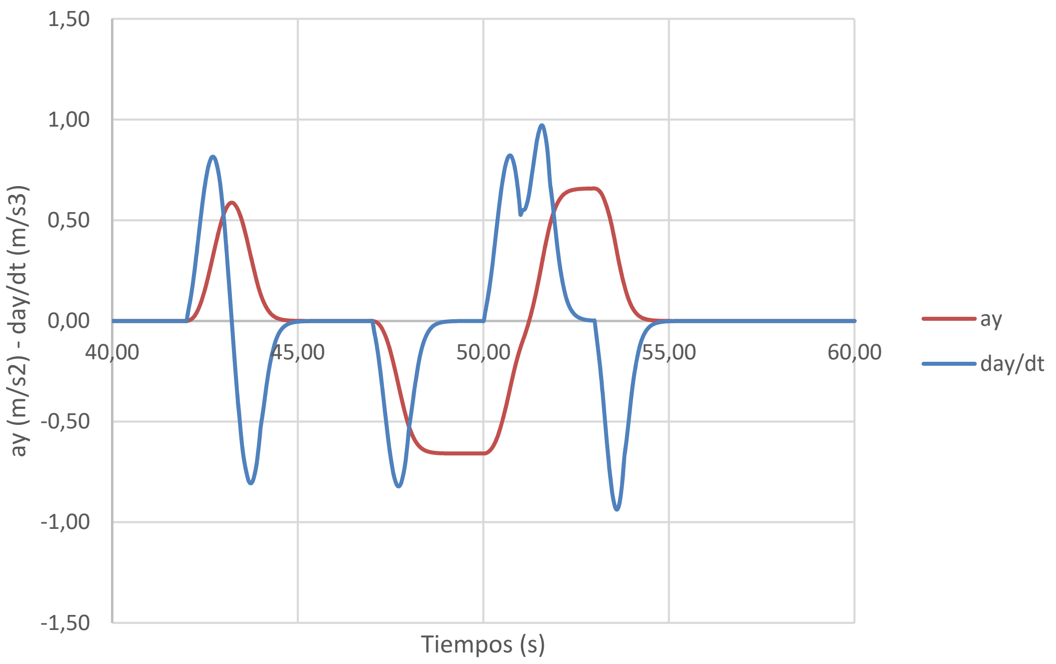

Figura 14: Aceleración y sobreaceleración en la maniobra

En el análisis de la velocidad de guiñada de la Figura 15 se aprecia que los valores obtenidos están muy por debajo del valor límite.

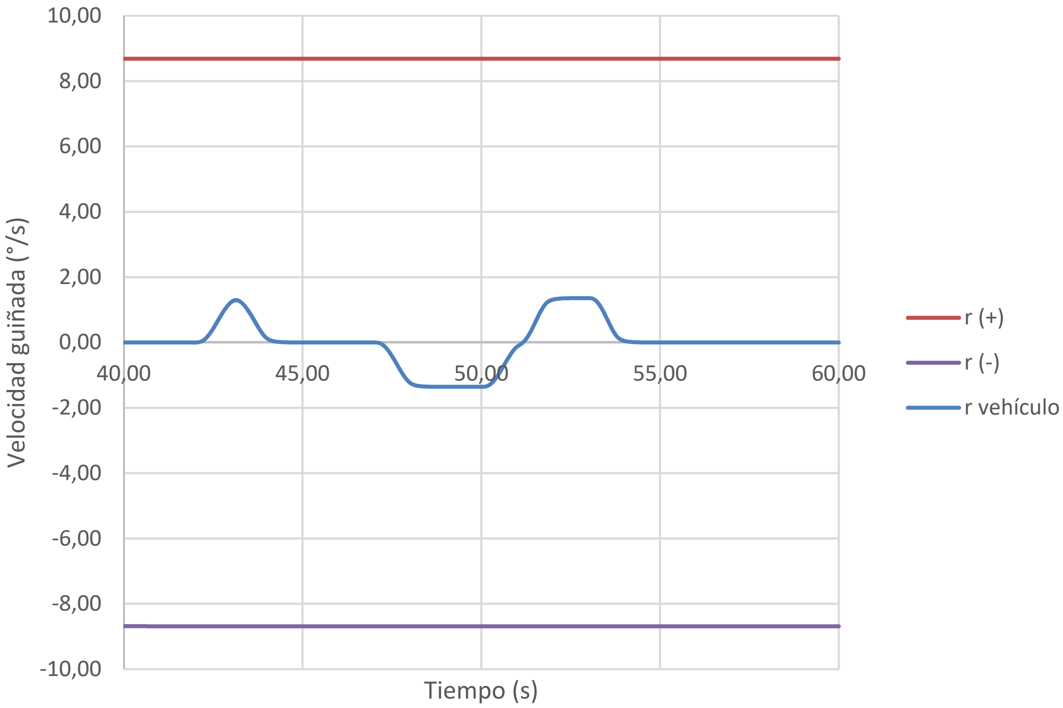

Figura 15: Valor de velocidad de guiñada del vehículo y límites

En el caso del ángulo de deriva que se representa en la Figura 16, ocurre como ocurría en el caso anterior, se tienen valores muy por debajo del límite.

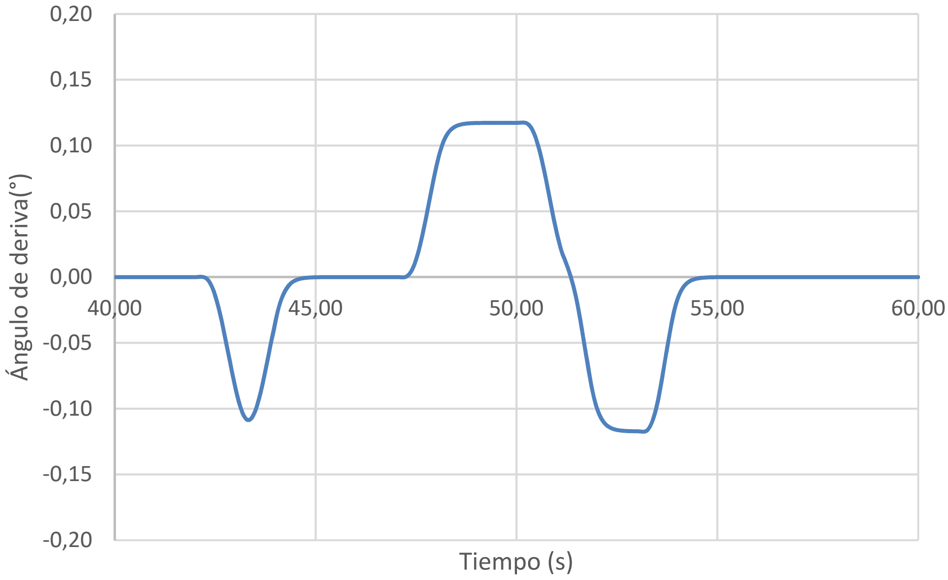

Figura 16: Ángulo de deriva del vehículo y límites

Con estos últimos análisis, se deduce que la maniobra se ha realizado con total seguridad para los conductores.

4. CONCLUSIONES

Se implementa el control para la realización de una maniobra de adelantamiento, en la que prima la seguridad de los pasajeros, ya que se asegura que no se superan los límites que puedan ocasionar lesiones al ser humano.

Los potenciales sobre el vehículo permiten posicionar el vehículo en la carretera y evitar que éste se salga de los límites durante el adelantamiento, cuando vuelve al carril derecho o que colisione con el resto de los vehículos de la vía, ya vayan delante, detrás, o en el carril de la izquierda adelantando, además de guiar al vehículo en todo momento para que la maniobra se realice correctamente.

Las regiones de estabilidad y los límites de sobreaceleración determinan la seguridad con la que se realiza la maniobra, procurando que nunca se sobrepasen los límites del vehículo, atendiendo a cada condición operativa y los límites que los seres humanos somos capaces de soportar.

Al realizarse un adelantamiento progresivo y nada agresivo, se evita el efecto sorpresa sobre el otro conductor y se reduce la posibilidad de accidente. Se controlan los límites de aceleración lateral, que pueden hacer que el vehículo derrape, dando lugar a una situación comprometida incluso para el resto de los usuarios de la vía.

Además, se controla la sobreaceleración que sufren los pasajeros durante la maniobra de adelantamiento mejorando la sensación de confort.

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REGULACIÓN VTCs Y TAXIS EN LA UE

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RESUMEN

Las licencias VTC, se definen como vehículos que tienen autorización para "ejercer la actividad de arrendamiento de vehículos con conductor". Su actividad, basada en licencias, es similar a la que desde siempre han empleado los chóferes y las limusinas. Se contrata a través de una aplicación o servicio telemático, sus tarifas no están controladas por la administración y las licencias no son de carácter unipersonal. En España, la regulación de estas licencias es competencia de las comunidades autónomas.

Pese a que la primera aparición de un servicio de estas características en Estados Unidos data de 2009, en la actualidad en Europa se carece de una legislación uniforme en relación con este nuevo modelo peer-to-peer y operan bajo licencias reservadas un servicio de conductor privado cuyos requisitos se alejan de las solicitadas al taxi tradicional para operar. Este nuevo escenario, donde se evidencian las diferencias entre los requisitos y característica del servicio de taxi tradicional ha provocado disconformidad en el sector en España, siendo destacable el caso de Madrid y Barcelona, donde la movilización de los taxistas ha impulsado cambios legislativos.

La cada vez más elevada presencia de estas nuevas plataformas en Andalucía hace necesaria un análisis de la realidad de este servicio en distintos países y ciudades, abarcando su estudio la ordenación del servicio, fiscal o tarifaria y laboral de estas plataformas.
En la comunicación se presentarían:

- Análisis inicial de las diferencias VTC/Taxi
- Legislación existente en materia de taxi y VTC o análogo
- Evaluación de licencias y tarifas en materia de taxi y VTC o análogo
- Análisis comparativo de la información recopilada (Benchmarking)
- Conclusiones y recomendaciones.

1. CONTEXTO

En la actualidad, en España hay 67.089 licencias de taxi y 5.890 de VTC, según datos del Ministerio de Fomento. La normativa reguladora de la actividad desarrollada por el servicio de taxi, establece fuertes restricciones en cuanto al número de licencias, calidad y seguridad en la prestación del servicio, así como en las tarifas a aplicar.

Por el contrario, para las empresas dedicadas a la actividad de arrendamiento con conductor, a nivel estatal, es de aplicación la Ley de Ordenación de los Transportes Terrestres (LOTT), que establece restricciones tanto en el acceso (marca un ratio de una VTC por cada 30 licencias de taxi) como en el ejercicio de la actividad.

Sin embargo, la realidad es que las competencias en esta materia están delegadas en los ayuntamientos, existiendo algunas ciudades donde exceden el límite establecido y colocan el ratio por debajo de lo establecido por la LOTT. Esto es precisamente el origen y causa de la polémica existente y el detonante de los enfrentamientos entre taxistas, conductores de vehículo privados y las administraciones en los últimos tiempos.

2. ¿Y QUE HACEN OTROS PAÍSES CON LOS UBER Y CABIFY?

PAÍS	LIBERAL.O ORDEN.	NORMATIVA	VTC OPERADOR	PRE CONTATACIÓN	FORMACIÓN	REGRESO BASES	GEOLOCAL.	CARGAS FISCALES	RESTRICCIONES VIA PUBLICA	ANTIGÜEDAD VEHICULOS	COND TEC. VEH..	TIEMPO COND
ALEMANIA	Ordenado	Estatal/ Regional	Permiso como vehículo de alquiler, conductores necesiten licencia	Si, pero sin tiempo previo establecido	La necesaria para obtener la licencia	Obligatoria	No	Mismas cargas que el taxi	No pueden estacionar en espacios reservados para Taxi	Las determinadas para los vehículos de alquiler	Las determinadas para los vehículos de alquiler	Deben pasar una inspección técnica que cada 6 meses o un año dependiendo del vehículo
AUSTRIA	Ordenado	Estatal	Los conductores de Uber son todos empleados de empresas de VTC	No, pero no pueden ser recoger clientes sin intermediación de la empresa VTC a la que	No	No regulado	No regulado	No se establecen regulaciones específicas	No pueden recoger clientes	No regulado, se imponen las restricciones de los vehículos de alquiler	No regulado, se imponen las restricciones de los vehículos de alquiler	Inspecciones determinadas para cualquier vehículo

Tabla 1: Europa (parte 1).

PAÍS	FRANCIA	ITALIA	ITALIA	PORTUGAL
LIBERAL.O ORDEN.	Ordenado	Ordenado	Ordenado	Ordenado
NORMATIVA	Estatal	Regional	Regional	Estatal
VTC OPERADOR	Deben registrarse como operadores VTC y vehículos	Funcionan a través de licencias VTC que están regulados por las regiones y los	Funcionan a través de licencias VTC que están regulados por las regiones y los	Deben establecerse como sociedades La obligación de un seguro común, un seguro de responsabilidad civil y de accidentes
PRE CONTATACIÓN	Si, pero no se determina de cuanto tiempo previo	Si, sólo pueden solicitarse vía app o internet. No pueden recoger clientes circulando por la ciudad sin previo aviso	Si, sólo pueden solicitarse vía app o internet. No pueden recoger clientes circulando por la ciudad sin previo aviso	No
FORMACIÓN	Si	No	No	Si
REGRESO BASES	Obligatoria	Si	Si	No
GEOLOCAL.	Si	No	No	No
CARGAS FISCALES	No se establecen regulaciones específicas	No se establecen regulaciones específicas	No se establecen regulaciones específicas	Impuesto del 5% de la comisión de intermediación Cargas fiscales iguales que a la de los Taxis
RESTRICCIONES VIA PUBLICA	No pueden estacionar en espacios reservados para taxi, la atención en la calle esta reservado a los taxis	No pueden usar espacios reservados para el Taxi, pero en los Aeropuertos, a través de	No pueden usar espacios reservados para el Taxi, pero en los Aeropuertos, a través de una	Los VTC se limitan a las llamadas vías comunes, no pudiendo aparcar y circular en vías reservadas a bus y taxi
ANTIGÜEDAD VEHICULOS	Menos de 6 años	Normativa de técnica de los vehículos de alquiler	Normativa de técnica de los vehículos de alquiler	Menos de 7 años
COND TEC. VEH..	4 puertas, de 4 a 9 plazas, potencia igual o superior a los 84 KW sin especificar gama o tipología. No sé aplican a los híbridos o eléctricos.	Normativa de técnica de los vehículos de alquiler	Normativa de técnica de los vehículos de alquiler	
TIEMPO COND	Deben someterse a inspecciones anuales	Deben pasar una inspección técnica que cada 6 meses o un año dependiendo del vehículo	Deben pasar una inspección técnica que cada 6 meses o un año dependiendo del vehículo	

Tabla 2: Europa (parte 2).

PAÍS	LONDRES-REINO UNIDO	DINAMARCA	RUSIA	FINLANDIA	SUECIA
LIBERAL.O ORDEN.	Ordenado	Liberalizado	No regulado	Liberalizado	Liberalizado
NORMATIVA	Municipal	Estatal	Municipal	Estatal	Estatal
VTC OPERADOR	Se debe obtener licencia como conductor, para el vehículo y como operador	Los operadores de servicio deben tener un permiso y los conductores del vehículo deben tener un	Se obliga a la obtención de licencia, pero no se	No existe distinción entre Taxi y VTC. Hay una única licencia para conductores y	Licencia para servicios de taxi aplicables a los operadores y una licencia aplicable a los
PRE CONTATACIÓN	Si, pero no se determina de cuanto tiempo previo	No	No regulado	No	No
FORMACIÓN	No	Necesaria capacitación	No regulado	Si	Para la obtención de la
REGRESO BASES	No	No	No regulado	No	No
GEOLOCAL.	No	No	No regulado	No	No
CARGAS FISCALES	No específica	Las que corresponden por el tipo de servicio	No regulado	Las mismas para taxi y VTC, es decir, transporte de pasajeros.	Las mismas para taxi y VTC, es decir, transporte de pasajeros.
RESTRICCIONES VIA PUBLICA	No pueden usar espacios reservados para el taxi y bus y deben pagar en la tasa de entrada al centro la ciudad.	No, no hay fronteras municipales para el servicio	No regulado	No, no hay fronteras municipales para el servicio	No, no hay fronteras municipales para el servicio
ANTIGÜEDAD VEHICULOS	Menos de 5 años para nuevas licencias y 10 para licencias existentes.	Menor de 6 años	No regulado	No, pero deben someterse a inspecciones anuales	No, pero deben someterse a inspecciones anuales
COND TEC. VEH..	No regulado	Vehículos aún deben estar equipados con sensores de asiento, video vigilancia	No regulado	Se deben someter a inspecciones técnicas anuales	Todos los vehículos deberán tener instalado un taxímetro
TIEMPO COND		Deben pasar una inspección técnica que cada 6 meses o un año dependiendo del vehículo	No regulado	Se deben someter a inspecciones técnicas anuales	Se deben someter a inspecciones técnicas anuales

Tabla 3: Europa (parte 3).

NEW YORK EE. UU.	TORONTO CANADÁ	RIO JANEIRO BRASIL	COLOMBIA	MÉXICO D.F MÉXICO	PAÍS
Liberalizado	Ordenado	Ordenado	Ordenado	Ordenado	LIBERAL.O ORDEN.
Municipal	Municipal	Municipal	Estatal	Municipal	NORMATIVA
	Empresas operadoras y conductores deberán adquirir una licencia de operación	Deben obtener una licencia y estar inscritos vehículo y conductor	Deben volcar sus datos de SINITT	Los conductores deben obtener una licencia para ofrecer el servicio	VTC OPERADOR
No	Si	No	No	No	PRE CONTATACIÓN
No	Para la obtención de la licencia	Necesaria para la licencia	Acreditar las empresas que los conductores están capacitados	No	FORMACIÓN
No	No regulado	No	No	No	REGRESO BASES
No	No	No	No	No	GEOLOCAL.
Ninguna específica	Régimen fiscal similar al del taxi	Debe pagar a la administración municipal una tasa	No	El 1,5% por cada viaje que es destinada al Fondo Público para el Taxi, la Movilidad y el Peatón	CARGAS FISCALES
No	No pueden usar los espacios reservados para el Taxi	No	No deben usar las vías reservadas para los taxis	No pueden hacer sitio o base, ni hacer uso de los espacios reservados al taxi	RESTRICCIONES VIA PUBLICA
Menor de 7 años	Menor de 7 años	No	No	No	ANTIGÜEDAD VEHICULOS
	Deben pasar inspecciones anuales y estar suscritos a un seguro de accidentes	No	No pueden ser vehículos particulares.	Un costo mínimo de 200.000 pesos, 12,668 dólares, y contar con aire acondicionado y bolsas de aire.	COND TEC. VEH..
		No se establece	Deben someterse a revisiones e inspecciones no se determina cada cuanto-	Deben someterse a inspecciones técnicas, como cualquier vehículo	TIEMPO COND

Tabla 4: América del Norte.

3. ANÁLISIS DETALLADO DE ALEMANIA

3.1. Las cifras

Las VTC operan en las tres de las principales ciudades de Alemania, UBER se encuentra en Berlín, Múnich y Düsseldorf, se han establecido otras plataformas como Taxify, pero de manera no continuada.

Actualmente Alemania cuenta con 56.000 licencias de Taxi, 8.161 de ellas en Berlín. No se tienen datos oficiales de número de licencias VTC, debido a que las administraciones no las han hecho públicas, pero se estima que en la capital operan 1.000 licencias de Uber TAXI, estableciendo una ratio aproximada de 1 VTC cada 8 Taxis en la ciudad de Berlín.

3.2. Cómo operan

Uber opera como servicio VTC a través de una app, donde el cliente solicita el servicio previo conocimiento del precio. Esta solicitud se remite a la centralita de la empresa de VTC adscrita a Uber que envía el aviso a los conductores para que realicen el servicio, pues estos deben partir desde la base de la compañía. El cobro se realiza mediante la aplicación.

Respecto a las tarifas son muy similares, si se toma el trayecto desde el Aeropuerto Berlín-Schönefeld hasta el centro de Berlín, la tarifa de UberX va de los 48€ a 55€ y en taxi convencional se mueve entre los 50€ a 56€.

En este caso las VTC están reguladas de manera nacional desde 2016 tras una sentencia de la Audiencia Territorial de Frankfurt que los equipara en gran medida a los taxis, es la normativa más restrictiva de los países europeos en los que opera estas plataformas.

Esta sentencia fundamentaba una serie de prerrogativas para igualar las condiciones del VTC con las del taxi tradicional. Estas se centran en regular el servicio prestado sin incidir en las cuestiones laborales y fiscales.

- Los conductores deben poseer una licencia de transporte de pasajeros para poder prestar servicio en una VTC. Es decir, deben ser conductores profesionales.
- Las empresas que operen con VTC, en consonancia con lo anterior, necesitan de una concesión para el transporte de pasajeros que es regulada por los Estados Federados, similar a las Comunidades Autónomas, que componen Alemania para operar, es decir una autorización para operar como empresa de transporte.
- Esto implica que los, vehículos deben estar dados de alta como vehículos de alquiler y estar asegurados en consecuencia.

El servicio Uber X opera en asociación con empresas de alquiler de vehículos con autorización para el transporte de pasajeros y cuyos conductores tiene la dicha licencia para transportar pasajeros.

La normativa establece como elemento fundamental la precontratación del servicio siendo obligatorio. Esta reserva no realiza directamente al conductor, sino que tiene que ser gestionada por la sede o base de la empresa a la que está adscrito el conductor. Los vehículos deben partir de la base o depósito privado de la empresa. Esto significa que no puede recoger clientes en recorridos de vuelta a la sede. Tienen obligación de volver a la base.

Aun exigiendo el gobierno federal, regulador de las licencias, un registro a las empresas operadoras, la cooperativa de taxistas, Taxi Deutschland, la más grande del país, protesta pues esta condición no es respetada por los conductores de Uber, enlazando unos viajes con otros por lo que piden un endurecimiento de la norma, mayor control y multas.

Del mismo modo, los vehículos están obligados a volver la base o depósito de la empresa a la que pertenecen tras un servicio, evitando de este modo que se mantenga circulando en busca de clientes.

Actualmente Uber opera en el país a través de UberX cuyos servicios se adaptan a la normativa germánica, estando prohibido otros servicios de la compañía como UberPop, que conectaba a particulares que quisieran desplazarse con dueños de vehículos, y UberBlack, la aplicación destinada al contrato de servicios de vehículos de alta gama de la compañía, pues estos no volvían a la base tras el servicio como implica la normativa para vehículos de alquiler con conductor.

3.3. El futuro

A finales de este año, el Ministerio de Transportes alemán ha mostrado su intención de renovar la Ley de Transportes, abriendo la puerta a la coexistencia del servicio de Taxi y VTC. El objetivo principal de esta nueva normativa es adaptar las condiciones marco para el transporte público a las necesidades cambiantes de movilidad de las personas y los nuevos desarrollos tecnológicos.

Algunos puntos del documento de puntos clave del Ministerio de Transportes ya son conocidos; "la mediación digital de los viajes" debe estar sujeta a aprobación, las empresas pueden ofrecer sus propias oportunidades de compartir el viaje a través de aplicaciones si "sustituyen, complementan o consolidan" el clásico servicio regular. Además, las empresas de alquiler de coches tendrían que ofrecer servicios para que varios usuarios pudieran compartir un viaje.

También contempla el servicio directo a pasajeros en la calle, sin precontratación, seguirá siendo un privilegio del sector del taxi. La reforma también prevé que a los municipios se les permite abolir a la obligación de regresar a base impuesta a empresas VTC.

4. CONCLUSIONES

Hay muchas diferencias sobre cómo se hace en los diferentes países de Europa. La incursión de estos servicios se ha realizado en muchos casos bajo figuras normativas en desuso como el alquiler vehículos de transporte con conductor, o limusinas y alquiler de vehículos de lujo, en su mayoría dirigidos a regular un transporte no modal, sino más bien empresarial o “de lujo”. Por lo que en muchos casos la regulación ha llegado tras la puesta en marcha de plataformas como UBER, una vez ya ganado un espacio comercial y modal.

En la mayoría de los países está regulado aunque, por ejemplo, en Rusia, se ha optado por evitado regularizarlo, y en los países escandinavos el servicio se encuentra liberalizado bajo fuertes restricciones. La normativa en su mayoría es estatal aunque en algunos casos como el de Alemania e Italia también delegan cierta competencia a las regiones. Como en España, la normativa existe a nivel municipal en Reino Unido y Rusia.

Las exigencias sobre el operador, la antigüedad de los vehículos y sus condiciones técnicas y otros factores, son muy variadas en todos los casos. Respecto al regreso a las bases es exigida aproximadamente en el 50 % de los países, como el caso descrito de Alemania.

Por último, en la mayoría de los países europeos la pre-contratación no se encuentra regulada, aunque en casos como en Francia y Alemania si se establece su obligatoriedad, pero sin determinar un tiempo previo necesario.

UN NUEVO PARADIGMA DE LA MOVILIDAD: EL AUTOBÚS ELÉCTRICO

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RESUMEN

Con respecto al transporte público, uno de los principales pilares de la movilidad urbana actual y futura en nuestras ciudades recae el autobús. Durante los últimos años y con el impulso de las nuevas políticas y leyes, la movilidad eléctrica pública está en auge, gracias al desarrollo tecnológico que ha permitido que la electricidad poco a poco vaya ganando terreno al resto de combustibles.

En efecto, los autobuses eléctricos están llamados a ser una de las principales soluciones de transporte en las ciudades, si bien su implantación está siendo relativamente lenta a excepción de China, donde hoy en día circula el 98% de los autobuses eléctricos del mundo.

Así, son muchas las ciudades que en los últimos años se han interesado por el cambio de su flota y la incorporación de autobuses eléctricos, con el claro objetivo de reducir las emisiones asociadas al transporte urbano. Sin embargo, la transición hacia el mundo eléctrico plantea serias dudas por la inherente novedad de estos nuevos vehículos, los costes de adquisición y mantenimiento, la necesidad de disponer de nuevas infraestructuras de carga, la complejidad técnica de esta nueva tecnología, así como la falta de experiencia con este tipo de autobús.

Bajo este escenario, el presente artículo pretende proporcionar una visión global sobre todos aquellos aspectos que condicionan la transición eléctrica de los autobuses, destacando el gran reto al que se enfrentan las ciudades para desplegar con eficacia amplias flotas de autobuses eléctricos.

1. INTRODUCCIÓN

Durante las últimas décadas, el transporte urbano y metropolitano ha crecido de forma notable, ligado especialmente a la expansión y el crecimiento de las grandes aglomeraciones urbanas. En particular, el crecimiento económico y del empleo en las grandes ciudades supone alrededor del 85% del PIB de la UE, por lo que son el motor del crecimiento económico.

Ahora bien, pese a las mejoras económicas proporcionadas por las ciudades, el bienestar y la calidad del aire han ido disminuyendo de forma drástica, ligado a la dependencia del transporte de los combustibles fósiles. Pese a las mejoras introducidas en los motores de combustión y la aplicación sucesivas normas EURO, el aumento de las emisiones de gases derivados de la combustión en los motores térmicos no ha hecho más que aumentar.

Así pues, en la actualidad en 23 de los 27 países de la UE se superan los estándares de calidad del aire (European Comission, 2016). Con respecto a los autobuses, en Europa son responsables aproximadamente del 0.3% de emisión de Monóxido de Carbono (CO), un 5% de Hidrocarburos (HC), un 9% de Óxidos de Nitrógeno (xNO), un 7.7% de las partículas en suspensión y un 5% de Dióxido de Carbono (CO2).

Si bien en términos generales la contribución de las emisiones de los autobuses urbanos es relativamente reducida, es cierto que es necesario llevar a cabo esfuerzos para mejorar la eficiencia de estos, de la misma forma que están realizando otros vehículos. En particular, las mejoras se fundamentan en tres grandes bloques de medidas: medidas de fomento del cambio modal, el uso racional de los medios de transporte y la renovación de flotas.

En cuanto a las medidas de cambio social y uso racional del vehículo, son numerosas las actuaciones implantadas por las ciudades, con resultados muy diversos. En cuanto a la renovación de flotas, en la actualidad se plantea una gran oportunidad para mejorar la eficiencia: los autobuses eléctricos.

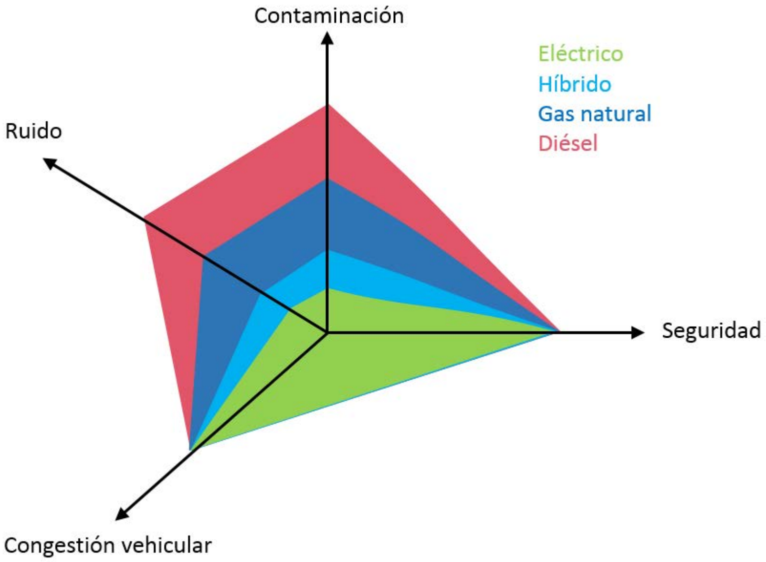

Figura 1: Comparación de los costes externos entre los modelos de buses de transporte público

En efecto, a lo largo del continente europeo son ya muchas las ciudades que están intentando apostar por el estudio, diseño e implantación de líneas de autobuses eléctricos, siendo parte de los programas fomentados por la Agencia Europea de Medio Ambiente.

Por ello, el presente artículo se centra en el estudio de los autobuses eléctricos en cuanto a su viabilidad económica, medioambiental y social que puede tener la utilización de este tipo de autobuses en las ciudades.

2. AUTOBUSES ELÉCTRICOS

En los últimos años la tecnología que sustenta el desarrollo de los autobuses urbanos ha experimentado un cambio notable. En particular, en el año 2019 circularon por las vías urbanas de diferentes ciudades más de 425.000 autobuses eléctricos, de los cuales el 99% está concentrado en diversas ciudades de China. Esto se debe a que, si bien la Unión Europea es una de las regiones punteras en investigación e innovación ecológica, los mayores productores de autobuses eléctricos se encuentran localizados en Asia. No obstante, se trata de un tipo de vehículo que se está adoptando en muchas ciudades europeas, destacando Ámsterdam, Berlín, Milán, o Paris, cuyos objetivos establecen la necesidad de tener toda su flota libre de emisiones para el año 2030.

Si bien existen muchos criterios y condicionantes técnicos, los autobuses eléctricos se caracterizan por ser aquellos vehículos que poseen un funcionamiento 100% eléctrico, al obtener la energía necesaria para realizar su función únicamente a través de motores eléctricos. En la actualidad, tanto los vehículos como las infraestructuras de carga son tecnologías emergentes con un alto grado de diversidad técnica, pero, al mismo tiempo, existe un número limitado de proveedores.

En cuanto a la forma de almacenar la energía, podemos destacar que existen tres grandes sistemas o tecnologías: baterías, catenaria e inducción.

Figura 2: Tecnologías existentes para los autobuses con motores eléctricos

2.1 Baterías

En este tipo de autobuses la energía se encuentra almacenada a bordo por medio de baterías. De esta forma, son la tipología de autobús eléctrico que presenta, a día de hoy, las mayores ventajas para su implantación en las redes de autobús modernas.

Si bien la tecnología de baterías presenta muchas alternativas técnicas, pudiendo clasificarse según el tipo de materiales utilizados y/o los métodos de carga empleados, en este apartado se llevará a cabo una descripción sintetizada con el objetivo de determinar las ventajas e inconvenientes que presentan este tipo de autobuses.

Entrando en materia, los materiales utilizados en las baterías que se instalan en los autobuses eléctricos están formadas, principalmente, por alguno de estos tres elementos: plomo-ácido, níquel y ion-litio. Con respecto a las baterías de plomo (Pb-acid), éstas estas compuestas por cátodo de dióxido de plomo, una placa de plomo como ánodo y un electrolito de ácido sulfúrico diluido. Esta configuración esta contrastada y es barata, siendo posible reciclar la misma al final de su vida útil. Sin embargo, la baja densidad de energía, su elevado peso y los largos tiempos de carga merman sus propiedades.

En cuanto a las baterías de níquel (níquel-cadmio Ni-Cd y níquel-hidruro metálico Ni-MH), poseen una mejor densidad de energía que las de plomo y un mayor número de ciclos de carga. Sin embargo, son poco eficientes en los procesos de carga y descarga y presentan problemas en bajas temperaturas. El impacto ambiental es elevado, por lo que ha llegado a prohibirse las de Ni-Cd.

Por último, la tecnología de baterías que ha facilitado el desarrollo de vehículos eléctricos está basada en el Litio. En este campo existen diferentes modelos, como son las de ion de litio (Li-ion), las de polímero de litio (Li-Po) y las de litio-ferrofosfato (LiFePO4). Este tipo de baterías poseen una alta densidad, poseen un peso ligero y bajo coste, lo que las hace especialmente útiles para su empleo en vehículos como los autobuses. Además, su mayor virtud reside fundamentalmente en la rapidez de carga, pues permite la carga completa en pocos minutos en función del sistema de carga que se emplee.

Tipo de batería	Voltaje nominal (V)	Dens. de energía (Wh/kg)	Poder específico (W/kg)	Ciclo de vida	Coste ($/kWh)	Impacto ambiental
Pb-acid	2.0	35 (baja)	180 (Pesada)	1000	60	Muy elevado
Ni-Cd	1.2	50-80	200	2000	250-300	Muy elevado (cadmio)
Ni-MH	1.2	70-95	200-300	<3000	200-250	Bajo
ZEBRA	2.6	90-120	155	>1200	230-345	Bajo
Li-ion	3.6	118-250	200-430	2000	150	Muy bajo
Li-Po	3.7	130-225	260-450	>1200	150	Muy bajo
LiFePO4	3.2	120	200-4500	>2000	350	Muy bajo
Li-S	2.5	350	-	300	100-150	En desarrollo
Zn-air	1.65	1400	80-140	200	90-120	En desarrollo
Li-air	2.9	1520-2000	-	100	-	En desarrollo

Tabla 1: Resumen de características de baterías para autobuses eléctricos.

Además de los elementos descritos, en la actualidad están desarrollándose otro tipo de baterías con el objetivo de mejorar la carga el rendimiento obtenido. De entre las más destacadas, es posible citar las de litio-azufre (Li-S), las zinc-aire (Zn-air) y las de litio-aire (Li-air). En la Tabla 1 se recogen las principales características de cada una de estas tecnologías.

2.1.1 Métodos de recarga

Tal y como ocurre con otros dispositivos provistos de baterías, tanto la durabilidad como el rendimiento de las mismas está directamente vinculado con la forma en la que se realiza la carga y descarga. Por este motivo, resulta fundamental analizar los procesos de carga realizados actualmente (Young et al., 2013), tal y como se verá en el apartado siguiente.

2.1.2 Autonomía

Una decisión importante y estratégica es la relativa a la autonomía o capacidad de almacenaje de las baterías. En efecto, es fundamental considerar que, para un autobús de 12 m, es posible emplear baterías con un rango de operación de pocos km (unos 50-60 km) hasta baterías con autonomía cercana a los 400-500 km. En realidad, pese a la aparente necesidad de autonomía, la verdadera cuestión se centra no tanto en los kilómetros disponibles con una carga, sino en las oportunidades de carga de la misma a lo largo del itinerario. Este aspecto se debatirá más adelante.

En cuanto a aspectos técnicos, la autonomía de la batería afecta negativamente a la capacidad de los pasajeros, pues a medida que se requiere mayor autonomía aumenta el volumen de la batería, lo que reduce la capacidad para alojar pasajeros, a la vez que aumenta el coste de adquisición y el peso del vehículo. Hay que tener presente que la batería representa, a día de hoy, alrededor del 50% del coste de un autobús eléctrico.

2.2 Catenaria

Este sistema de carga, similar al empleado por los trenes, se basa en el suministro de energía a través de cables suspendidos que se conectan al autobús. Tradicionalmente los vehículos que emplean este tipo de sistema son llamados trolebús. La principal ventaja reside en los costes relativamente reducidos frente al resto de alternativas, pues los componentes y los vehículos son más económicos, además de aligerar el peso de los mismos por no ser necesario el uso de baterías a bordo. Algunos países donde existe este tipo de autobús son: Rusia, República Checa, Eslovaquia, China, Canadá, Ecuador, Argentina, Paraguay, Nueva Zelanda e Italia, entre otros.

Sin embargo, su mayor inconveniente reside en que la ruta es rígida. Si bien es cierto que el uso de una pequeña batería hace que este tipo de autobuses pueda realizar maniobras y pequeños desplazamientos sin el suministro energético proporcionado por los cables. No es tan sencillo modificar un recorrido de forma rápida y sencilla, pues es necesario desplazar los cables que aportan la energía.

Además, existe un cierto impacto visual y una limitación de altura, pues los vehículos que circulan bajo la misma deben respetar un margen de seguridad para evitar problemas.

2.3 Inducción

En cuanto a las tecnologías de inducción, hay que tener presente que los vehículos que usan este sistema poseen baterías, las cuales se cargan mediante la citada inducción. En cierta medida, este sistema únicamente cambia el sistema de carga, pero se sigue manteniendo el dispositivo de almacenaje en el vehículo. La diferencia respecto al sistema convencional de baterías reside, fundamentalmente, en la tecnología y forma en la que se produce la recarga.

En particular, la carga inductiva se lleva a cabo mediante un campo electromagnético generado por unas bobinas situadas en el suelo, capaz de generar un cierto voltaje a otras bobinas alojadas en el autobús y que son las que se encargan de cargar las baterías del vehículo. De esta forma, el proceso de recarga puede ser llevado a cabo en las paradas, en la propia vía por donde circula el vehículo o en depósito.

3. INSTALACIONES DE RECARGA DE BATERÍAS

Analizando las tecnologías de carga existentes, el autobús eléctrico posee 3 opciones claramente diferencias: carga en depósitos, en paradas (de oportunidad) y el cambio de baterías.

Cada una de estas tecnologías tiene distintas implicancias operacionales y requiere una infraestructura particular, lo que resulta en diferencias importantes respecto de la gestión, mantenimiento y operación que habitualmente se lleva a cabo con autobuses convencionales.

En concreto, la programación de horarios, el dimensionamiento de la capacidad de la batería, las estaciones de recarga y los ciclos de conducción deben establecerse en función de las características de los sistemas de recarga establecidos. Así pues, las tecnologías de recarga en depósitos y en paradas parecen ser las tecnologías con mayores beneficios, las cuales se describen a continuación.

3.1 Recarga en depósitos

La terminal de carga está instalada en la cochera donde, en las horas nocturnas donde no hay servicio, los autobuses están conectados a cargadores que recargan las baterías por un periodo e intervalo de tiempo determinado, según el sistema de carga y la batería empleada.

En particular, el tiempo de carga es variable, pudiendo ir desde los 30 minutos hasta las 8-9 horas, pues depende de la capacidad de la batería, el nivel inicial de la misma y la tipología, entre otros aspectos.

En este tipo de modelos los autobuses necesitan instalar unas baterías con gran capacidad, pues es necesario que posean una autonomía suficiente a lo largo del día para cubrir todas las actividades. De lo contrario, pese a que se podría plantear su uso con una menor autonomía, existe el inconveniente de no poder estar circulando durante todas las horas que dura un servicio diario.

A su vez, este tipo de instalaciones requiere un gran espacio y un coste asociado que puede ser importante, así como un complejo sistema de gestión de las baterías.

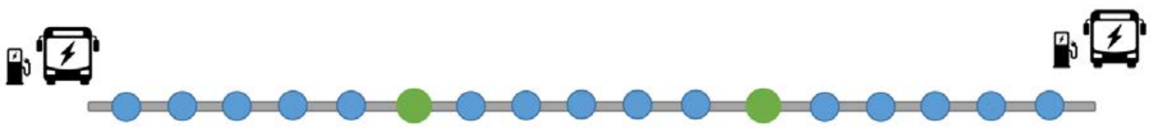

Figura 3: Esquema de recarga en depósitos

3.2 Recarga en paradas

3.2.1 Recarga en cabecera de las paradas

En este caso, los puntos de carga están instalados en tanto en la parada inicial como final de la línea por la que circula el autobús. Este esquema permite una infraestructura de carga mucho más económica respecto a la recarga en paradas, debido a la reducción en el número de cargadores necesarios. A su vez, el proceso de recarga se simplifica puesto que los buses se mantienen en carga durante los tiempos que permanecen en las cabeceras para conceder tiempo de descanso a los conductores, así como también tiempo para regular la línea, en caso de desajuste.

Con este escenario se debe considerar si el tiempo que están los vehículos parados en la cabecera es suficiente para satisfacer la recarga necesaria para mantener la autonomía del autobús a lo largo de su funcionamiento, en función de su consumo eléctrico y de la capacidad de los sistemas de carga considerados.

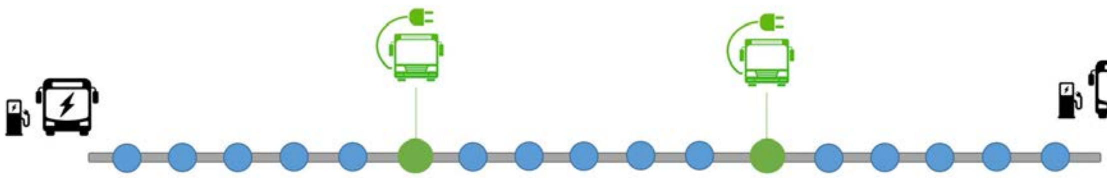

Figura 4: Esquema de recarga en cabecera de paradas

3.2.2 Recarga en paradas intermedias

En este esquema los terminales de carga se localizan en todas las paradas (o gran parte de las mismas) a lo largo del recorrido del autobús. El tiempo de carga es mínimo (tiempo durante subida/bajada de viajeros), por lo que los sistemas de carga deben tener gran capacidad para poder suministrar mucha energía en un corto período de tiempo. Tanto la cantidad de puntos de carga como las necesidades energéticas hacen que este esquema de operación sea de los más costosos frente a las otras alternativas.

Figura 5: Esquema de recarga en paradas intermedias

3.3 Cambio de baterías

Existen varias ciudades chinas donde se han realizado pruebas en estaciones de intercambio de baterías (Beijing, Jinan y Zhengzhou). Para ello los autobuses tienen una capacidad y configuración de batería similar a la de la carga de rápida, pero siendo en este caso reemplazadas por robots que permiten extraer las baterías descargadas y reemplazarlas por baterías cargadas, cuyo proceso implica un tiempo entre los 10 a 20 minutos.

Si bien se han llevado a cabo diferentes pruebas, las estaciones de intercambio de baterías son muy caras, los autobuses deben regresar necesariamente a estas estaciones para efectuar el cambio y los sistemas de intercambio de baterías no están estandarizados, por lo que no parece ser una alternativa que tenga demasiado futuro.

4. CONSUMO ENERGÉTICO

La demanda energética para un autobús eléctrico depende de múltiples factores, como la velocidad, distancia de la ruta, número de pasajeros, temperatura, topografía, calidad de la vía y comportamiento del conductor. En términos generales y según las diferentes pruebas realizadas en distintas ciudades europeas, el consumo para vehículos de 12 m varía entre los 0,7 y 2,8 kWh/km.

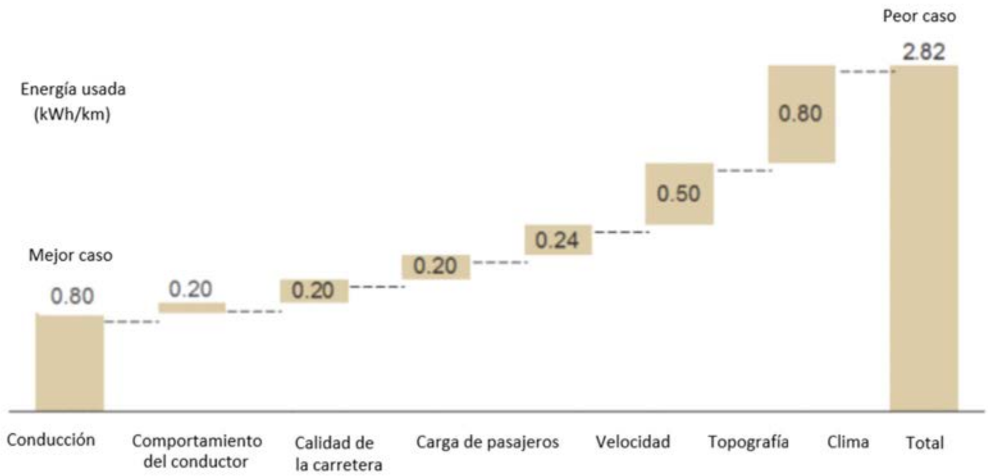

Figura 6: Consumo energético según diferentes aspectos. Fuente: Andersson, M. (2014). Energy storage solutions for electric bus fast charging stations.

En este sentido es importante hacer notar que el rendimiento se hace muy sensible a las condiciones climáticas. Los consumos pueden llegar a ser 50% mayores en temporadas muy cálidas y con alto uso del sistema de aire acondicionado o, por el contrario, en tiempos de mucho frío y un alto uso de calefacción.

Por otro lado, de cara a la explotación hay que tener presente que es altamente recomendable que las baterías funcionen en un rango entre los 15% y el 85% de su capacidad total, con el objetivo de asegurar el buen funcionamiento a lo largo de la vida útil y minimizar la pérdida de la capacidad a medida que aumenta el número de ciclos de carga.

Otro aspecto a considerar son las temperaturas de funcionamiento de las baterías. En efecto, tanto las altas como las bajas temperaturas pueden influenciar tanto el rendimiento como el proceso de carga. En particular, para temperaturas bajas se estima que el rendimiento se reduce alrededor del 10% a 0°C, 20% a -20°C y 25% a -30°C.

Por último, hay que tener presente que los vehículos eléctricos pueden contar con dos tipos de frenado: el mecánico y el eléctrico.

El frenado eléctrico es aquel que se realiza mediante la conexión de una impedancia variable con el generador que está acoplado a la transmisión, obteniendo así una desaceleración paulatina que depende de la velocidad y la posición del pedal de freno. Basa su efecto en actuar como generador cuando el vehículo se encuentra desacelerando, recuperando así la energía cinética desde las ruedas y convirtiéndola en electricidad, mejorando el rendimiento

Por otro lado, sólo para la detención total o para frenados críticos, se utiliza el freno mecánico convencional.

5. ESTRATEGIAS PARA IMPLANTAR LÍNEAS CON AUTOBUSES ELÉCTRICOS

Uno de los grandes retos que enfrenta el uso de autobuses a batería es el montaje y puesta en operación de la infraestructura de recarga de alta potencia necesaria para hacer posible el funcionamiento de una ruta de autobuses electrificada. En este caso abordaremos las particularidades asociadas a una línea de autobús eléctrico con batería, al ser la opción que mayor interés posee en la actualidad.

Es importante hacer notar que los sistemas de transporte masivo que usan energía eléctrica se han de desarrollar simultáneamente con los sistemas de distribución de electricidad. Este aspecto debe ser resuelto para garantizar una adecuada planificación de la expansión y aumento de capacidad de un sistema de transporte, en relación con la generación, distribución y transmisión de energía, minimizando las afectaciones que puedan limitar la capacidad de oferta del servicio de transporte.

Aspectos como la cantidad de estaciones de carga que se necesitan, el número de cargadores, la programación de los períodos de carga para evitar demoras son aspectos a determinar previo a la implantación de este tipo de autobuses.

A su vez, el efecto de una red de autobuses eléctrico en la red de distribución varía según cómo se abastece su demanda, en que puntos de la red, cuando y en qué cantidad se requiere la potencia de abastecimiento, etc. Además, los autobuses eléctricos necesitan transformar la energía eléctrica procedente de la red mediante la conversión de corriente alterna a continua y viceversa, utilizando equipos de electrónica de potencia, rectificadores e inversores.

Otro de los aspectos claves en la explotación de este tipo de autobuses lo constituye la autonomía. En los últimos años, se han reportado en numerosos documentos información sobre el rendimiento de buses híbridos y eléctricos. En efecto, la evaluación de la demanda energética se ha convertido en un requisito previo importante para la planificación y el despliegue de grandes flotas de autobuses eléctricos y la infraestructura de carga requerida.

6. CONCLUSIONES

Los vehículos eléctricos están cobrando una relevancia cada vez más notable en todo el mundo, en gran medida por lo benéficos medioambientales que presentan en cuanto a la reducción de emisiones en las ciudades. En este sentido,

De esta forma, a lo largo del presente artículo se ha puesto de manifiesto los factores y condicionantes respecto a la implantación de líneas de autobús urbano basado en vehículos eléctricos con baterías.

El gran reto al que se enfrentan las ciudades en su transición hacia el mundo eléctrico recae no sólo sobre la infraestructura, sino que debe considerar la forma de operar este nuevo tipo de vehículo, por lo que es necesario explorar las diferentes estrategias de carga para determinar aquella más adecuada según las necesidades de cada ciudad.

En particular, las decisiones que se tomen en los estadios más tempranos dependerá el buen funcionamiento de las futuras líneas urbanas.

Así pues, para garantizar el buen desarrollo e implantación de líneas urbanas eléctricas las ciudades se deben explorar mecanismos innovadores para adquirir y financiar la compra tanto de vehículos como de infraestructuras de carga, así como para garantizar la coordinación de las partes interesadas.

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VEHÍCULOS AUTÓNOMOS, FORMA URBANA Y NUEVOS ENFOQUES DE PLANIFICACIÓN BACKCASTING: UNA REVISIÓN DE LAS INVESTIGACIONES RECIENTES

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RESUMEN

La introducción de vehículos autónomos (VA) en los próximos años implicará un cambio disruptivo que no sólo va a afectar a la movilidad, sino que podría tener un considerable impacto en las ciudades y el conjunto del territorio.

Los principales efectos esperados se derivan de las oportunidades de regeneración de zonas urbanas previamente asignadas al tráfico y aparcamiento, y su potencial para aumentar la dispersión urbana debido a la mejora de la accesibilidad. En el momento actual estamos en un periodo crítico de transición en el que, para garantizar que su implantación tenga los efectos deseados en las ciudades/territorios, es necesario desarrollar nuevos enfoques de planificación que permitan a las administraciones identificar con suficiente antelación las políticas clave para encajar los nuevos sistemas de transporte y formas de movilidad con la visión que tenemos de las ciudades del futuro.

El objetivo de este artículo es revisar el estado actual de los cambios tecnológicos ligados a los VA, las investigaciones sobre sus implicaciones para el transporte y el desarrollo urbano y, más detalladamente, las recientes aproximaciones de planificación backcasting presentes en la literatura en el marco de los diversos esquemas de construcción de escenarios.

La revisión de estudios que emplean este tipo de planificación, basada en la creación de escenarios ideales y la identificación de medidas y políticas necesarias para alcanzar el futuro deseado, se realiza de manera sistemática mediante una búsqueda de palabras clave en las

principales bases de datos internacionales (WoS, Scopus y Google Scholar), complementada con técnicas de bola de nieve hacia adelante y hacia atrás.

Frente a otros métodos de planificación, la metodología backcasting aplicada a estudios de VA es más novedosa y está comenzando a emplearse con fuerza, si bien solo desde muy recientemente y enfocada sobre todo a su primera fase, consistente en establecer la visión del futuro. Asimismo, los estudios realizados hasta ahora resaltan su carácter más proactivo y más adecuado ante cambios significativos que requieren políticas distintas de las usuales para lograr el escenario de futuro deseado a largo plazo.

1. INTRODUCCIÓN

La introducción de las tecnologías de conducción autónoma es vista como la siguiente revolución que puede producirse tanto en el campo del transporte como en el funcionamiento de las ciudades y los territorios. Históricamente las innovaciones en el campo de la movilidad, del tranvía al coche particular, han tenido un profundo impacto en la forma urbana, permitiendo una extensión de las ciudades más allá de su centro tradicional (Rodríguez, 2020). Por lo tanto, es posible que esta nueva forma de movilidad incentive cambios importantes, tanto en la manera en la que las personas realizan sus desplazamientos cotidianos como en la elección de sus lugares de residencia y trabajo, y que todo ello conlleve importantes transformaciones en la forma urbana.

Los Vehículos Autónomos (VA) no son una hipótesis tecnológica futura, sino que en gran medida son una realidad actual que ya está presente en los *Advanced Driver Assistance Systems* (ADAS) de vehículos convencionales, así como en desarrollos tecnológicamente más complejos como los realizados por empresas como Tesla Inc. o Waymo en Estados Unidos. Los efectos de la automatización y la conectividad del transporte de viajeros y de mercancías pueden ser múltiples, desde impactos más directos en el transporte debidos a incrementos en la capacidad de las infraestructuras o impactos en la reducción de los costes del viaje o en la partición modal de las distintas áreas urbanas, hasta cambios en la estructura y la morfología urbana derivados de nuevas pautas de localización de hogares y empresas o de la reestructuración del espacio físico de las ciudades dedicado al desplazamiento y al estacionamiento de los vehículos (Milakis et al., 2017b).

El hecho de que estos cambios puedan ir en múltiples direcciones y ser muy significativos ha llevado a plantear la necesidad de planificar la implantación de los VA de forma ordenada. Por ello distintos investigadores y expertos han recurrido a métodos de planificación basados en técnicas diversas, entre las que se encuentra, como una de las más destacadas, la metodología conocida como backcasting (Dreborg, 1996). Este método de planificación tiene un fuerte componente normativo, ya que busca definir en primer lugar cuál es el futuro deseado, en este caso del sistema urbano o territorial. Además, la planificación backcasting puede plantear también cuáles serían las políticas más efectivas para alcanzar ese futuro deseado, así como la organización de las mismas en el tiempo, es decir, qué políticas habría que aplicar en las diferentes fases del proceso de planificación (e.g. implementación inicial, consolidación y alcance de la visión deseada).

En el apartado siguiente se revisan las últimas novedades relativas al estado de desarrollo tecnológico de los VA. A continuación, en el apartado 3, se repasan los principales estudios de la literatura especializada sobre los potenciales efectos que estos vehículos podrían tener tanto sobre el transporte como sobre la forma urbana. En el apartado 4 se introducen los enfoques de planificación aplicados a los VA y se analiza especialmente la metodología backcasting, resaltando las fortalezas y debilidades de este tipo de planificación. Finalmente, en el último apartado, se ofrecen las conclusiones obtenidas a partir de los resultados expuestos.

2. ESTADO DEL ARTE SOBRE LA SITUACIÓN ACTUAL DEL DESARROLLO TECNOLÓGICO DE LOS VA

2.1 Desarrollo tecnológico y comercialización

Las primeras predicciones sobre vehículos capaces de conducirse solos se remontan hasta los años 30 del siglo pasado, pero no es hasta principios de los 80 cuando se realizan las primeras investigaciones y experimentos sobre VA (Anderson et al., 2016; Townsend, 2014). Desde ese momento, el grado de automatización en los vehículos ha ido aumentando progresivamente, a medida que han surgido nuevos avances tecnológicos, pero es realmente durante la última década cuando se ha observado una verdadera apuesta por el desarrollo y futura comercialización de los mismos.

En el año 2014, la Sociedad de Ingenieros de Automoción (SAE On-Road Automated Vehicle Standards Committee, 2014) propuso una clasificación sobre los distintos niveles de automatización de los vehículos, denominada J3016, ampliamente aceptada por investigadores, técnicos y fabricantes. En 2018, la SAE actualizó esta clasificación, creando una nueva representación visual para proporcionar nuevos detalles sobre las características de cada uno de los seis niveles de la clasificación. En un primer tramo se encuentran los niveles 0 a 2, en los que el conductor sigue siendo humano, aunque ayudado por sistemas ADAS de asistencia puntual o ante emergencias (nivel 0), de guiado o de control de velocidad de crucero (nivel 1) o de guiado y de control de velocidad de crucero al mismo tiempo (nivel 2). A partir del nivel 3 se produce ya la automatización progresiva en la que el conductor humano no conduce, pero sí puede ser solicitada su intervención en determinadas situaciones (nivel 3), la automatización es completa, aunque sólo en determinados ámbitos y condiciones (nivel 4) y, finalmente, la automatización se produce ya en cualquier tipo de ámbito y condición (nivel 5), incluidas situaciones meteorológicas adversas o entornos urbanos.

En el ámbito de la tecnología de conducción autónoma, tres empresas destacan sobre el resto dado el grado de desarrollo tecnológico y nivel de operación real que han alcanzado. Estas son Waymo (propiedad de Alphabet-Inc./Google), Tesla Inc. y Uber-ATG. Waymo cuenta actualmente con una flota de entre 300 y 400 taxis autónomos operando en varias ciudades del área metropolitana de Phoenix (Arizona) (Hawkins, 2020).

Estos vehículos, que pueden clasificarse en un nivel de automatización según la SAE de entre 3 y 4, pueden ser utilizados por cualquier usuario registrado en su plataforma ofreciendo, por lo tanto, un servicio de taxi autónomo plenamente operativo en condiciones reales, aunque en un área de operación todavía restringida. El sistema requiere que la compañía realice labores de digitalización completa del área en el que van a desplazarse los vehículos mediante tecnología LiDAR. En caso de que surjan dificultades en el desplazamiento de los vehículos, o por la incapacidad de un vehículo para tomar una decisión, un operador humano puede actuar en remoto. La compañía cuenta actualmente con más de 20 millones de millas (32 millones de kilómetros) recorridas en carreteras de EE.UU. (Waymo, 2020).

A diferencia de Waymo, Tesla Inc no actúa como un proveedor de servicios de taxi, sino como un fabricante de vehículos que, entre otras características, tienen capacidad para la conducción autónoma. Los vehículos de Tesla disponen de un sistema para el apoyo a la conducción conocido como Hardware 2 (desde 2016) o Hardware 3 (desde 2019) basado en cámaras, sensores de ultrasonidos y un sistema de radar frontal más económico que el proporcionado por la tecnología de 360 grados de LiDAR. Este sistema permite a los vehículos de Tesla ofrecer ADAS, como el mantenimiento de carril, el control de crucero, al auto-aparcamiento o el reconocimiento automático de las señales de tráfico. El nivel de autonomía alcanzado por los vehículos de Tesla se sitúa entre el 2 y el 3, si bien la compañía asegura que, con la configuración Hardware 3 y nuevas versiones de su software *AutoPilot*, sus vehículos podrán alcanzar los niveles 4 y 5 en pocos años. La compañía ha declarado haber realizado más de 3 billones de millas en las carreteras de EE.UU. mediante el uso de *AutoPilot*, obteniendo información de los usuarios para la mejora del software de Inteligencia Artificial de los vehículos. En materia de seguridad los datos aportados por la empresa registran un accidente por cada 3,45 millones de millas conducidas con *AutoPilot* frente a un accidente cada 1,27 millones de millas en los vehículos conducidos de forma manual y sin medidas de seguridad activas (Tesla Inc, 2020). Sin embargo, hay que tener en cuenta que actualmente el uso del sistema *AutoPilot* de Tesla sólo está autorizado en autopistas, por lo que no es del todo comparable con los datos de conducción manual, ya que estos incluyen también la circulación en carreteras convencionales y en entornos urbanos.

La compañía Uber en su división ATG (*Advanced Technologies Group*) presentó en 2016 su primer servicio de taxis autónomos en el área urbana de Pittsburgh (EE.UU.). El sistema de sensórica de los vehículos Ford estaba basado en 20 cámaras, GPS y un sistema LiDAR (Hook, 2016). En 2017 la compañía empezó a operar en Arizona con nuevos vehículos

Volvo XC90, si bien cada VA sólo estaba autorizado a circular con la presencia de un ingeniero de la empresa en el puesto del conductor como medida de seguridad. Esto no evitó que la compañía tuviera un accidente con un peatón fallecido en 2018. Este y otros factores han provocado que la compañía haya vendido a finales de 2020 su división ATG a la *start-up* Aurora, en la que ha invertido además 400 millones de dólares adicionales (Metz y Conger, 2020).

Aurora no tiene previsto continuar con el desarrollo de taxis autónomos sino de camiones con capacidad autónoma. Por lo tanto, este es uno de los casos más claros de desarrollo tecnológico y comercial en el que la empresa no ha obtenido los resultados esperados por problemas técnicos y legales, por lo que ha preferido la desinversión y reinversión en una compañía externa que le permita acceder a las innovaciones tecnológicas que se vayan produciendo en el campo de la movilidad autónoma, pero asumiendo un menor nivel de riesgo.

2.2 Iniciativas para promover la implantación de VA en España

Aunque a mediados de la pasada década España se sitúo a la vanguardia de los países europeos con la regularización y la realización de una prueba real de conducción autónoma entre Vigo y Madrid (DGT, 2015; Chapela, 2015), el desarrollo tanto tecnológico como legislativo posterior para la implantación de los VA ha sido en general muy escaso, quedando cada vez más alejado de las prácticas internacionales.

Actualmente, España se sitúa en el puesto 22 de 30 del ranking de países que evalúa, mediante un índice global desarrollado por la firma consultora KPMG, la preparación ante la llegada de los VA (KPMG, 2020). Este índice agrupa 28 indicadores en cuatro categorías relativas al desarrollo político y legislativo (puesto 23 de 30), el desarrollo tecnológico y de la innovación (puesto 23), infraestructura (puesto 15) y aceptación del consumidor (puesto 17). Ante esta valoración, el informe recomienda que España incremente el número de iniciativas y pruebas piloto y desarrolle de su ley de movilidad para fomentar la implantación de los VA.

A nivel tecnológico, tanto en Europa como en España se han llevado a cabo proyectos de adecuación de las infraestructuras a la conducción autónoma. Uno de los más relevantes es *C-Roads* (Kernstock, 2019), al que se incorporó España en 2017 invirtiendo 9 millones de euros, junto con 16 países europeos y otros miembros asociados. *C-Roads* pretende acelerar el despliegue de los *C-ITS* (sistemas de transporte inteligente cooperativos) en Europa y en España a partir del desarrollo de múltiples proyectos piloto. En España se han desarrollado 5 de estos proyectos: DGT 3.0 (de escala nacional), SISCOGA Extended (Vigo), Madrid, Cantábrico y Mediterráneo (DGT, 2017). Estos proyectos piloto se centran en el uso de las tecnologías de comunicación Wi-Fi (ITS-G5) y móvil (3G/4G/5G) para la transmisión de información y la coordinación de los vehículos, incluyendo la presencia de VA.

Entre las iniciativas legislativas que se están desarrollando, en julio de 2020 se presentó a consulta pública el anteproyecto de la Ley de Movilidad Sostenible y Financiación del Transporte, que plantea entre sus objetivos de actuación la regulación de la digitalización y automatización del transporte (MITMA, 2020). Así mismo, a finales de 2020 el Gobierno de España firmó un Memorando de Entendimiento con el Gobierno de Francia para mejorar la interoperabilidad y armonizar la normativa entre ambos países en relación a los vehículos autónomos y conectados (Gobierno de España, 2020).

En lo que respecta a la preparación para la llegada de los VA, destaca la falta de actuación de momento desde el ámbito de la planificación regional y urbana, a pesar de las ya numerosas llamadas de atención realizadas desde el ámbito académico (Cohen y Cavoli, 2019; Milakis et al., 2017a; González-González, 2020; Legacy et al., 2018; Nogués et al., 2020; Papa y Ferreira, 2018), hecho que se agrava considerando el horizonte temporal que abarcan dichos planes. Esto es así no solo en el caso de España, sino prácticamente de todos los países, a excepción de algunas alusiones en documentos americanos, principalmente de planificación del transporte (Dupuis et al., 2015; Freemark et al., 2019; Saghir y Sands, 2020). Esto es debido, en gran medida, a la incertidumbre que tienen los decisores políticos sobre el uso y los impactos positivos y negativos que pueden ocasionar tanto en el transporte, como en los usos de suelo y la morfología urbana estos vehículos (Cavoli et al., 2017; Nogués et al., 2020; Saghir y Sands, 2020).

3. EFECTOS DE LA INTRODUCCIÓN DE LOS VA

3.1 Efectos sobre el transporte

El sistema de transporte es el ámbito que se va a ver afectado en primer lugar y de manera más directa y contundente por los VA. Es por ello que la literatura científica se ha centrado en tratar de identificar, valorar y cuantificar estos impactos por encima de otros considerados de segundo o tercer orden (Milakis et al., 2017b). Se prevé que los VA tengan importantes efectos sobre el sistema de transporte que pueden afectar tanto al valor del tiempo de viaje percibido por los usuarios como a las distancias de viaje, así como a la partición modal y a la generación de viajes en general, produciendo potencialmente un gran cambio en cómo los usuarios realizarán sus desplazamientos cotidianos. Dado que los VA aún no están disponibles y no se tienen datos empíricos, los estudios que analizan estos efectos aplican principalmente modelos y simulaciones de tráfico, modelos de elección discreta, generalmente basados en encuestas de preferencias declaradas (PD), así como otras técnicas.

Uno de los efectos más citados y discutidos es si existirá y cuál será la magnitud de un cambio en el valor del tiempo de viaje de los conductores. Si se produce una reducción en el valor del tiempo dentro de los vehículos esto se podría traducir en la posibilidad de que los conductores aceptaran realizar viajes más largos. El estudio de estos potenciales cambios se ha llevado a cabo utilizando diversas técnicas como las encuestas de PD y los modelos de elección discreta (Homem de Almeida Correia et al., 2019; Krueger et al., 2016; Steck et al.

2018) o las técnicas de construcción de escenarios y las estimaciones realizadas por expertos (Milakis et al., 2017a).

Ligado por lo tanto al fenómeno anterior, los estudios generalmente han supuesto que podría producirse un incremento de los kilómetros recorridos por los VA (Soteropoulos et al., 2019). Este tipo de estudios han utilizado modelos de simulación del transporte basados en agentes (Fagnant y Kockelman, 2014) o en actividades (Childress et al., 2015) para ofrecer sus estimaciones.

Especialmente relevante es el hecho de si se considera o no que los VA serán utilizados de forma compartida en el viaje (VAC). En este caso, y si un número significativo de viajes fueran realizados en VAC, si bien los vehículos presentes en la carretera se podrían reducir muy significativamente, el número total de kilómetros recorridos por éstos podría aumentar dada la producción de viajes en vacío y la captación de viajes desde otros modos.

El efecto que los VA y los VAC tendrán sobre otros modos de transporte es por lo tanto un tema abierto y crucial para conocer sus efectos desde el punto de vista de la sostenibilidad.

El método más utilizado para estudiar los posibles cambios en la partición modal ha sido la recolección de datos mediante encuestas de PD que permiten la estimación de modelos con los que simular las cuotas de mercado de los modos tradicionales y de los nuevos modos autónomos en diferentes escenarios. Existe el debate de si los VA, y sobre todo los VAC, pueden ser una gran competencia para el transporte público tradicional y para los modos activos (Ashkrof et al., 2019), algo que podría ser muy negativo desde el punto de vista de la movilidad sostenible e incluso de la salud pública.

Por otro lado, la generación de viajes en coche puede verse afectada por dos efectos contrapuestos. Por un lado, los VA pueden suponer, dada su habilidad para la detección de otros vehículos y el movimiento coordinado, un aumento de la capacidad de las infraestructuras de transporte. Este tipo de efectos de incrementos de capacidad han sido simulados, considerando distintos niveles de penetración de mercado de los VA, mediante modelos de tráfico (Shladover et al., 2012; Liu et al., 2018). Sin embargo, estos aumentos de capacidad, y consiguientes disminuciones en los tiempos de viaje derivados de una menor congestión, podrían ser contrarrestados por una mayor demanda inducida de viajes. Este fenómeno ha sido simulado estimando la elasticidad de la generación de viajes a los cambios en la accesibilidad y calculando cómo podría variar ésta con los nuevos tiempos de viaje más reducidos que implicaría la existencia de los VA (Meyer et al., 2017).

Otro aspecto analizado que podría influir en el tráfico es el relacionado con el aparcamiento. Diversos autores como Fagnant y Kockelman (2014), Martínez y Viegas (2017) y Zhang et al. (2015) han estimado mediante simulación que hasta el 90% de las plazas de aparcamiento en áreas urbanas podrían ser eliminadas si se contara con una oferta suficiente de VAC que eviten tiempos de espera elevados. Pero no sólo se eliminarían, sino que la distribución espacial de los mismos cambiaría. Según Zhang y Guhathakurta (2017) la existencia de tarifas por aparcar en el área urbana central podría cambiar la demanda de los aparcamientos, relocalizándola desde el centro urbano a los barrios residenciales periféricos y especialmente a aquellos con menor nivel de ingresos, donde el precio por aparcar sería gratuito.

Obviamente este sería un efecto problemático, ya que esto podría generar distancias de viaje más largas, mayor congestión y mayor gasto energético.

Millard-Ball (2019) microsimuló también efectos similares, observando que los usuarios podrán hacer que sus vehículos aparquen en localidades más alejadas, o que incluso no aparquen, provocando la generación de más tráfico y congestión a la espera de que su usuario vuelva a querer desplazarse. Además, las políticas de creación de mayor oferta de aparcamiento gratuito en las periferias podrían incrementar aún más este problema. El autor propone en cambio aprovechar la llegada de los VA a las ciudades para introducir una tarificación doble: por utilizar la vía para circular y por distancia de viaje, con el objetivo de internalizar las externalidades generadas por los vehículos.

3.2 Efectos sobre la forma urbana

Los estudios sobre los efectos que podrían tener, directa e indirectamente, los VA en la forma urbana han sido más escasos, si bien comienza a producirse cierto consenso en sus resultados. Estos estudios han usado técnicas como la construcción de escenarios y herramientas de simulación para obtener previsiones realistas de estos efectos, partiendo de supuestos sobre cuáles serán las características predominantes de la movilidad autónoma en el futuro. Los efectos estudiados pueden agruparse en dos grandes bloques (Heinrichs, 2016): cambios en la localización de la población, las actividades urbanas y la atractividad de los distintos vecindarios, y liberación de espacios hasta ahora ocupados en el desplazamiento o estacionamiento de los vehículos.

Como se ha citado en el apartado anterior, los VA pueden tener un fuerte impacto en el valor del tiempo asignado por los usuarios a sus desplazamientos y, por lo tanto, podrían verse incrementadas las longitudes de viaje con el consiguiente aumento de la accesibilidad de barrios o localidades periféricas hasta ahora menos atractivas para residir. Esto ha hecho plantearse a algunos autores que los VA podrían potenciar aún más los procesos de localización dispersa, tanto de la población como de las actividades económicas, especialmente en las ciudades de mayor tamaño (Childress et al., 2015; Soteropoulos et al., 2019). Esto podría ser un problema para la sostenibilidad futura de las áreas urbanas, dadas las implicaciones negativas que tienen los desarrollos urbanos dispersos basados en la movilidad en coche (Hennig et al., 2016).

Una de las primeras aproximaciones a las visiones de los impactos de los VA en los entornos urbanos fue planteada por Townsend (2014). Este autor se basó en la creación de cuatro visiones arquetípicas mediante el método de futuros alternativos: crecimiento o expansión de las tendencias actuales; colapso, en el que las condiciones actuales se deterioran y algunos sistemas críticos fallan; restricción, que limita el crecimiento en función de los recursos; y transformación, un cambio disruptivo que alcance un futuro basado en la innovación. En atención a los impactos esperados en los usos de suelo y el transporte, Townsend apuntó a que la automatización del transporte de viajeros llevaría a una renovada expansión urbana (*sprawl*), y a una consolidación de las llamadas ciudad de borde (*edge city*) en el escenario de crecimiento.

En el escenario de colapso se esperaría un incremento generalizado y desmesurado de la congestión, con un aumento de la movilidad a demanda, y disminución de la vitalidad y espacio de las zonas peatonales. En el caso del escenario de restricción, se podría esperar un sistema basado en autobuses autónomos regionales que consolidaran los suburbios cercanos a los centros urbanos existentes, mientras en el caso del escenario de transformación, los cambios en la propiedad y el auge de los medios digitales y la innovación conllevaría a una densificación de las ciudades, basada en desarrollos residenciales de pequeño tamaño, ciudades con más servicios y actividades, y desplazamientos cortos, en los que la movilidad peatonal y en bicicleta serían protagonistas.

El cambio de los patrones de localización en las áreas urbanas ha sido analizado por otros autores mediante métodos basados en técnicas de simulación para realizar estimaciones. Thakur et al. (2016) utilizaron un modelo de interacción entre el transporte y los usos del suelo (modelo LUTI) para estudiar las implicaciones de los VA en el Gran Melbourne. Esto lo realizaron mediante la simulación de cuatro escenarios en los que se combinaba la reducción del valor del tiempo con la presencia de *ridesharing* (trayectos compartidos). Así, la reducción del valor del tiempo implicó en las simulaciones un incremento claro de las longitudes de viaje y un menor uso del transporte público, con pérdida de población en el centro urbano en favor de localizaciones más periféricas. En cambio, una mayor importancia de la movilidad mediante *ridesharing* tuvo un efecto opuesto, menores kilómetros recorridos por los vehículos y un incremento de la población en el centro urbano. La combinación de los dos efectos al mismo tiempo tuvo efectos similares a este último escenario, pero más moderados. Por lo tanto, parece que los servicios de *ridesharing* podrían compensar los efectos de mayor dispersión urbana y mayor uso del coche de los escenarios con VA de uso privado.

Siguiendo una línea similar a la anterior, Zakharenko (2016) desarrolló un modelo de elección de ubicación basado en la teoría de la economía urbana para una ciudad idealizada bidimensional monocéntrica de forma semicircular, que calibró para una ciudad típica representativa de Estados Unidos. Este modelo asumió que los trabajadores podían elegir entre no desplazarse, desplazarse en vehículos tradicionales y desplazarse en vehículo autónomo teniendo en cuenta los costes fijos, variables y de estacionamiento de cada alternativa. Según los resultados, con la introducción de VA alrededor del 97% de la demanda diaria de estacionamiento se trasladaría a un cinturón de aparcamiento exclusivo en la periferia urbana.

Esto, a su vez, liberaría terrenos para otros usos y tendría un impacto positivo en la densidad de la actividad económica en el centro de la ciudad, impulsando las rentas del suelo. Por otra parte, la reducción de los costes de transporte debido a los VA aumentaría las distancias de viaje y haría que la ciudad expandiera su superficie en más de un 7% y los alquileres de los terrenos disminuyesen aproximadamente un 40% fuera del centro de la ciudad.

Milakis et al. (2017b) consideraron los cambios potenciales en la forma urbana asociados a la introducción de la conducción autónoma como impactos de segundo orden, basándose en el concepto de efecto dominó. Su estudio de revisión, realizado a partir de una búsqueda de la literatura científica en las principales bases de datos internacionales, resalta la escasa atención prestada a este tema. Para estos autores, los VA podrían tener un impacto tanto en la escala espacial macro (regional) como en la micro (local). A nivel regional, la mejora de la accesibilidad general derivada del menor coste del transporte, unida a la mejora de la accesibilidad individual debido a la posibilidad de las personas sin acceso a un automóvil de viajar en VA, podría incidir en la ubicación de la población y actividades incrementando los procesos de periurbanización y el desarrollo de nuevos centros. A nivel local, los VA podría transformar el paisaje urbano. La reducción de la demanda de estacionamiento fuera de la vía pública podría traer cambios en el uso del suelo (desarrollos residenciales, comerciales, espacios verdes, etc.) y en el diseño de los edificios (es decir, carriles de acceso, jardinería), facilitando nuevos desarrollos para usos del suelo más amigables para las personas.

Otros autores como Riggs et al. (2019) han proporcionado evidencia de que la tecnología autónoma puede tener diferentes impactos en distintas áreas de las ciudades como el centro, los suburbios o los bordes rurales. Los autores documentaron un taller realizado en julio de 2017 en el Simposio de vehículos autónomos (AVS 2017), en el que estudiaron los posibles cambios en el entorno construido en dos contextos urbanos diferentes: una ubicación suburbana de tranvía de los años 1920-1930 y una ubicación suburbana de posguerra de los años 1970 más periférica, ambas localizadas en Portland, Oregón, aunque los sitios estaban destinados a representar condiciones típicas en los Estados Unidos. Para evaluar los escenarios utilizaron un método de *charrette*, un proceso participativo en el que los expertos llevan a cabo una serie de diálogos con la comunidad para consensuar soluciones. Los resultados ofrecen información sobre cómo la tecnología autónoma tendría potencialmente diferentes impactos en los usos del suelo, el diseño del espacio público, la densidad urbana, la localización de la población y las actividades según la tipología de espacio urbano. Los resultados también revelan que los VA pueden afectar las decisiones modales de manera diferente según la ubicación, y cómo los responsables de la planificación urbana pueden formular soluciones de diseño y políticas de entorno construido para promover un urbanismo sostenible y habitable.

Otro trabajo interesante es el de Maia y Meyboom (2018), en el que también se analizaron los efectos de los VA en la ciudad a partir de la creación de escenarios posibles formados en base a la metodología de *Scenario learning*. Para ello, plantearon una serie de fases que comienzan con la identificación de los factores y fuerzas principales que pueden guiar la implantación de los VA y su clasificación en atención al nivel de incertidumbre y al nivel de impacto que pueden tener en el proceso. Una vez clasificados los factores se identificaron las relaciones de dependencia entre ellos para posteriormente establecer la construcción de 4 escenarios en función del cruce ortogonal entre los dos conjuntos de factores más relevantes, esto es, más inciertos y con mayor impacto.

En este caso se seleccionaron "regulación y fuerzas del entorno urbano", que distingue entre apoyar el transporte público frente a apoyar los VA y "fuerzas de mercado y de estilo de vida", que distingue entre una adopción rápida (progresivo) y una adopción lenta (conservador) de las nuevas tecnologías. En el caso de regular para apoyar los VA en un contexto progresivo, el principal impacto sería la dispersión urbana, en contraste con la apuesta por el transporte público en un contexto progresivo, que haría menos atractivos los nuevos desarrollos urbanos por su escasez de servicios públicos y liberalizaría espacios en los centros urbanos.

Estos estudios a un nivel macro sobre cambios en la localización de la población y las actividades que podrían ser incentivados por el funcionamiento de los VA, se han complementado con estudios a nivel más micro sobre los impactos en los usos del suelo. El efecto más examinado es la posible liberación de espacios en los centros urbanos debido a cambios en la localización y número de los espacios de aparcamiento. Como se ha comentado anteriormente, las simulaciones realizadas apuntan a una posible eliminación de hasta el 90% de las plazas de aparcamiento en áreas urbanas implicando una cantidad importante de superficie liberada. Duarte y Ratti (2018) llevaron a cabo la revisión de una serie de estudios sobre liberación de espacios destinados a parking, señalando que en ciudades como Melbourne y Los Ángeles las plazas de aparcamiento suponen una superficie equivalente al 76-81% del área del centro urbano. Esto se traduciría en cerca de 567.000 ha. liberadas para 2040 en el conjunto de EE.UU., según un informe de la Asociación del Plan Regional de la región metropolitana de Nueva York (RPA, 2017). Estos espacios podrían reconvertirse, por ejemplo, en zonas verdes, equipamientos o viviendas asequibles.

Además, esta liberación de espacio de estacionamiento podría ser aún mayor gracias a la optimización del mismo, esto es, debido al rediseño de los espacios de aparcamiento que permitiría la automatización. Nourinejad et al. (2018) realizaron estimaciones a este respecto, considerando la reducción del espacio destinado a apertura de puertas, eliminación de pasillos, etc., lo que podría suponer una reducción media de entre un 62% y un 87% del espacio requerido actualmente.

La liberación de espacio ofrece por lo tanto una gran oportunidad para la recualificación de zonas urbanas y la configuración de centros urbanos más densos y con mayores estándares de calidad. Milakis et al. (2017b) también revisan estos aspectos, y señalan que en los espacios previamente asignados al aparcamiento y circulación de los vehículos podrían ejecutarse nuevos desarrollos residenciales, comerciales y recreativos, o bien este espacio extra podría convertirse en carriles para vehículos de transporte público o usos que faciliten la movilidad activa, por ejemplo, espacios verdes, aceras más amplias o carriles bici. El impacto de la optimización del aparcamiento puede ser aún mayor en las zonas céntricas, donde edificios de garajes y plazas de aparcamiento podrían reconvertirse a otros usos, dando lugar a zonas céntricas más dinámicas.

Duarte y Ratti (2018) señalan que los garajes en edificios privados podrían convertirse en usos productivos como el comercio minorista y usos más nobles, desde viviendas sociales a espacios públicos, como los 51 *parklets* creados en San Francisco desde 2010, a los que han seguido muchos otros en todo el mundo. Según Sousa et al. (2018) si el espacio antes destinado a los coches se utilizase para construir carriles bici de calidad, cabría esperar un aumento del uso de la bicicleta, descongestionando las calles y atrayendo a la gente al centro de las ciudades.

Por tanto, los efectos de los VA en el transporte y el desarrollo urbano no van a depender tanto de la tecnología y el nivel de automatización de los vehículos sino sobre todo de la regulación de esta tecnología y de la gobernanza de las ciudades y regiones (Stead y Vaddadi, 2019). Es por ello, que resulta imprescindible definir claramente los objetivos de las ciudades y optar por enfoques de planificación proactivos para lograr los futuros deseados (Cohen y Cavoli, 2019; Legacy et al., 2018; González-González et al., 2020; Papa y Ferreira, 2018).

4. NUEVOS ENFOQUES DE PLANIFICACIÓN

4.1 Técnicas de planificación basadas en escenarios

Dentro del conjunto de técnicas que pueden emplearse en el campo de la planificación urbana y del transporte, la construcción de escenarios es una de las más conocidas, dada la necesidad de construir descripciones de un futuro posible y probable para plantear distintas líneas de actuación en el presente. Börjeson et al. (2006) clasificaron las técnicas de construcción de escenarios en tres grupos principales: predictivas, exploratorias y normativas. Estos tres tipos de técnicas responden a tres posibles preguntas sobre el futuro en un determinado campo de planificación: qué pasará en el futuro, qué podría pasar y cómo llegar a un objetivo deseado. Así, las técnicas predictivas buscan seleccionar el escenario más probable que ocurrirá en el futuro, bien dada la tendencia actual del sistema estudiado (escenario *Business-as-Usual*), bien ante un cambio de política o la ocurrencia de un evento especificado (escenarios *What-if*). Este tipo de predicciones suelen realizarse en el marco de algún tipo de modelo formal que intenta replicar las características fundamentales del funcionamiento y equilibrio del sistema estudiado.

Las técnicas exploratorias en cambio están basadas en la construcción sistemática de escenarios que pueden ocurrir plausiblemente en el futuro, aunque sea incierto si van a producirse realmente. La construcción de escenarios se realiza habitualmente construyendo una matriz estructurada en torno a los principales factores que se considera podrán ser claves en la evolución del sistema en el futuro (Schwartz, 2012). Este tipo de técnica permite que los planificadores tengan en cuenta distintos factores y situaciones que podrían presentarse aceptando la incertidumbre asociada al futuro. Además, los escenarios pueden generarse en función tanto de factores externos, fuera del control de la planificación, como de factores internos, describiendo el rango de las posibles consecuencias que implica actuar sobre elementos estratégicos.

Finalmente, el método de construcción de escenarios de tipo normativo descansa en la idea de alcanzar un objetivo o un conjunto de objetivos deseados. Alcanzar este escenario deseado puede implicar la aplicación de toda una serie de políticas que simplemente ajusten la situación de partida (*preserving scenarios*) o bien, si se considera que el escenario deseado no es alcanzable bajo las circunstancias actuales, de otro conjunto de políticas que contribuyan a cambiar estructuralmente el sistema estudiado (*transforming scenarios*).

Es en este segundo caso en el que se encuadra el enfoque conocido como backcasting o planificación retrospectiva, en el que se diagnostica como necesario un cambio de tendencia en el sistema estudiado que la aplicación de las políticas derivadas del ejercicio de planificación ayudará a alcanzar.

El enfoque backcasting se aplica cada vez más en los estudios de futuro en los campos relacionados con la planificación urbana (Carlsson-Kanyama et al., 2003; Phdungsilp, 2011; Bibri y Krogstie, 2017) y del transporte (Åkerman y Höjer, 2006; Banister et al., 2000; Höjer et al., 2000; Hickman y Banister, 2014; Soria-Lara y Banister, 2017). Esto se debe a que se considera un método especialmente adecuado cuando se esperan cambios disruptivos -aunque no se refieran específicamente a los VA-, que requieren una modificación drástica de las políticas a implementar.

Dentro de la metodología backcasting pueden diferenciarse a su vez distintas formas de aplicación. Según los principales agentes implicados, el contenido de la planificación puede ser establecida por grupos multidisciplinares de investigadores (*think-tank*), por expertos (*expert-led backcasting*) o mediante consultas (*participatory o collaborative backcasting*), ya sea a expertos, grupos de interés y ciudadanos en general (Doyle y Davies, 2013; Robinson et al., 2011).

Si se tiene en cuenta el foco principal del proceso de planificación puede distinguirse, de acuerdo con Wangel (2011), entre la planificación backcasting orientada al objetivo final del escenario deseado (*target-oriented*), la planificación centrada en los medios requeridos para alcanzar ese objetivo (*pathway-oriented*) y la basada en establecer los agentes y grupos de interés que pueden llevar a cabo las acciones identificadas para alcanzar el objetivo (*action-oriented*). Además, según Wangel (2011), de 21 investigaciones backcasting revisadas por el autor, la mayoría fueron *target-oriented* o *pathway-oriented*, mientras que la planificación *action-oriented* ha estado menos presente en la literatura.

En cuanto a su estructura, la metodología backcasting puede descomponerse en una serie de fases. Según los casos de aplicación, algunos autores han aplicado una metodología en tres fases, mientras que otros han utilizado un proceso algo más detallado en cinco fases. Soria-Lara y Banister (2017) han propuesto diferenciar tres fases a la hora de aplicar la planificación backcasting.

La fase de *Visioning* o de definición de la imagen futura deseada, la fase de *Policy Packaging*, de identificación de las políticas y su organización temporal en paquetes de política que pueden conducir a esa imagen deseada, y la fase de *Appraisal* o de evaluación de las políticas para intentar prever su efectividad, aceptación social y potenciales problemas de implementación. Otros autores como Quist et al. (2006) han propuesto en cambio diferenciar cinco fases en la metodología, incluyendo una fase preliminar en la que se establecerían los objetivos de la planificación, y una fase final de monitorización de la aplicación de las políticas que se han derivado del proceso.

4.2 El uso del backcasting en la planificación sobre vehículos autónomos

En este apartado se examina el contenido de los estudios recientes elaborados en el periodo 2000-2020 que emplean enfoques de tipo backcasting en el campo de la movilidad y, más concretamente, de los VA. Los estudios analizados proceden de dos fuentes principales: documentos y publicaciones académicas en revistas científicas, actas de congresos y libros; e informes de organismos públicos. Los estudios se identificaron mediante una búsqueda en la Web of Science (WoS), Scopus y Google Scholar (GS) utilizando combinaciones de la palabra backcasting con las palabras clave: autonomous vehicles, autonomous mobility, automated transport, self-driving car, driverless car y mobility on-demand, complementados con técnicas de bola de nieve hacia adelante y hacia atrás.

En total, se identificaron 15 fuentes bibliográficas que aunaban las palabras seleccionadas. Dado que el objetivo del estudio se centra en la aplicación del backcasting se desecharon 2 referencias que tratan por un lado la revisión bibliográfica de estudios sobre la elaboración de escenarios futuros para analizar los impactos de los VA en los patrones de desarrollo urbano y la forma urbana (Stead y Vaddadi, 2019), y por otro la idoneidad de distintos métodos de planificación para implantar políticas que regulen los VA (Li et al., 2019). Finalmente se seleccionaron 13 fuentes para su examen en el presente estudio (Tabla 1). En la WoS se identificaron 7 documentos, mientras que la búsqueda en GS arrojó resultados en su mayor parte repetidos, encontrándose 5 artículos adicionales. En Scopus se localizaron los mismos documentos que en los buscadores anteriores. Por último, se encontró 1 artículo más mediante la metodología bola de nieve.

Como puede verse en la Tabla 1, la mayor parte de los documentos encontrados, 10 de los 13 (77%), se centran en la primera de las fases del backcasting, el *visioning*, y 5 presentan la segunda de las fases, *policy packaging* and *pathway*, ya sea bien de manera individual bien conjuntamente con el *visioning*. Finalmente, sólo un documento se enfoca específicamente en la fase final de evaluación, *appraisal*. Esta distribución se corresponde además con el desarrollo temporal de los trabajos, apareciendo las últimas fases del backcasting en los documentos más recientes.

Documento	Buscador y palabras clave	Fase de backcasting	Tipo de backcasting
Marchau y van der Heijden (2003)	WoS: B + AT	Visioning	Participatory
Chapin et al. (2016)	Citado por Stead y Vaddadi (2019)	Visioning	Participatory
Vaddadi (2017)	GS: B + AV	Visioning	Think-tank
Papa y Ferreira (2018)	GS: B + ATV	Visioning (critical decisions)	Think-tank
Höltl et al. (2018)	WoS: B + AT	Visioning	Think-tank
Karlsson y Fredriksson (2019)	GS: B + AV	Visioning + Policy packaging	Mixed: Think-tank + Participatory
Dragomanovits et al. (2020)	GS: B + AV	Forecasting+ Backcasting: Policy packaging	Think-tank + Expert-lead
González-González et al. (2019)	WoS: B + AV GS: B + AV	Problem orientation - Visioning	Think-tank
González-González et al. (2020)	WoS: B + AV GS: B + AV	Visioning + Policy packaging	Think-tank
Nogués et al. (2020)	WoS: B + AV GS: B + AV	Appraisal	Mixed: Think-tank + Participatory
Staricco et al. (2019)	WoS: B + AV GS: B + AV	Visioning	Mixed: Think-tank + Participatory
Vitale Brovarone et al. (2019)	GS: B + AV Scopus: B+ AV	Policy Packaging	Participatory
Staricco et al. (2020)	WoS: B + AV GS: B + AV	Visioning + Policy packaging	Mixed: Think-tank + Participatory

Tabla 1: Publicaciones que aplican backcasting para planificar un futuro con vehículos autónomos

* Palabras clave: backcasting (B), autonomous vehicles (AV), autonomous mobility (AM), automated transport (AT), automated vehicles (ATV), self-driving car (S), driverless car (D)

La mayor parte de los estudios de *visioning*, 8 de los 10 (80%), emplearon un backcasting de tipo *think-tank*, es decir, las decisiones fueron tomadas por los propios grupos de investigación. Solo 2 de los casos de esta fase fueron participativos.

En los casos en los que se trata la segunda fase de *policy packaging*, o identificación y organización de las políticas, la mayor parte de los estudios emplea el enfoque participativo (3 de 5). Los estudios de políticas que no utilizaron la participación emplearon una aproximación de tipo *think-tank* o mixta *think-tank* con *expert-lead* (expertos).

Por último, el estudio que realiza la tercera fase de *appraisal* se basa en un proceso participativo *o participatory backcasting*. Es de destacar que todos los estudios que optan por la participación realizan consultas a expertos y grupos de interés, obviando de momento la consulta pública a la ciudadanía.

La primera aportación identificada es la correspondiente a Marchau y van der Heijden (2003). Estos autores realizaron un trabajo pionero de planificación mediante backcasting aplicado al caso de los sistemas de *Automated Vehicle Guidance* (AVG), que se podrían asimilar al concepto más actual de VA, en los que se automatiza la aceleración, el frenado y la dirección de los vehículos. Para ello aplicaron una metodología organizada en tres grandes pasos. En primer lugar, la construcción de diferentes conceptos de AVG utilizando *morphological analysis*.

En segundo lugar, el estudio de las condiciones de implementación de los conceptos de AVG propuestos mediante la aplicación del método Delphi, para lo que recurrieron a 117 expertos de los cuales 40 completaron hasta la tercera ronda de respuestas.

Por último, realizaron una evaluación mediante preferencias declaradas a 485 conductores y poseedores de una flota de coches sobre si los conceptos propuestos podrían ser realmente llevados a cabo. Este proceso permitió a los autores eliminar todos los sistemas de AVG que fueron considerados implausibles, poco prometedores o que no presentaron una aceptación, seleccionando únicamente los que fueron considerados como más viables.

Sin embargo, no es hasta casi 15 años más tarde cuando comienzan realmente a aparecer nuevos estudios e informes que tratan de visualizar y planificar la llegada de los VA. Chapin et al. (2016) se plantearon cómo podría tener que adaptarse el espacio urbano a las nuevas necesidades creadas por los VA.

Para desarrollar su informe realizaron una sesión participativa de *visioning* en Florida sobre los posibles impactos en ámbitos como cambios en los sentidos de las calles, gestión de puntos de subida/bajada de viajeros, cambios en los espacios de aparcamiento, cambios en la señalización, convivencia con los modos activos e incluso posibilidades abiertas para la regeneración urbana.

Para ello se consideraron dos escenarios temporales: uno con una implantación parcial de los VA (2040) y otro con una implantación total (2060). Los resultados obtenidos permitieron a los autores recomendar ciertos pasos para preparar a las ciudades para la implantación de los VA, tales como incorporarlos en el diseño de la red vial, establecer estándares para el tamaño y localización de puntos de subida y bajada de viajeros, identificar oportunidades para el desarrollo de antiguos espacios de aparcamiento y repensar los diseños de las intersecciones de forma que fuesen seguras para los peatones y ciclistas y admitiesen el uso de los VA.

Vaddadi (2017) se realizó una pregunta similar en el desarrollo de su trabajo de máster, en el que propuso distintos escenarios de aplicación a la ciudad de Ámsterdam. Para ello planteó un backcasting que desarrolla dos escenarios con un horizonte de 2040, considerando un alto uso compartido de los VA (*car on demand*) frente a un uso privado individual mayoritario (*luxury driving*).

Estableció entonces 4 fases temporales para aplicar las herramientas o medidas necesarias de planificación y propuso un conjunto de 7 guías de planificación que comprenden la cooperación de las autoridades de transporte público y empresas de desarrollo de los VA, regulación del uso de calzadas y tasas a aparcamientos, incentivos para el desarrollo de la economía compartida y políticas para promover la colaboración público-privada entre otras.

Además de ello, planteó una serie de 6 conceptos o guías de diseño urbano para llevar a cabo los cambios deseados consistentes en espacios flexibles, tecnológicamente amigables, reconversión de los aparcamientos en la calle (batería o línea) como nuevos pequeños espacios verdes o de múltiples actividades (*street parklets*), coexistencia de distintos modos de transporte de manera segura, reordenación de calles y cambio de la finalidad de los actuales grandes aparcamientos en superficie.

Papa y Ferreira (2018) utilizaron la metodología backcasting en una aproximación combinada con la metodología exploratoria para analizar las posibles consecuencias de los VA sobre la accesibilidad. La definición de escenarios futuros, uno optimista y otro pesimista, se realizó mediante la técnica exploratoria mientras el backcasting fue empleado para la identificación de decisiones críticas en relación a las medidas políticas y de planificación a implementar.

Las decisiones críticas encontradas por estos autores hacen alusión al uso compartido de los VA, el apoyo al transporte público, la sostenibilidad ambiental, los sistemas de información de redes, la cooperación autónoma, las políticas de usos de suelo y de aparcamiento, la regulación de tráficos intermodales, el diseño de la red de transporte, la exclusión social o la gestión de datos. Como conclusión del estudio los autores afirmaron que es necesario analizar qué ciudades y regiones pueden ser más vulnerables para la aparición de escenarios futuros no deseados y estudiar cómo evitar estos escenarios, para lo que hacen hincapié en el papel fundamental de la planificación para guiar el proceso de implantación de los VA.

Höltl et al. (2018) utilizaron la metodología backcasting también en el contexto de planificación del transporte, aunque sin tratar específicamente el tema de los vehículos autónomos, sino considerando éstos como uno de los posibles avances tecnológicos en el horizonte temporal contemplado, el 2050. El objetivo de su estudio era definir una hoja de ruta (*pathways*) que permitiera alcanzar la reducción de un 60% en las emisiones de Gases de Efecto Invernadero (GEI) planificadas en el Libro Blanco del Transporte (European Commission, 2011).

Los autores crearon un escenario de referencia y tres escenarios adicionales en los que se cumplía el objetivo de reducción de emisiones en base a dos factores: la velocidad de la transición en el ámbito de la tecnología del automóvil (más rápida o más lenta) y el tipo de posesión de coche (prevalencia de la posesión y uso del coche de forma privada o transición hacía la multimodalidad). De su estudio se deriva que los VA pueden tener un impacto positivo y colaborar, junto con la electrificación de los vehículos y las reducciones de emisiones por kilómetro recorrido, en alcanzar los objetivos fijados de emisiones de GEI para 2050.

Otro estudio relativo a la planificación backcasting del transporte es el realizado por Karlsson y Fredrikson (2019). Este estudio explora la afección de los VA en el transporte de pasajeros en el entorno urbano utilizando entrevistas semi-estructuradas para definir las condiciones del futuro sostenible, las brechas existentes entre la realidad actual y el futuro deseado y las acciones y estrategias que podrían ayudar a alcanzarlo. Entre estas acciones los expertos consultados identificaron como especialmente relevante la creación de incentivos para potenciar los modos de transporte compartidos sobre el uso privado de los VA. Por ello los autores propusieron utilizar la metodología de *Design Thinking* para la creación de una plataforma de taxi compartido que permitiera dar pasos hacia el futuro deseado mediante la reducción de la posesión de coche.

Dragomanovits et al. (2020) presentaron recientemente el primer avance del desarrollo de una herramienta online de toma de decisiones sobre la implantación de los VA con el objetivo de servir de ayuda a técnicos y autoridades municipales, regionales y nacionales. Esta herramienta se estructura en dos módulos, uno de conocimiento previo y otro de estimación. El primero de ellos funcionaría como repositorio en el que se puede consultar bibliografía sobre impactos clasificados en tres grupos principales: impactos directos, impactos sistémicos e impactos más amplios, así como resultados de proyectos aplicados en las ciudades participantes en el proyecto de desarrollo de la herramienta. El segundo módulo se estructura a su vez en un subsistema que sería capaz de realizar estimaciones *forecasting* para diversos escenarios considerando diferentes parámetros de entrada, y otro subsistema backcasting que, a partir de la selección de objetivos políticos, sería capaz de proponer las intervenciones que podrían conducir a una visión deseada.

A partir de 2019 nos encontramos con el trabajo de dos grupos de investigación que tratan las distintas fases del backcasting en publicaciones sucesivas. Por un lado, las publicaciones de González-González et al. (2019, 2020) y Nogués et al. (2020) abordaron las tres fases principales del backcasting, considerando el análisis de los posibles impactos urbanos de los VA para identificar los objetivos a perseguir, las medidas a implementar para guiar la implantación de los VA y su evaluación. La primera de las aportaciones identificó los objetivos de planificación fundamentales que han de perseguir las ciudades del futuro en atención a los principales documentos y agendas internacionales y comparó estos objetivos con los potenciales impactos descritos en la literatura científica.

De este modo se identificaron las oportunidades y amenazas que los VA pueden introducir para alcanzar ciudades atractivas, saludables y sostenibles, ofreciendo una primera aproximación a los objetivos de las políticas de planificación necesarias y a las medidas para alcanzarlos, como la apuesta por la mixticidad de usos, la limitación del acceso a vehículos motorizados en ciertas zonas del centro de las ciudades, y la adopción de sistemas de transporte multimodal, compartido y de gran calidad.

La segunda aportación se centró en la identificación del escenario deseado y las decisiones y medidas de planificación más relevantes para la implantación de los VA en los entornos urbanos. Para ello, se identificaron las dos decisiones estratégicas que sirven de base para la creación de cuatro escenarios de *visioning* futuros: la apuesta por la movilidad compartida y la necesidad de limitar el acceso motorizado a zonas céntricas de la ciudad.

Con el fin de lograr el escenario más favorable los autores establecieron, desde la revisión bibliográfica, una serie de medidas de planificación que se ordenaron y clasificaron en ocho paquetes de políticas (*policy packages*) y tres fases temporales (*policy paths*), desde la actualidad hasta el horizonte temporal de 2050. Estas fases se corresponden con una primera transición segura y compartida, enfocada a la convivencia temporal de los VA y los vehículos convencionales, una segunda fase centrada en la promoción de la movilidad compartida y activa, y una última fase, nombrada reconquista urbana, que aboga por mejorar el entorno urbano redefiniendo los espacios y usos de manera que los ciudadanos vuelvan a ser los protagonistas de la ciudad.

En la última de las aportaciones de este grupo (Nogués et al., 2020) se evaluaron los impactos potenciales de los VA y las políticas/paquetes de políticas que podrían ser más efectivas para alcanzar un escenario de ciudad deseada. Para ello se realizó una encuesta que fue distribuida a un panel de 55 expertos de los ámbitos de la planificación urbana, territorial y del transporte. Los resultados obtenidos mostraron escepticismo sobre los impactos positivos de los VA frente a una mayor confianza en los potenciales efectos negativos, tales como el aumento de los viajes realizados en coche y la dispersión urbana.

De las políticas propuestas, los encuestados consideraron más efectivas para paliar estos efectos y conducir al escenario preferido la potenciación de los modos de movilidad activa y el transporte público, la restricción del acceso de los modos motorizados a las áreas urbanas centrales y el aprovechamiento de los posibles espacios liberados por los vehículos convencionales para otros usos, como la mejora de las zonas verdes y los equipamientos. Además, la mayor parte de los expertos consultados consideraron que los paquetes de política planteados podían ser efectivos o muy efectivos para alcanzar el escenario deseado, a excepción de las medidas para combatir la dispersión. Estos resultados permiten conocer la efectividad de determinadas políticas de cara a futuras actuaciones y ayuda a los responsables de la planificación a establecer medidas para controlar procesos no deseados.

Por otro lado, los trabajos de Staricco et al. (2019, 2020) y Vitale Brovarone et al. (2019) trataron dos de las fases del backcasting participativo en el caso concreto de la ciudad de Turín. Las primeras aportaciones del 2019 relataron la aplicación de la fase de *visioning*, estableciendo tres escenarios en los que se evaluaron los impactos que pueden ocasionar distintas regulaciones de la circulación y el aparcamiento de los VA en la sostenibilidad y habitabilidad de la ciudad. Con la ayuda de un grupo focal formado por 7 expertos y entrevistas a 44 representantes locales (*stakeholders*) se realizó la evaluación y validación de las visiones a 2050 desarrolladas por el equipo de investigación para elegir la más recomendable. El resultado de la consulta fue -a pesar de considerarlo poco verosímil para Italia, pero sí para países nórdicos (Vitale Brovarone et al., 2019)- la recomendación del tercer escenario de fuerte regulación de los VA, en el que se restringe el acceso de VA privados a vías secundarias en zonas residenciales, promoviendo el uso de vehículos compartidos, transporte público, y especialmente los modos activos como prioritarios en estos entornos, y en el que se propone el uso de aparcamientos multinivel cercanos a las principales vías y a las afueras de las zonas residenciales. Uno de los aspectos identificados por los autores como relevantes para estudios futuros fue la escala de análisis, afirmando que sería oportuno analizar entornos metropolitanos más amplios que solamente la ciudad, con el fin de analizar otros impactos como la dispersión urbana, así como el uso de modelos LUTI que simulen las relaciones del sistema de transporte con la localización de las actividades (Staricco et al., 2019).

El documento de 2020 presentó una evaluación de las dos fases de *visioning* y *policy packaging* llevadas a cabo durante la investigación en Turín, identificando los principales retos y puntos críticos encontrados en el proceso. La fase de *policy packaging* se desarrolló, al igual que la de *visioning* explicada anteriormente, utilizando una combinación de metodologías *think-tank* y participativa. Al mismo tiempo que se consultó a los expertos mediante entrevistas sobre la visión más recomendable, se les requirió que identificaran las posibles medidas de planificación para alcanzar esta visión. De esta consulta el equipo de investigación propuso una lista de 18 medidas que fueron posteriormente debatidas en una jornada de trabajo con 8 expertos locales, resultando finalmente un total de 33 acciones clave. Estas acciones se agruparon en atención a seis temas y fueron clasificadas según tres categorías principales: política, tecnología y transformación del espacio urbano, indicando además los principales actores involucrados y la década de implementación.

Uno de los principales retos del proceso, señalado por los participantes del mismo, fue la gran incertidumbre que todavía existe respecto al horizonte temporal de la implantación de los VA, la aparición conjunta de otras innovaciones del transporte, como el transporte aéreo, y de nuevos modelos de explotación del mismo, como los sistemas MaaS y el uso compartido. Esta problemática parece que puede ser reducida con el uso mixto del procedimiento *think-tank* y el participativo, que ayudó a restringir todas las incertidumbres generadas en los participantes. Esta combinación también fue útil para contrarrestar la complicada definición de las fases de implantación de las políticas.

En este mismo contexto, la organización de las medidas de planificación en fases fue más sencilla cuando se referenció a periodos temporales intermedios (Staricco et al., 2020). Otro de los aspectos críticos fue la contextualización de la visión, en lo que respecta a la evolución socioeconómica, territorial y ambiental de la zona, que están muy interrelacionadas entre sí y con el sistema de transporte.

Para resolver este reto el estudio planteó utilizar las condiciones socioeconómicas definidas en un documento de planificación ya aprobado, el plan de transporte de la región. Por último, la voluntad y disponibilidad de los expertos locales a participar en el estudio también condiciona enormemente el procedimiento, así como el escaso o excesivo conocimiento sobre el tema. Para lidiar con esta problemática los investigadores emplearon diversas técnicas que permiten intercambiar estos conocimientos entre los participantes.

5. CONCLUSIONES

En esta ponencia se ha abordado la situación actual del desarrollo tecnológico de los VA y cómo su evolución plantea un escenario en el que estos vehículos podrían estar operativos en las ciudades en un plazo de tiempo relativamente corto. Los avances se están produciendo muy deprisa y los países se esfuerzan por impulsar su implantación, aunque con distinto grado de implicación. Desafortunadamente, España está perdiendo el empuje inicial y corre el riesgo de quedarse rezagada respecto a otros países occidentales.

Se espera que la automatización, según se ha expuesto en apartados anteriores, tenga efectos potenciales diversos y de distinto signo y magnitud, tanto sobre el transporte como sobre la forma urbana. Muchas de las investigaciones tienden a dedicar más atención a los impactos positivos y a escala local; no obstante, los impactos dependerán de la forma en la que los VA sean utilizados, así como de la implementación de políticas clave en materia regulatoria y fiscal, entre otras.

Una cuestión en la que los estudios hacen hincapié es en el papel fundamental de la planificación para encauzar con antelación la llegada de los VA y guiar su proceso de implantación. Sin embargo, fuera de la esfera académica e investigadora no existen todavía planes en la práctica de la planificación.

Desde el ámbito de la investigación, el elevado grado de incertidumbre de los cambios asociados a la conducción autónoma ha llevado a los investigadores, de acuerdo con la literatura académica examinada en esta ponencia, a plantear nuevos enfoques de planificación. En este trabajo se han expuesto los diversos métodos de planificación de escenarios y se han revisado más detalladamente aquellos estudios que se han centrado en la planificación de tipo backcasting, un método de planificación proactivo más novedoso y adecuado ante escenarios disruptivos que requieren cambios drásticos en las políticas para lograr el futuro deseado a largo plazo.

Esta revisión ha partido de una recopilación exhaustiva de artículos científicos en los principales buscadores de información, considerando el periodo 2000-2020, complementada con la técnica de bola de nieve.

Esta búsqueda ha permitido detectar las investigaciones que han utilizado el método de planificación backcasting, así como caracterizar la forma en que la han aplicado, si la han complementado con otros métodos alternativos y qué puntos fuertes y débiles presenta esta línea de investigación en su conjunto.

De la revisión bibliográfica realizada puede señalarse que hasta la fecha se han llevado a cabo escasos estudios sobre este tema, si bien en los últimos años han experimentado un notable crecimiento. La mayor parte de las investigaciones detectadas se han centrado en la fase de definición de la imagen futura deseada, con un menor desarrollo de la fase de propuesta de políticas y de paquetes de política que permitan dar pasos hacía la visión deseada, y una sola aportación en el caso de la fase de evaluación de la efectividad y problemática asociadas a estas políticas.

Respecto a los agentes implicados en el proceso de planificación, en la mayoría de los estudios las decisiones fueron tomadas por los propios investigadores o bien se basaron en la consulta a expertos y grupos de interés.

Dado que las visiones de futuro y las propuestas y evaluación de políticas, especialmente si son realizadas por expertos, pueden no ser lo suficientemente imaginativas, algunos investigadores destacan la necesidad de incorporar también la opinión de los ciudadanos, ya que además de que pueden proporcionar ideas más inesperadas, ayuda a que todos los interesados se pongan de acuerdo sobre las decisiones y pasos a seguir en el proceso.

Finalmente puede concluirse que las metodologías backcasting aplicadas hasta el momento son variadas, no existiendo un procedimiento plenamente consolidado y aceptado. Algunas investigaciones combinan el método backcasting con técnicas de construcción de escenarios y otras técnicas complementarias aplicadas a la planificación.

De cara al futuro se requerirán nuevas investigaciones que combinen la estrategia creada, mediante una planificación de tipo backcasting o mediante otros métodos, con técnicas de evaluación, ya sean basadas en simulación o en conocimiento experto, que permitan realizar estimaciones realistas sobre qué efectos es previsible obtener.

Además, también será necesario el uso de herramientas de monitorización y seguimiento de la estrategia diseñada para determinar de forma continua si se están produciendo los resultados esperados de impulso a ciudades y territorios más deseables y sostenibles.

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EL VEHÍCULO AUTÓNOMO Y EL MEDIO AMBIENTE: UNA REVISIÓN DE LA LITERATURA CIENTÍFICA

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RESUMEN

El cambio climático y el desarrollo sostenible son actualmente materias prioritarias en las agendas de todos los países y organizaciones mundiales. Dado que el transporte -y principalmente el vehículo privado- es uno de los sectores más contaminantes, la mejora de su eficiencia ambiental se ha convertido en un objetivo de máxima relevancia. En esta línea, los avances tecnológicos apuntan hacia nuevos modos entre los cuales el vehículo autónomo (VA) presenta un enorme potencial.

Este artículo hace una revisión de la literatura científica existente sobre los efectos ambientales derivados de la irrupción de los VA. Para ello se utilizan las herramientas Scopus y WoS, estableciendo categorías de búsqueda según los medios físicos que pueden verse afectados (aire, suelo…). La revisión no solamente se centra en las emisiones, el campo más explorado, sino que amplía el foco a los cambios en los usos del suelo y sus implicaciones, y a la contaminación acústica y lumínica, con el objetivo de adquirir una perspectiva más general que la conseguida hasta ahora.

Los artículos analizados presentan enfoques diferentes, aunque principalmente centrados en tres aspectos: consumos y emisiones en diferentes escenarios, hábitos del consumidor frente a las posibilidades de uso e interrelaciones con el resto de sistemas de transporte. Las estrategias y planteamientos para obtener resultados son también heterogéneos. Así, el análisis de emisiones se suele basar en modelos matemáticos con resultados variables, aunque en general se observa que la mayor eficiencia en la conducción favorecida por las comunicaciones vehículo a todo (V2X) conlleva ahorros energéticos y reducción de emisiones, amplificadas si se opta por la movilidad compartida.

No obstante, otros estudios indican que las prioridades de los usuarios pueden llevar a escenarios donde, al maximizarse el beneficio individual, se produzcan efectos ambientales negativos, lo que conduce a la necesidad de establecer una planificación que permita dar pasos hacia el modelo de desarrollo deseado.

1. INTRODUCCIÓN

En 2015 había casi 1.300 millones de vehículos en uso en todo el mundo, de los cuales casi 1.000 millones correspondían a vehículos de pasajeros (OICA, 2020), cifra que puede duplicarse para finales de la década de 2020 o principios de la década de 2030 según los parámetros actuales (Sperling y Gordon, 2009). Esto hace que el vehículo privado (incluyendo todos los tipos: turismos, SUV, pequeñas furgonetas, etc.) suponga aproximadamente el 60% de las emisiones de los gases de efecto invernadero (GEI) dentro del sector del transporte, que es a su vez el mayor contaminante dentro de todos los sectores económicos ya que emite casi 2.000 millones de toneladas de CO_2 equivalente a la atmósfera por año, es decir, casi un 30% de las emisiones totales en el caso de EE.UU. (US Environmental Protection Agency, 2020).

Con el objetivo de alcanzar una economía sin emisiones, el reto de conseguir un sector del transporte sostenible ambientalmente tiene gran importancia en la agenda de la mayoría de las organizaciones nacionales e internacionales. Actualmente, el estudio del transporte sostenible como parte del más amplio concepto de desarrollo sostenible es objeto de gran atención por parte de investigadores y agentes políticos y económicos (Zhao et al., 2020). La UE tiene como objetivo reducir las emisiones del sector del transporte en un 60% para el año 2050 con respecto a datos de 1990 (European Commission, 2011).

En este contexto, el vehículo autónomo muestra un gran potencial gracias a su circulación más eficiente con vehículos más ligeros, seguros y eléctricos, además de favorecer la adopción de la movilidad compartida. Aunque estos potenciales beneficios sean sustanciales, su uso puede generar unos importantes riesgos y desafíos que deben ser gestionados para que tales beneficios sean efectivos (Legacy et al., 2018).Teniendo en cuenta que el 70% de los GEI se emiten desde las ciudades (IEA, 2016), parece evidente que afrontar el objetivo de reducción de emisiones debe considerar la dualidad vehículo privado-ciudad.

La tecnología que permitiría alcanzar el grado de autonomía necesario para influir positivamente en el medio ambiente está todavía en desarrollo. En general, se considera que el máximo beneficio se conseguirá, entre otros factores, con el grado de automatización 5 según el estándar comúnmente aceptado. Este estándar considera 6 niveles, desde la nula automatización (nivel 0) hasta la completa automatización (nivel 5) con la que el vehículo es capaz de operar en cualquier condición ambiental o estado de la infraestructura (SAE, 2018).

Las estimaciones que diferentes autores hacen sobre la disponibilidad de esta tecnología son muy variables, en general alrededor de 2030, considerando que serán necesarios 10 o 20 años más para conseguir un escenario con una mayoría de vehículos autónomos (Milakis et al., 2017a; Hörl et al., 2016). Independientemente de la aceptación de una nueva tecnología por los consumidores, si se considera el ratio de sustitución de la flota de vehículos de pasajeros en la UE-28 del 5,6% (ICCT, 2018), no sería factible un alto grado de presencia de vehículos autónomos (VAs) en las carreteras antes de 25 años.

Algunas proyecciones económicas consideran que el vehículo autónomo y los servicios de movilidad generarán una cifra de negocio de 7 trillones de USD (5,9 billones de euros) para 2050, más que el PIB en 2017 de Japón y Brasil combinados (Lanctot, 2017), lo que supone un importante incentivo para su desarrollo. Incidiendo en su potencial, Greenwald y Kornhauser (2019) proponen una serie de motivos por los que el vehículo autónomo puede suponer una gran oportunidad de mejora para la sociedad: 1,3 millones de víctimas anuales en accidentes en el mundo, 600 billones de horas de conducción al año con una ocupación de asientos muy baja, vehículos detenidos el 96% del tiempo, el estrés que provoca la conducción, las posibilidades comerciales, las posibilidades para complementarse con los servicios de transporte público, etc. En definitiva, la consideración de las calzadas como recursos públicos limitados cuyo uso debe ser optimizado y para lo cual deben ser tenidas en cuenta las preferencias de los usuarios, muchas veces contradictorias, como la decisión antieconómica de mantener el vehículo privado y usar servicios de movilidad bajo demanda (los conocidos en España como Vehículos de Transporte con Conductor o VTC).

Debido a todas estas oportunidades y capacidades para modificar el transporte en el futuro, se está desarrollando una gran cantidad de literatura científica sobre los vehículos autónomos. De hecho, el vehículo autónomo en general es uno de los temas con una mayor atención dentro de la literatura científica hoy en día, con un ritmo de publicación de artículos creciendo por encima del 30% anual cuando la media en la literatura científica está en el entorno del 8-9% (Marçal el al., 2019). Entre toda la literatura que se genera al respecto, los estudios sobre los impactos ambientales, aunque escasos aún, empiezan a tener más presencia por la importancia de la reducción de emisiones a nivel global que podrían implicar.

En general, la literatura científica cuando estudia las repercusiones en el medio ambiente de los vehículos autónomos se centra en el consumo energético y las emisiones de GEI, analizando el vehículo autónomo individualmente, en grupo, como flotas de vehículos o como medio de transporte genérico integrado en el sistema general de transporte. Milakis et al. (2017b) identifican el consumo energético y la polución atmosférica como un efecto de tercer orden en el modelo “ripple effect” adaptado a la conducción autónoma. En ese modelo, los efectos de primer orden serían los producidos sobre el propio tráfico, el coste de viaje y la selección del modo de transporte. En el segundo orden se sitúan los efectos sobre el vehículo en propiedad, los usos del suelo y las infraestructuras.

En el tercer nivel se sitúan los efectos ambientales, la seguridad vial, la economía y la igualdad social y la salud pública. Wadud et al. (2016) identifican una serie de factores con efectos ambientales positivos –eco-driving (conducción eficiente), platooning (agrupación de vehículos circulando en fila), reducción de las congestiones, menor aceleración/frenado, disminución de accidentes, movilidad compartida y ajustes de diseño gracias a los sistemas de seguridad– y negativos –aumento de la velocidad en autopistas, incremento de peso debido a elementos de confort y entretenimiento, reducción del coste del tiempo de viaje que implica más kilómetros recorridos y acceso de nuevos usuarios.

Hay diferentes aproximaciones para estudiar los efectos del transporte en el medio ambiente que se pueden particularizar para el caso concreto de los vehículos autónomos. Taiebat et al. (2018) definen cuatro niveles de estudio: nivel "vehículo": funcionamiento, diseño, electrificación, platooning; nivel "sistema de transporte": coste del viaje, servicios de movilidad, usos, congestión, capacidad; nivel "sistema urbano": implicaciones en las infraestructuras, VAs y sistema de producción de energía, usos del suelo; y nivel "sociedad": cambio en las costumbres de viajar, usos compartidos y cambios en otros sectores. Por otro lado, según Dean et al. (2019) la gran mayoría de estudios se interesan directamente en la eficiencia energética, las emisiones y las implicaciones por kilómetros recorridos por vehículo (VKT) y muestran menor interés en el estudio del ciclo completo de vida o la contaminación acústica.

Los cambios en el uso del suelo, punto que está recibiendo creciente atención en los estudios recientes por los posibles efectos tanto positivos –liberación de espacio urbano– como negativos –dispersión urbana–, tienen gran repercusión ambiental. En ese sentido, Wilson y Chakraborty (2013) agrupan los efectos ambientales de la dispersión urbana, en "aire": pérdida de la calidad del aire, efecto isla de calor, olas de calor extremo; "energía": emisiones; "suelo": pérdida de suelo agrícola, pérdida de terreno natural y de hábitat; "agua": inundaciones, exceso de consumo de agua y restricciones de suministro, equilibrio hidrológico y pérdida del agua de lluvia.

También Bicer y Dincer (2018) identifican siete efectos ambientales derivados de los vehículos a lo largo de su ciclo completo de vida: agotamiento de recursos abióticos, acidificación, eutrofización, calentamiento global, toxicidad en humanos, reducción de la capa de ozono y toxicidad del suelo. Muchos de estos factores no se están teniendo en cuenta en la cuantificación de los impactos medioambientales de la implantación de los vehículos autónomos.

Por el momento no hay muchas revisiones con un punto de vista holístico sobre los impactos ambientales del vehículo autónomo. Sí hay artículos que hacen cierto compendio de la literatura publicada pero dentro de un análisis más amplio del "estado de la cuestión".

Dentro de aquellos que hacen una revisión concreta, Kopelias et al. (2020) analizan dos tipos de estudios desarrollados entre 2008 y 2019: estimaciones en base a propuestas lógicas sobre cómo los VAs y VEs (vehículos eléctricos) modificarán el consumo de combustible y las emisiones, y modelos matemáticos que utilizan distintos datos de entrada para obtener resultados sobre distintos escenarios simulados.

La conclusión es que el medio ambiente se ve afectado directa o indirectamente por 11 factores: vehículos eléctricos/combustibles alternativos; diseño y tamaño del vehículo; platooning; eco-driving; selección de ruta óptima; reducción de las congestiones de tráfico; kilómetros recorridos por vehículo; movilidad bajo demanda o compartida; nivel de penetración en el mercado; uso por población sin posibilidad de conducir y la predisposición del consumidor hacia el modo de transporte.

Autores como F. Liu et al. (2019) también analizan 12 grupos de datos para evaluar consumo y emisiones con alguna ligera variación respecto al anterior ya que, además de agrupar o detallar algunos de los conceptos antes indicados, incorpora otros como el ratio de sustitución de vehículos, la posible circulación a mayor velocidad y la reducción de accidentes.

Como se puede ver, algunos de los factores enumerados dependerán de la aceptación por parte del usuario. En ese sentido, Whittle et al. (2019) integran los resultados de una serie de entrevistas con expertos en transporte junto con un análisis de literatura existente para analizar qué influye en la toma de decisiones de los usuarios, que a su vez tendrá que ver con el nivel de penetración en el mercado del vehículo autónomo y si el vehículo será mayoritariamente usado de manera compartida o no.

Proponen grupos de factores relacionados con la demografía (como el poder adquisitivo), la motivación (la autonomía), los hábitos y las normas sociales y el acceso y la predisposición hacia el transporte público.

Con una visión más general, Martínez-Díaz et al. (2019) proponen un análisis amplio sobre todos los efectos de los VAs aunque no exactamente basado en una revisión sistemática de la literatura existente. En general identifican los mismos factores ya mencionados, como por ejemplo: aspectos tecnológicos, movilidad compartida, demanda, seguridad vial, aceptación social, etc. Sin embargo, mencionan dos aspectos que no aparecen citados anteriormente, el impacto territorial y las consideraciones éticas y legales.

Las implicaciones legales quedarían fuera de los efectos medioambientales de los VAs pero no así el impacto territorial, que puede hacer evolucionar la nueva movilidad hacia un escenario más sostenible o hacia uno opuesto y más contaminante (Nogués et al., 2020).

2. METODOLOGÍA

La revisión de la literatura existente sobre las implicaciones ambientales de la implantación del vehículo autónomo se llevó a cabo a partir de los buscadores Scopus y Web of Science.

Dado que un primer resultado sobre vehículos autónomos arrojó decenas de miles de referencias, fue necesario filtrar la búsqueda mediante palabras clave. Para ello se utilizó un primer bloque de palabras con las que habitualmente se hace referencia al vehículo autónomo en la literatura científica, al que se añadieron una serie de palabras para definir más la búsqueda según los parámetros del estudio. En el cuadro siguiente se incluyen las palabras clave generales utilizadas.

“Automated” OR “Autonomous” OR “Self-driving” OR “Driverless”
AND
Vehicle(s) OR Car(s)

Tabla 1: Palabras clave generales.

La búsqueda se amplió a los términos relacionados con impactos medioambientales en los diferentes medios físicos, incluyendo dos conceptos ambientales que pueden verse afectados por la implantación del vehículo autónomo en sentido positivo o negativo, la contaminación acústica y la contaminación lumínica.

AIRE	“Emissions” OR “Pollution” OR “Global Warming” OR “Greenhouse” OR “Carbon” OR “Air Quality”
SUELO	“Built environment” OR “Land use” OR “Urban form” OR “Territorial Impact”
AGUA	“Water Pollution” OR “Water Contamination” OR “Aquatic Toxicity”, “Water Consumption”
OTROS	“Noise Pollution”, “Light Pollution”

Tabla 2: Palabras clave específicas.

El procedimiento se desarrolló en tres fases. Una primera consistió en la identificación de artículos con las palabras clave indicadas. Se tuvieron en cuenta solamente los artículos publicados en inglés en revistas científicas. Después de identificados, se hizo una revisión para eliminar los artículos duplicados (se realizó la búsqueda con dos herramientas, WoS y Scopus) y aquellos que no correspondían al ámbito de estudio (por ejemplo, vehículos autónomos marinos). Los artículos restantes fueron los que se analizaron en esta investigación, estructurados según los temas de búsqueda.

En algunos casos, para reforzar o completar algún punto de vista, ampliar un análisis o incluir referencias sobre cuestiones aún no suficientemente desarrolladas se recurrió a la técnica “bola de nieve” en un sentido u otro.

3. RESULTADOS

La mayor parte de los resultados obtenidos hacen referencia al impacto medioambiental en general, al nivel de consumo energético o a las emisiones. Sobre el impacto en el uso del suelo comienza a desarrollarse un cuerpo de literatura con varias referencias, pero apenas se refieren a efectos ambientales sino urbanísticos. No se encontraron referencias que identifiquen efectos en el medio acuático como consecuencia de la irrupción del vehículo autónomo y, sin embargo, sí empiezan a analizarse los efectos en la contaminación acústica y lumínica. Finalmente se han seleccionado 90 artículos y se han tenido en cuenta varios más como resultado de las búsquedas según la técnica "bola de nieve".

Palabras clave	Fuentes identificadas	Duplicados/Fuera de tema	Revisión inicial	No representativos	Selección
"Emissions", "Pollution", "Global Warming", "Greenhouse", "Carbon", "Air Quality".	968	812	156	79	77
"Built Environment", "Land Use", "Urban Form", "Territorial Impact"	139	89	50	39	11
"Water Pollution", "Water Contamination", "Aquatic Toxicity", "Water Consumption"	18	18	0	0	0
"Noise Pollution"	16	12	4	3	1
"Light Pollution"	2	1	1	0	1

Tabla 3: Número de referencias seleccionadas.

Por cada medio se identificaron subtemas, siendo más notables estas divisiones en los aspectos más estudiados, como por ejemplo en el caso de las emisiones. Se encontraron análisis con gran cantidad de enfoques, desde el punto de vista operacional de un vehículo en particular y en su interacción con otros vehículos en situaciones de conducción concretas donde la conducción más eficiente y las comunicaciones V2V (vehículo a vehículo) y V2I (vehículo a infraestructura) son determinantes. Igualmente hay estudios a nivel de flota y de servicios de movilidad compartida o bajo demanda, a nivel de ciudad o país, con combustibles convencionales o propulsión eléctrica, etc.

A continuación se exponen los resultados de los efectos producidos en los diferentes medios afectados, cuyo esquema puede verse en la figura 1.

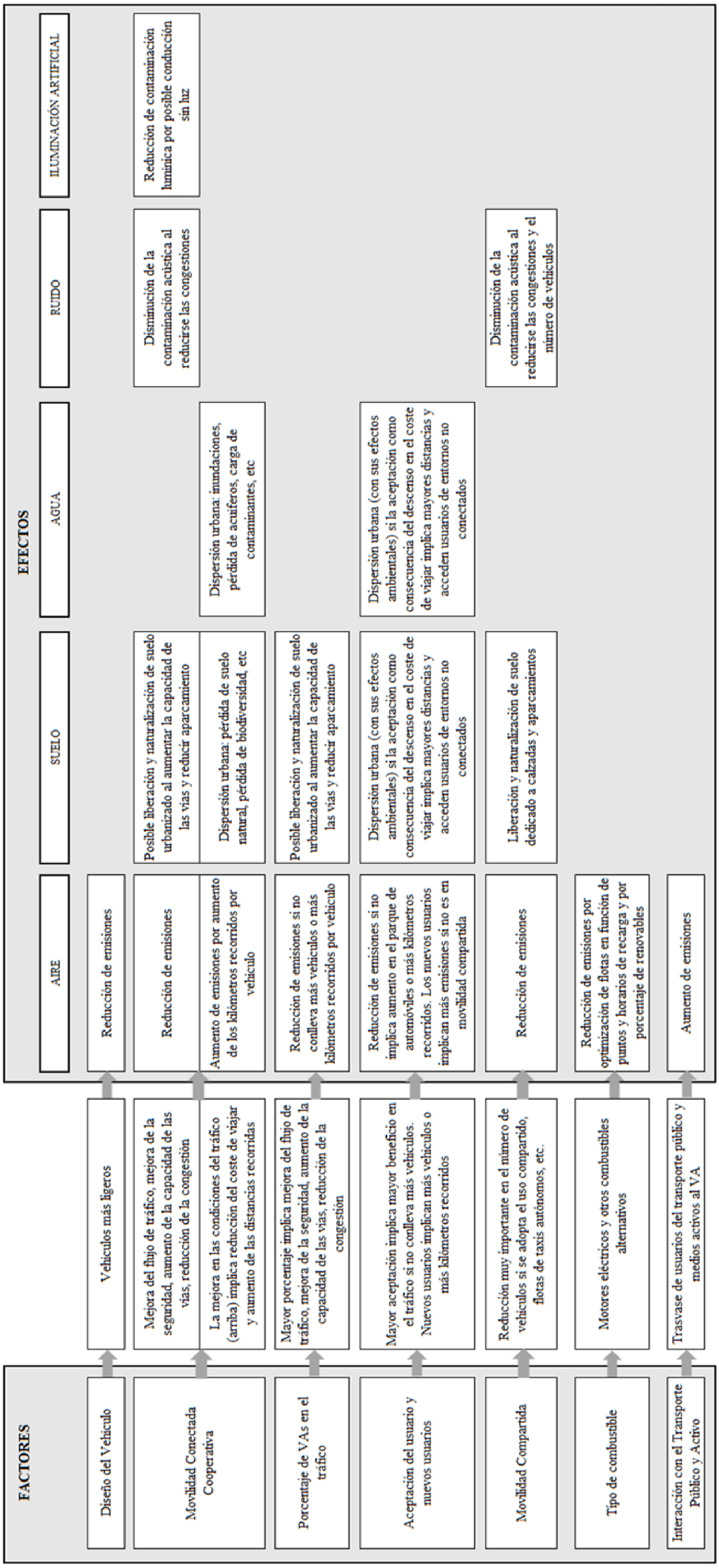

Figura 1: Efectos del vehículo autónomo en el medio ambiente.

3.1 Efectos en la calidad del aire: polución atmosférica, emisiones

3.1.1 Efectos debidos al diseño, los sistemas integrados y la circulación de los VAs

Dentro de las variables que afectan al consumo y a las emisiones del VA, en primer lugar se podrían considerar las derivadas de su propio diseño, de los sistemas de conducción empleados y de los equipos necesarios para el propio vehículo y para sus ocupantes. En ese sentido, C. Zhang et al. (2019) discretizan los consumos energéticos de un vehículo autónomo eléctrico, concluyendo que el 53,4% se consume en acelerar y vencer las resistencias al rozamiento; el 20,7% en pérdidas en el motor incluso con los motores eléctricos más eficientes; el 17,2% se pierde por las baterías y el sistema de recarga; el 3,68% por la climatización (HVAC) y el resto por los sistemas de sensorización, computación, aire acondicionado, etc. En definitiva, toda mejora en la eficiencia en la circulación redundará en menores consumos y por tanto menores emisiones.

Aparte de las mejoras puramente mecánicas (motores, baterías, etc.), gran parte de la eficiencia energética del VA se consigue mediante la mejora general del flujo del tráfico gracias a los sistemas de automatización cooperativa. Z. R. Wang et al. (2020) distinguen 5 diferentes conceptos operacionales cooperativos de los vehículos autónomos conectados (VACs) con beneficios para la seguridad, la movilidad y la sostenibilidad: 1) Control de Crucero Adaptativo Cooperativo (Cooperative Adaptative Cruise Control, CACC) y Platooning; 2) Incorporación Cooperativa en Accesos de Autopistas (Cooperative Merging at Highway On-Ramps); 3) Armonización de Velocidad en Autopistas (Speed Harmonization on Highways); 4) Conducción Eficiente Cooperativa en Intersecciones Señalizadas (Cooperative Eco-driving at Signalized Intersections); 5) Conducción Eficiente Cooperativa en Intersecciones No Señalizadas (Cooperative Eco-driving at Non-Signalized Intersections); clasificando además sus potenciales beneficios ambientales, siendo mayores en el caso 4) seguido del 1) y ya menor en el resto de los conceptos.

Numerosos estudios modelizan los conceptos operacionales antes indicados. Uno de ellos es la mejora del tránsito de los VAs en las intersecciones mediante las conexiones entre vehículos y/o con la propia infraestructura, con evidentes consecuencias medioambientales en cuanto a la reducción de las emisiones al conseguir mayor fluidez de tráfico (Almannaa et al., 2019; Astarita et al., 2019; Bento et al., 2019; Bichiou y Rakha, 2019; Chen y Liu, 2019; Feng et al., 2018; Filocamo et al., 2020; Jiang et al., 2018; Z. Li et al., 2015; Lin et al., 2017; C. Wang et al., 2020; Z. Wang et al., 2020).

Lo mismo ocurre con las rotondas (Cao y Zöldy, 2020), carriles de aceleración/acceso a autopistas (Ding et al., 2020) o circulación general (Xiao et al., 2020), e igualmente, diversos autores proponen mejoras en el flujo del tráfico reduciendo aceleraciones y frenazos mediante límites de velocidad cooperativos u otros sistemas combinados relativos al control de la velocidad (Arefizadeh y Talebpour, 2018; Guo et al., 2020; C. L. Liuet al., 2019; C. S. Miao et al., 2018; Stebbins et al., 2017; Yu y Fan, 2019; X. Zhang et al., 2019).

Además de la optimización de ciertos movimientos y la conducción en general, diversos estudios analizan los efectos de la incorporación a los VAs de varios sistemas de análisis, control y gestión de múltiples parámetros con los que también se obtienen reducciones importantes en el nivel de emisiones (Djavadian et al., 2020; C. R. Lu et al., 2019a; J. Q. Ma et al., 2019; Mahdinia et al., 2020; Phan et al., 2020; Rong et al., 2018; Tu et al., 2019; Zhai et al., 2019)

Independientemente de operaciones concretas o de la aplicación de diferentes sistemas, Stogios et al. (2019) analizan la fluctuación en las emisiones simulando ciertas condiciones de tráfico y en función de cómo se programen los parámetros de conducción.

Otras funciones que se avanzan tienen que ver, por ejemplo, con las posibilidades del aparcamiento en doble fila con estacionamientos dinámicos que, a la vez que aumentan la capacidad de aparcamiento en horas determinadas, reducen las emisiones frente a la opción de circular en vacío hasta un parking (Estepa et al., 2017).

No obstante, algunos estudios alertan sobre la necesidad de considerar el ciclo completo de vida de un vehículo y no centrarse solamente en su fase operativa. Patella et al. (2019a) tienen en cuenta tres fases: producción, uso y final de vida útil. Los resultados indican que, por unidad de vehículo, el autónomo es el que más impacto ambiental genera. Las emisiones correspondientes a la fase de construcción, mantenimiento y fin de vida útil, de media son un 35% superiores a los de un vehículo convencional de combustión interna, un 22% superiores a los de un vehículo híbrido y un 5% superiores a los de un vehículo eléctrico pese a que, en la fase operacional, el vehículo autónomo consigue ahorros del 60%, si bien es cierto que este resultado es muy dependiente del “pool” de generación de energía eléctrica y de las hipótesis consideradas en la fase operativa.

3.1.2 Efectos con tráfico mixto VAs/VCs (vehículos autónomos/vehículos convencionales) y grados de penetración en el mercado de los VAs

La penetración del vehículo autónomo será gradual, por lo que durante un periodo de tiempo considerable lo habitual será la convivencia de vehículos autónomos y vehículos convencionales, conectados o sin conectar en ambos casos, y cuyos tiempos de respuesta ante la información recibida y la toma de decisiones varían enormemente. En experimentos de campo en circuito cerrado, la presencia de VAs, incluso en bajos porcentajes (5%), estabiliza el tráfico y suaviza los intervalos de parada-aceleración consiguiendo reducciones de emisiones del 15% en CO_2 y hasta el 73% en NO_x (Stern et al., 2019). No obstante, en modelizaciones de tráfico real con vehículos con conductor, vehículos autónomos y vehículos autónomos conectados, no siempre la presencia de vehículos autónomos mejora las condiciones del tráfico ya que, si no están interconectados, al considerar parámetros de seguridad y confort en situaciones de alta densidad de tráfico, reducen la velocidad y obligan a bajar la velocidad del resto de vehículos, disminuyendo la capacidad de las vías y generando más congestión (Mattas et al., 2018).

Rafael et al. (2020) estudian el impacto de los VAs en la calidad del aire en una zona urbana con un ratio de penetración del 30%, produciéndose un ligero incremento en emisiones de CO_2 y NO_x como consecuencia de un aumento en la demanda y de aceleraciones después de paradas; sin embargo, en un escenario de vehículos autónomos con un 30% eléctricos se consiguen reducciones en emisiones, variando según la época del año e incluso del día en función de la composición de la generación eléctrica. Simulaciones en entornos urbanos de un vehículo autónomo conectado con propulsión híbrida gestionados mediante modelos predictivos y estrategias “eco-driving” muestran resultados satisfactorios en cuanto a reducción de emisiones (S. Wang et al., 2020)

Se aprecia en diferentes estudios que el ratio de VAs en el tráfico afecta a dos parámetros fundamentales, a su vez relacionados con las emisiones: la capacidad de la vía y el límite de velocidad, de tal manera que es esperable una reducción en las emisiones en la medida que crece la presencia de VAs y por tanto mejora la capacidad de las vías, siempre y cuando esto no conlleve aumentos en los límites de velocidad por encima de un óptimo estimado en 95 km/h (Hwang y Song, 2019).

Igualmente, en una simulación de un tramo de autopista real, con modelos de tráfico relativamente congestionado (entre el 0,7 y el 0,9 de la capacidad de la vía), la introducción de VAs arroja beneficios en cuanto a las emisiones generadas, que disminuyen a medida que aumenta el porcentaje de VAs, pero si se si simula un escenario extremo fuertemente congestionado -3 veces la capacidad de la vía- con el 100% de VAs, aunque mejora el flujo de vehículos, se produce degradación medioambiental como consecuencia de una mayor densidad de tráfico (Li y Wagner, 2019). Es decir, en situaciones de congestión, los VAs conectados aumentan la capacidad de las vías, pero generan más emisiones en términos absolutos (Makridis et al., 2020).

De forma similar, Jin et al. (2020) modelizan un entorno de tráfico mixto concluyendo que el flujo de vehículos mejora con la presencia de VAs, gracias al procesamiento de la información que suministran los vehículos que van por delante. Sin embargo, este flujo se puede desestabilizara medida que aumentan los tiempos de respuesta de los conductores de los vehículos convencionales así que, un aumento del ratio de penetración de vehículos autónomos puede mejorar la eficiencia y hacer descender las emisiones. Sin embargo, el ahorro de combustible, y por tanto el descenso de emisiones de un vehículo concreto, no siempre conlleva ahorros y descenso de emisiones de todo el sistema.

De hecho, la localización de los VAs dentro de la fila de vehículos circulando debe tenerse en cuenta en los análisis y así, si al frente de una hilera de vehículos parte convencionales y parte autónomos se sitúa un vehículo autónomo, todo el grupo puede conseguir hasta un 2% adicional de ahorro de combustible y linealmente reducir las emisiones (C. R. Lu et al., 2019b).

Al igual que está siendo desarrollada la optimización de movimientos en intersecciones con tráfico exclusivamente de VAs, también empiezan a estudiarse las intersecciones con combinaciones de VAs y vehículos parcialmente conectados, consiguiendo, en general, mejorar el rendimiento de la intersección y, por tanto, reduciendo las emisiones (Jiang et al., 2017; Z. Yao et al., 2020; Kamal et al., 2020), aunque con bajos niveles de penetración de VAs conectados las emisiones pueden aumentar debido al comportamiento ineficiente de los vehículos con conductor no conectados (McConky y Rungtan, 2019).

También la implementación de los sistemas ACC (Adaptative Cruise Control) tiene su influencia en entornos de tráfico mixto ya que incluso un grupo de vehículos heterogéneos, parte convencionales y parte autónomos, tiene unos niveles de consumo y de emisiones inferiores a los de un grupo de vehículos convencionales gracias a estos sistemas, incluso mejorando en la medida que el ratio de penetración en el mercado de los VAs es mayor (Huang et al., 2020). F. Ma et al. (2019) incluso proponen mejoras en el consumo energético, y por tanto en las emisiones, respecto a las actuales propuestas de sistemas ACC utilizando estrategias predictivas con modelos no lineales. También Ghiasi et al. (2019) proponen un sistema para armonizar la velocidad entre vehículos autónomos, vehículos conectados pero no autónomos y vehículos con conductor y no conectados, es decir, a todo el flujo de tráfico, y adaptable en tiempo real.

3.1.3 Efectos de la movilidad compartida, vehículos autónomos compartidos (VACs) y otras flotas de VAs

Las tecnologías de la comunicación han supuesto un cambio radical en la movilidad urbana, reduciendo los tiempos de búsqueda de pasajeros en los que habitualmente incurren los servicios de taxi tradicionales. Las plataformas de servicios de movilidad permiten a pasajeros y conductores optimizar oferta y demanda, lo que lleva a disminuir viajes en vacío y, por tanto, consumos y emisiones. Solamente en términos de coste se estiman ahorros de hasta 6.000 USD por familia en EE.UU. utilizando servicios de movilidad compartida en vez de tener vehículo en propiedad (Anderson et al., 2014).

Los investigadores viendo el potencial que presentan este tipo de plataformas para reducir el número de vehículos en circulación, garantizando el mismo nivel de servicio, junto con las posibilidades que presentan los AVs para la mejora del tráfico, han empezado a estudiar los efectos de las flotas de vehículos autónomos (VACs – Vehículo Autónomo Compartido, Autonomous taxis o aTaxis) como posibles opciones de transporte alternativas a los vehículos convencionales.

El procedimiento habitual para estos análisis son las modelizaciones (en general “agent-based”) de entornos urbanos, genéricos o reales (Austin-Texas, Nueva York, Tokio, Lisboa…), con diferentes variables: tamaño de flota, tarifa, tiempos de espera, patrones de distribución, motor eléctrico o convencional, distribución de puntos de recarga, niveles de congestión, tasas por emisiones, etc.

Diferentes resultados indican que un solo vehículo autónomo es capaz de sustituir hasta 11 vehículos convencionales (Fagnan y Kockelman, 2014) o entre 7 y 10 si se tiene en cuenta la relación tiempo de espera/coste del sistema (Iacobucci et al., 2018), con la consiguiente reducción de emisiones, que en el caso de taxis eléctricos autónomos podrían llegar al 87-94% con respecto a los vehículos convencionales con conductor (Greenblat y Saxena, 2015).

Tres modelizaciones desarrolladas tomando como base la ciudad de Austin, Texas (EE.UU.) y sus patrones de transporte, desarrollo urbano, demografía y desplazamientos de vehículos, analizan el desempeño y los efectos de una flota de taxis autónomos en el sistema. Gawron et al. (2019) avanzan reducciones del 60% en emisiones en el periodo 2020-2050 frente a los vehículos convencionales. Este estudio considera los efectos directos e indirectos de los subsistemas de sensorización y computación, eco-driving y conectividad en las intersecciones, kilómetros recorridos en vacío, parking, recarga, mejoras en el diseño, penetración del motor eléctrico, movilidad compartida y tiempo de vida útil, aunque no tiene en cuenta los efectos del "platooning", las congestiones ni el incremento de velocidad en entornos urbanos.

La reducción comentada del 60% se debe principalmente a la electrificación (57%). Es interesante señalar que el modelo avanza posibles reducciones del 87% para 2050 en un escenario de generación eléctrica con el 92% de renovables, incremento de movilidad compartida para reducir los VKT un 22%, una mayor vida útil de los vehículos (hasta 643.738 km) y una serie de mejoras en la eficiencia, diseño y consumo.

J. Liu et al. (2017) estudian los efectos de las tarifas del servicio de taxi autónomo concluyendo que, si las tarifas son suficientemente bajas, se pueden conseguir reducciones en emisiones entre el 16,8 y el 42,7% frente a vehículos convencionales; no obstante, el exceso de millas recorridas por los AV reduce los porcentajes anteriores, aunque sin comprometer el beneficio global según el modelo.

Sin tener en cuenta los efectos de las tarifas, un estudio usando los datos de la flota de taxis de Nueva York (NYC) concluye que cambiando el sistema de taxis tradicional por una flota de taxis autónomos compartidos se pueden mantener los niveles de servicio con un 59% menos de vehículos y reduciendo las emisiones en 725 toneladas de CO_2 al día (Lokhandwala y Cai, 2018).

También modelizando una flota de taxis en Manhattan, en el centro de la ciudad de Nueva York, pero en este caso con taxis autónomos eléctricos compartidos, Bauer et al. (2018) concluyen posibles reducciones de emisiones de hasta el 73% con respecto a la misma flota con motores de combustión interna, considerando la composición actual del suministro eléctrico en Nueva York y estableciendo una determinada infraestructura de recarga de baterías. Los costes y las emisiones además mejoran si las recargas se pueden programar durante el día cuando la energía eléctrica proveniente de la generación solar está operativa.

Sin embargo, H. Zhang et al. (2020), estudiando las necesidades de infraestructura de recarga de una flota de VAs eléctricos en entornos urbanos, concluyen que en la medida que las flotas aumentan en tamaño por encima de un óptimo y aumenta la capacidad de las baterías, las emisiones se incrementan al realizarse más recargas durante la noche cuando la producción eléctrica con renovables desciende. Para que un sistema de taxis autónomos eléctricos conectados y compartidos sea eficiente deben hacerse estimaciones adecuadas de las necesidades de servicio por áreas geográficas y establecer un ratio correcto de vehículos por punto de recarga, pudiendo llegar a reducciones de emisiones del 42% condicionadas sobre todo por factores como la rapidez de carga además del rango de uso y el parque de vehículos (H. Miao et al., 2019)

Calculando el impacto de la sustitución de todos los desplazamientos en vehículo privado y autobuses tradicionales por una flota de taxis autónomos en una ciudad europea de tamaño medio como Lisboa, Martínez y Viegas (2017) también obtienen resultados positivos en cuanto a reducción de emisiones, llegando casi al 40% en el mejor escenario.

Aunque los modelos realizados tomando como ejemplo tramas y datos de ciudades reales, en general avanzan resultados positivos en cuanto a reducción de emisiones, las conclusiones no tienen por qué ser extrapolables a cualquier otra ciudad. En un intento de hacer un análisis más general estableciendo diferentes categorías de ciudades, Oke et al. (2020) concluyen que la introducción de los servicios de movilidad con vehículos autónomos en ciudades con redes importantes de transporte público es contraproducente para la congestión, ya que los usuarios tienden a cambiar del transporte público hacia los VACs; en ciudades grandes muy dependientes del vehículo privado, poco densificadas y con poco desarrollo del transporte público, no parecen tener efecto la penetración de los VACs y, sin embargo, es en ciudades más densas con un uso moderado del transporte público donde la penetración de la movilidad compartida con vehículos autónomos obtiene mejores resultados para reducir la congestión.

Diversos estudios analizan la introducción de tasas contaminantes para fomentar la movilidad compartida. En ese sentido, Jones y Leibowicz (2019) diseñan una serie de escenarios de movilidad compartida con VACs de cuyo análisis concluyen que, incluso con planteamientos sin tasas contaminantes, se consiguen descensos en las emisiones hacia 2035 llegando en 2050 a la mitad de los obtenidos en 2015, pero si se aplican tasas a los gases contaminantes de manera escalonada, se aprecian descensos más pronunciados en las emisiones y mucho antes, llegando a casi cero en 2050. En general, se demuestra que un sistema con una significativa adopción de VACs es menos costoso y genera menos emisiones, incluso si se doblan los VKT con respecto a los vehículos convencionales que sustituyen.

No obstante, algunos modelos analizando exclusivamente los desplazamientos a los lugares de trabajo (commuting) obtienen resultados no tan prometedores desde el punto de vista ambiental.

Si bien con un 20% de taxis autónomos sería posible dar el mismo servicio que toda la flota de vehículos privados dedicados a los viajes de traslado a los centros de trabajo, con una reducción del coste de viaje del 38%, las emisiones de gases de efecto invernadero aumentan un 25% debido principalmente a los recorridos “en vacío” para ir a buscar al siguiente ocupante (M. Lu et al., 2018).

F. Yao et al. (2020) modelizan un escenario híbrido con conductores y vehículos autónomos de servicios de movilidad a gran escala, concluyendo que en la medida en que se van sustituyendo vehículos con conductor por VAs las emisiones descienden llegando hasta reducciones del 12,3%.

3.1.4 Efectos del sistema de transporte conjunto y visiones generales

Una línea de análisis consiste en el estudio de los efectos del coche autónomo considerando su implantación global dentro de un sistema de transporte. Los efectos del vehículo autónomo en el consumo energético y las emisiones no son muy relevantes a pesar de un mayor grado de eficiencia en la conducción, pero donde sí es capaz de producir grandes transformaciones es en el sistema de transporte general, por sus interacciones con otros medios y por su potencial para cambiar ciertos hábitos entre los usuarios. Por ejemplo, hoy en día las emisiones diarias del transporte generadas en una gran área metropolitana como puede ser Toronto, corresponden en un 96% al vehículo privado, mientras que el 4% restante corresponde al transporte público, que sin embargo realiza el 32% de los traslados. Con la introducción del VA, se observa que podrían aumentar los kilómetros recorridos y las emisiones, sin embargo, si el estudio se realiza con VAs eléctricos se pueden conseguir reducciones en las emisiones a nivel regional del 5% (A. Wang et al., 2018).

El modelo generalista de Noussan y Tagliapietra (2020) analiza el efecto de la digitalización sobre la demanda de transporte, el consumo de energía y las emisiones en la UE-28 comparando dos escenarios diferentes, Digitalización Responsable (DR) y Digitalización Egoísta (DE), y dos horizontes temporales, 2030 y 2050. Cada escenario presenta diferentes hipótesis para 4 áreas: movilidad como servicio, movilidad compartida, vehículos autónomos y digitalización en otros sectores (e-commerce, teletrabajo). Se concluye que la demanda total de transporte aumenta y el coche sigue siendo el medio de transporte más utilizado, aunque en 2050 disminuye su uso en el escenario DR a favor del transporte público y bicicleta. En cuanto al consumo energético, el modelo muestra que el consumo general permanece estable hasta 2030, descendiendo en 2050 en el escenario DR hasta un 34% respecto a los valores actuales como consecuencia del efecto combinado de un cambio hacia medios más eficientes y un uso del coche compartido con más pasajeros por vehículo. La tendencia en las emisiones sigue aproximadamente el mismo patrón que el consumo de energía, consiguiendo para 2050 un descenso del 43% respecto a las emisiones de 2015 debido a las mejoras tecnológicas. El escenario DE, en el que la tecnología se usa de manera que se maximice el beneficio individual, muestra un aumento del 7% en el consumo energético para 2050, disminuyendo las emisiones un 8% debido a las mejoras tecnológicas.

En otro modelo generalista, F. Liu et al. (2019) calculan las emisiones de los vehículos de pasajeros en China según la penetración de los VAs teniendo en cuenta una larga serie de factores, como las ventas de vehículos, el ratio de supervivencia, la distancia anual recorrida, consumos y emisiones relacionadas basados en eco-driving, incremento de la velocidad, mejora de la circulación (conectividad e intersecciones), reducción de accidentes, platooning, diseños específicos (optimización del tamaño, menor carga de elementos de seguridad, mayor carga de sensorización, computación, confort y entretenimiento), carga aerodinámica y otros. El modelo no asume cambios muy radicales en cuanto a evolución de la penetración en el mercado y distancias recorridas así que los resultados indican que no se perciben reducciones importantes en cuanto a emisiones hasta 2050, incluso podrían darse incrementos. Solamente a partir de 2045, con unos mejores parámetros de consumo y una mayor penetración de VAs se podrían ver mejoras en la reducción de emisiones a nivel global.

3.2 Efectos en el suelo

El impacto ambiental del vehículo autónomo en el suelo (y por tanto en los hábitats naturales) no está siendo objeto de estudio por el momento, pese a que varios autores ya indican que uno de los posibles efectos indeseados es la agudización de la dispersión urbana, siendo este fenómeno uno de los ya estudiados en la literatura científica desde la perspectiva del vehículo convencional.

Si nos atenemos únicamente al impacto del vehículo autónomo en la forma urbana, sí está recibiendo creciente atención por parte de los investigadores ya que, como se ha dicho, por sus propias características reúne el potencial suficiente como para multiplicar ciertos efectos indeseados o favorecer nuevas, e impensables hasta este momento, posibilidades de uso del suelo. Dentro de los primeros podemos contar con que, al no tener que conducir, los usuarios del vehículo autónomo podrán dedicar el tiempo de viaje a trabajar o a actividades de ocio, haciendo disminuir el coste de viajar y estando más dispuestos a recorrer largas distancias, afectando a la toma de decisiones en cuanto al lugar de residencia o a la localización de las empresas. Por otro lado, las mejoras del flujo del tráfico que avanzan los VAs hacen más fáciles los desplazamientos urbanos y más atractivo el espacio del centro de las ciudades y eso redunda en que, bajo ciertas circunstancias, ganaría atractivo para sus habitantes permanecer en la ciudad y no mudarse a zonas residenciales alejadas.

Un parámetro que definirá, por tanto, la actuación de los usuarios es el valor del tiempo de viaje un indicativo de cuánto está dispuesto a pagar el viajero por disminuir el tiempo que asignan a viajar de carácter subjetivo, y por tanto influenciado por multitud de factores: contexto espacial urbano-suburbano-rural, normas sociales, estatus, forma de vida, etc. En diversos estudios se aprecia que la introducción del vehículo autónomo disminuye el coste de viajar, en mayor o menor medida, pero eso ocurre tanto para usuarios urbanos como para suburbanos y rurales.

Esto, puede implicar diferentes tendencias en la forma urbana, algunas de ellas opuestas: desde un crecimiento suburbial e improbable densificación de los centros urbanos hasta el crecimiento de ambos polos, la periferia y los centros urbanos (Milakis et al., 2018). Gelauff et al. (2019) obtienen que, en un escenario de alta automatización combinado con buenas prestaciones de transporte público en las grandes zonas urbanas de Holanda, la población tiende a aumentar en las grandes metrópolis y sus suburbios, disminuyendo en ciudades más pequeñas y sus suburbios. Zhong et al. (2020) analizando zonas metropolitanas de tamaño medio en EE.UU. concluyen que la reducción del tiempo de viaje es más pronunciada cuando se trata de VAs privados y entre habitantes de zonas suburbanas, llegando al 32%, pero también es importante entre los usuarios urbanos, lo que no redunda en apreciables redistribuciones de población. Moore et al. (2020) igualmente obtienen ahorros en el valor del tiempo de viaje del 30%, pero predicen una expansión urbana horizontal del 68%. Bin-Nun y Binamira (2020) observan que la implantación de los VAs ocasionaría aumentos de población en las zonas más urbanizadas (hasta el 12%) frente a pérdidas de población en las zonas rurales menos densamente pobladas.

Como se puede apreciar en los diferentes estudios, la tendencia hacia la dispersión urbana (sprawl) como consecuencia de la penetración del vehículo autónomo a veces arroja resultados contradictorios. Larson y Zhao (2020), a pesar de que la mayoría de los modelos conducen al sprawl, también analizan esa ambigüedad concluyendo que es producida por la tensión entre la reducción del coste del viaje al trabajo, el incremento de costes por el aumento de la congestión y el aumento de la densidad urbana como consecuencia del nuevo uso residencial de la superficie de parking no necesaria con los VAs.

Si no se adopta el uso compartido y el espacio de parking no se dedica a uso residencial, el modelo resultante es un modelo urbano disperso. Kang y Kim (2019) también observan para Seúl y su área metropolitana un aumento de la superficie suburbana mientras que se densifica el principal centro comercial, perdiendo tierras agrícolas que pasan a uso residencial y con descenso general del suelo dedicado a actividades comerciales.

Por otro lado, varios estudios se centran en otro de los aspectos significativos y positivos: la posibilidad de liberación de espacio urbano actualmente dedicado a vías y aparcamiento. No obstante, se alerta que solamente en combinación con políticas activas adecuadas se podrá desarrollar todo su potencial (González-González et al., 2020).

Así, la reducción del espacio dedicado a aparcamiento puede llegar a ser muy significativa con la adopción de la movilidad compartida (W. Zang et al., 2015). No obstante, algunos estudios reflejan que, al mismo tiempo que se libera espacio de aparcamiento en los centros metropolitanos, los vehículos recorren mayores distancias diarias y se produce un aumento de la superficie dedicada al aparcamiento en la periferia (Harper et al., 2018; W. Zang y Wang, 2020).

Desde el punto de vista ambiental, los anteriores efectos o posibilidades se trasladan a sus repercusiones en el consumo energético y las emisiones de gases de efecto invernadero pero, siendo la agudización de la dispersión urbana una de las posibles consecuencias negativas de la implantación del vehículo autónomo, se hace necesario considerar los efectos contaminantes no solamente en el aire sino en el resto de medios, entre ellos el suelo.

Johnson (2001) resume los impactos que diferentes investigadores identifican en relación con la dispersión y entre ellos, los siguientes afectan al suelo: pérdida de tierras ambientalmente frágiles, espacios abiertos más reducidos, pérdida del atractivo paisajístico, ausencia de vistas del paisaje (montañas), paisaje monótono o inapropiado, pérdida de tierras de cultivo, reducción de la biodiversidad, aumento de la escorrentía y aumento de las inundaciones, pérdida de vegetación nativa y fragmentación de los ecosistemas.

Muchos de los efectos en el suelo son más fácilmente apreciables que medibles y de ahí la dificultad en su estudio. También es evidente que hay impactos cuyos efectos perniciosos no se aprecian hasta que pase un cierto tiempo y además la percepción del riesgo asociado a estos impactos es variable entre diferentes individuos. De ahí quizá que todavía no se encuentren dentro de la literatura científica artículos que aborden el problema de los efectos contaminantes en el suelo como consecuencia de la introducción del vehículo autónomo como medio de transporte de relevancia.

3.3 Efectos en el agua

Los cambios en el uso del suelo son uno de los principales factores que contribuyen a la degradación de la calidad del agua. Como se ha podido ver en el punto anterior, la expansión suburbana es uno de los posibles efectos de la penetración del vehículo autónomo y, por tanto, además de impacto en la calidad del aire y del suelo, tendrá impactos indeseados en la calidad del agua.

La urbanización provoca cambios sustanciales en los sistemas hidrogeológicos ya que, al incrementarse la superficie construida impermeable, aumenta la ocurrencia e intensidad de las inundaciones, disminuye la recarga de acuíferos, elimina los pequeños cursos de agua superficial, altera la permeabilidad del resto del terreno natural y aumenta la carga de contaminantes, a la vez que también aumenta la demanda de agua para la población y sus servicios.Considerando la presencia de nitratos (NO_3-_N), fosfatos (TP) y Escherichia Coli en los cursos naturales de agua, R. Wang et al. (2021) obtienen que los desarrollos urbanos más densos son más efectivos en la reducción de nitratos y fosfatos, aunque pueden tender, dependiendo de la época del año, a aumentar la presencia de E. Coli, pero en general concluyen que la degradación de los flujos naturales de agua es consecuencia del “sprawl”. S. Wang et al. (2019), igualmente, analizando la degradación y disminución de los recursos hídricos como consecuencia de la urbanización suburbana en una megalópolis como Pekín desde la década de los años 90, concluyen que tales niveles pueden comprometer el futuro la sostenibilidad de la ciudad.

Si, como avanzan ciertos estudios, hay relación entre un posible aumento de la expansión urbana de baja densidad y la adopción del AV como medio de transporte masivo, deberían considerarse sus probables graves efectos en el medio acuático más allá de las emisiones generadas. A la vista de los resultados obtenidos en las plataformas WoS y Scopus, no hay por el momento literatura que tenga en cuenta estos efectos.

3.4 Contaminación acústica

La contaminación acústica y la contaminación atmosférica son los dos factores de riesgo más importantes para la salud en los espacios urbanos y son responsables de más del 75% de las enfermedades atribuibles a condicionantes ambientales (Hanninen et al., 2014), siendo el tráfico rodado uno de los mayores emisores de ruido.

Para el análisis de los efectos sobre la salud de la contaminación acústica se suelen emplear los parámetros L_{dn}, nivel día-noche, que es el nivel de sonido equivalente de 24h con los niveles de sonido nocturnos incrementados en 10dB(A) y el L_{den}, nivel día-tarde-noche. La población residente en entornos urbanos en países industrializados está expuesta a niveles L_{dn} por encima de 50dB(A) y hay suficiente evidencia científica que afirma que exposiciones por encima de esos niveles puede inducir disfunción auditiva, hipertensión, cardiopatía isquémica, irritación y alteraciones del sueño (Passchier-Vermeer y Passchier, 2000).

A pesar del potencial del VA para modificar el futuro del transporte y los hábitos de los usuarios, no hay apenas literatura que estudie el impacto que su penetración puede tener en un factor de riesgo para la salud de tal relevancia.

No obstante, algunos primeros estudios, como el realizado por Patella et al. (2019b) analizando los efectos de la penetración del AV en una red de carreteras real (Roma), indican que en un escenario con 100% de presencia de vehículos autónomos las vías urbanas interiores se beneficiarían de descensos en la contaminación acústica al reducirse la congestión, mientras que aumentaría la contaminación en ciertas autopistas de acceso como consecuencia del mayor número de trayectos extra-urbanos.

3.5 Contaminación lumínica

Otro de los contaminantes asociados a los entornos urbanos y las vías de transporte es la luz artificial por la noche. Aunque no se ha desarrollado suficiente evidencia científica sobre sus efectos en la salud, diversos estudios alertan de que, al afectar al comportamiento, el sueño y la melatonina, podría ser un factor de riesgo en desórdenes metabólicos como la obesidad y las enfermedades cardiovasculares, ciertos tipos de cáncer y salud mental (Flies et al., 2019).

Además de en la salud humana, la luz artificial tiene impactos negativos en los ecosistemas (Gaston et al., 2015) y consume una gran cantidad de energía, generando 1900 Mt de CO_2 al año (IEA, 2006).

Al igual que con la contaminación acústica, se ha desarrollado poca literatura en relación con el vehículo autónomo a pesar de que, al no tener conductor, se podría reducir en gran medida la necesidad de luz artificial en ciertos entornos, ya que la iluminación de las calles y de los aparcamientos constituyen el 90% de la iluminación exterior. En ese sentido, Stone et al. (2019) analizan las posibilidades de eliminar iluminación en aparcamientos y autopistas, además de promover un análisis del diseño de los AVs para que sean capaces de circular en la oscuridad en condiciones de seguridad.

3.6 VAs y usuarios: percepción general y compatibilidad con otros medios de transporte

Como se ha podido ver, los efectos ambientales del vehículo autónomo son muy sensibles al grado de penetración, su forma de uso y su interacción con otras formas de transporte. Algunos modelos, teniendo en cuenta los porcentajes de VAs en el conjunto de la flota de vehículos, si son compartidos o no, su impacto en la red de infraestructuras, la posibilidad de viajar “de puerta a puerta”, la reducción del valor del tiempo de viaje y la incorporación de los potenciales usuarios que no conducen, concluyen que, para el horizonte de 2050, los kilómetros por vehículo podrían aumentar un 50%, que el uso del transporte público podría descender un 18% y el uso de los modos activos (andar en bicicleta y a pie) podría bajar un 13% (May et al., 2020). Por tanto, es muy importante conocer la respuesta del usuario hacia esta nueva tecnología y la forma en que considera su uso.

Para analizar estos aspectos, diferentes autores dirigen encuestas y entrevistas con espectros más o menos amplios. Potoglou et al. (2020) analizan las preferencias de los usuarios por los VAs y los combustibles alternativos, identificando y explorando las diferencias entre seis países y sus diferentes segmentos de población. Los resultados indican que, por ejemplo, los participantes japoneses son los que más valoran los avances del VA, quizá por ser una sociedad cuya economía está basada en la alta tecnología o porque anticipan las ventajas que los VAs pueden ofrecer a una población envejecida. Los participantes alemanes, suecos y británicos no tienen esa predisposición positiva y los resultados para EE.UU. varían con respecto a otras encuestas anteriores, indicando actualmente una menor predisposición, quizá derivada de los accidentes ocurridos con VAs. También se encuentran diferencias entre los diversos grupos sociales encuestados resultando, en general, que los más jóvenes están más dispuestos a aceptar altos niveles de autonomía en los vehículos mientras que los que se definen como menos innovadores, menos concienciados ambientalmente y que viven en zonas rurales tienen menor predisposición. Un resultado llamativo se encuentra dentro de los encuestados de Suecia, que pese a autodefinirse como ambientalmente responsables y valorar positivamente los VEs, no consideran interesante el máximo nivel de automatización de los VAs, quizá por un cierto escepticismo sobre los verdaderos beneficios ambientales de los mismos. En este sentido, Müller (2019) incluye en su estudio la actitud del encuestado hacia la protección ambiental y la innovación, concluyendo que una actitud positiva hacia esos factores predispone hacia una mejor aceptación del VE y el uso compartido, pero no necesariamente hacia el VA.

Se observa en ciertos estudios que la penetración en el mercado de los VAs podría cambiar ciertos hábitos actuales relacionados con la movilidad activa y el transporte público, a su vez relacionados con mayores beneficios para la salud y para el medioambiente. Son los segmentos de población más joven los que más utilizan estos medios y a su vez los más dispuestos a adoptar nuevas tecnologías como el VA, lo que puede redundar en un trasvase de usuarios. En este sentido, Booth et al. (2019) han realizado una encuesta con el objetivo de explorar en qué grado son usuarios de modos de transporte activo y en qué medida estarían dispuestos a sustituirlos por VAs. Se concluye que un 48% de los encuestados estarían dispuestos a sustituir el transporte público por un vehículo autónomo, al igual que el 32% de los que usan la bicicleta y el 18% de los que andan.

Blau et al. (2018) han estudiado la influencia de los vehículos autónomos en los usuarios de bicicletas compartiendo las mismas vías, concluyendo que el VA supone un elemento disuasorio para los usuarios de la bicicleta a pesar de presuponer una conducción mucho más segura frente a los vehículos convencionales, por lo que los ciclistas llegan a doblar la preferencia por infraestructuras separadas con respecto a las condiciones actuales. También Latham et al. (2019) se preguntan si la penetración de los VAs desplazarán otros modos de transporte o permitirán una mayor y más igualitaria configuración del espacio urbano. Mediante un experimento con ciclistas haciendo un giro a la derecha en una calle urbana de Carlisle (Reino Unido) con doble sentido de circulación llega a la conclusión de que, pese a las normas formales e informales que regulan una maniobra tan simple, los diferentes usuarios tienen múltiples razonamientos sobre lo que se considera razonable y apropiado. Por ello, y aunque actualmente los VAs se están desarrollando partiendo de calzadas convencionales con tráfico motorizado, deben tener el objetivo de circular en entornos donde se priorice el movimiento y la seguridad de los usuarios no motorizados.

De nuevo respecto a la interacción o desplazamiento que el vehículo autónomo pueda ejercer sobre los modos de transporte activo, y en definitiva sobre la salud pública, Crayton y Meier (2017) identifican que algunas posibilidades beneficiosas desde el punto de vista de la salud pública no lo son tanto desde el punto de vista ambiental si no se regulan correctamente. La capacidad del VA para circular de manera más segura redundaría en menores emisiones al evitar los atascos generados por los accidentes, lo que es positivo, pero el acceso a una movilidad autónoma por parte de población actualmente imposibilitada para conducir implicaría un aumento en los kilómetros recorridos por vehículo y por tanto más emisiones. En definitiva, se percibe como negativo tanto para la salud pública como para el medioambiente un desplazamiento desde medios de transporte activo hacia el vehículo autónomo, por el aumento del sedentarismo y las enfermedades asociadas y por la sustitución de hábitos de movilidad sin emisiones por transporte con cierto grado de emisiones.

El potencial que el vehículo autónomo tiene para conseguir un transporte más sostenible medioambientalmente se basa en que el usuario cambie la preferencia actual hacia el coche privado por un uso compartido con varios usuarios por viaje.

Para comprobar si ese cambio de tendencia es posible, Stoiber et al. (2019) analizan la influencia de varios instrumentos para fomentar el uso del transporte compartido en un escenario de total presencia de VAs. En este caso, un 61% de las respuestas eran favorables a escoger VAs compartidos mientras que el 39% sigue prefiriendo un uso privado. El porcentaje de aceptación de uso compartido es superior a otros estudios anteriores, pero se puede deber a que en este caso no se da la opción de escoger un transporte convencional que no sea autónomo, lo que sugiere que los usuarios están más dispuestos al uso compartido en un escenario de total penetración de VAs al no poder optar por opciones más conocidas.

Dentro de la literatura existente, una forma de análisis consiste en realizar entrevistas a expertos sobre sus puntos de vista acerca de diferentes posibilidades. Lang et al. (2019) conducen una serie de entrevistas cuyos resultados indican que los vehículos eléctricos seguirán creciendo en importancia, pero a pesar de la creciente conciencia ambiental los usuarios no parecen inclinados a otras alternativas como los VA.

Se percibe, no obstante, que los vehículos autónomos tendrán un papel muy importante en el futuro y que es el sector tecnológico con el crecimiento más rápido y un mayor grado de innovación, todo ello estimulado por la competitividad y las alianzas entre empresas. Sin embargo, alcanzar la autonomía completa todavía requerirá un cierto tiempo debido a los costes y a la necesidad de establecer nuevos estándares en la legislación vigente. Adicionalmente, los entrevistados indican que, desde su punto de vista, los usuarios están todavía tratando de averiguar en qué consisten los cambios y sus consecuencias.

También entre los expertos encuestados por Nogués et al. (2020) se aprecia cierto escepticismo sobre los efectos de los VAs -incluso utilizados de modo compartido- en los entornos urbanos, de tal manera que para evitar problemas de sostenibilidad en el futuro se deben implementar políticas activas, como la promoción de los modos de transporte activos, la mejora del transporte público, las restricciones para los vehículos privados en el centro de las ciudades y la promoción de una más compacta y mejor estructurada trama urbana.

4. CONCLUSIONES

Los efectos ambientales de los vehículos autónomos están generando una gran cantidad de estudios con resultados muy dispares y enfoques muy diferentes, aunque principalmente centrados en analizar consumos y emisiones en diferentes escenarios. Para conseguir sus objetivos los investigadores adoptan diferentes estrategias y planteamientos. Si se trata de analizar emisiones se suelen basar en modelos matemáticos con resultados variables y muy dependientes de los parámetros que asumen en la modelización. La mayor eficiencia en la conducción y la posibilidad de la circulación en grupo favorecida por las comunicaciones V2X indican ahorros energéticos y reducción de emisiones, amplificadas si los usuarios optan por la movilidad compartida al conseguir una reducción significativa del parque automovilístico sin pérdidas en los niveles de servicio.

No obstante, otros análisis indican que las prioridades de los usuarios pueden llevar a escenarios donde todos los potenciales beneficios que aporta la tecnología son usados para maximizar el aprovechamiento individual, provocando efectos ambientales negativos con respecto al estándar actual. Igualmente, la tendencia del usuario puede provocar un cambio en el uso del más conveniente transporte activo (uso de la bicicleta, andar) o del transporte público hacia el vehículo autónomo, aún en su modalidad compartida, lo que también tendría efectos contraproducentes en el medio ambiente y a su vez en la salud pública.

Además, ciertos impactos negativos como la dispersión urbana no solamente deben ser estudiados desde el punto de vista del aumento de las emisiones, sino que el efecto negativo se multiplica si se tienen en cuenta la degradación del suelo, el paisaje, los ecosistemas y los recursos de agua natural. Igualmente, nuevas posibilidades que se apuntan, como la posible reducción de la contaminación lumínica, redundarían, por ejemplo, en posibles descensos muy importantes en consumos energéticos y emisiones del sistema global. Es decir, las consecuencias positivas o negativas pueden amplificarse de una manera exponencial si se tiene en cuenta todo el posible espectro ambiental afectado (aire, suelo, agua, ruido, luz artificial, etc.). En este sentido sería importante que futuros estudios tuvieran una visión más amplia en cuanto a los efectos ambientales del vehículo autónomo puesto que potenciales beneficios directos, por ejemplo, en el descenso de las emisiones según un cierto modelo, pueden ser mayores si se aplica la posible reducción de las emisiones por una menor necesidad de iluminación nocturna o la “naturalización” del suelo urbano liberado. También sucede al contrario, modelos que indican incremento de emisiones debido al aumento de vehículos o a las mayores distancias recorridas, pueden ser mucho más perniciosos si se tienen en cuenta las probables degradaciones del suelo, los hábitats naturales y los recursos hídricos como consecuencia de la dispersión urbana.

Muchos de los efectos sobre el suelo y los recursos hídricos naturales son más difíciles de analizar puesto que no son fácilmente evaluables de forma cuantitativa, necesitan plazos más amplios para ser apreciados y además son susceptibles de visiones subjetivas. Sin embargo, las consecuencias de no ser tenidos en cuenta son relevantes por sí mismos y por su interrelación con el resto de los efectos ambientales.

Existe un consenso entre los expertos al considerar que el vehículo autónomo es una tecnología que marcará el devenir del transporte en las próximas décadas, pero hoy en día existen tantas incertidumbres tecnológicas para considerarlo viable en un plazo razonable que el usuario no es capaz de valorar realmente sus potenciales beneficios. Es un hecho que la movilidad está sufriendo una importante transformación con respecto a los usos tradicionales (VEs, VTCs) y que una mayor conciencia medioambiental acelerará este proceso, aunque a día de hoy no parece que ese sea un motivo que favorezca la implantación del VA. La dificultad que supone prever el grado de aceptación y cómo será usada una tecnología tan disruptiva hacen que los resultados de los estudios sean muy variables e incluso antagónicos.

Sin embargo, sí se puede apreciar un cierto pensamiento general por el que el beneficio social óptimo de los sistemas de transporte futuros debe incluir una movilidad autónoma, compartida y complementaria con el resto de medios, y para ello se requiere la motivación de todos los usuarios.

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A GIS-BASED EVALUATION OF THE E-MOPED SHARING SYSTEMS IN SPAIN

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ABSTRACT

Sharing mobility is currently one of the most innovative features of metropolitan transportation and is rising along with the development of mobile phones and apps. Riders can rent bicycles, motorcycles, cars or PMVs like mopeds, usually electric, for short-time periods, usually per minute. Vehicle-sharing companies have entered the megalopolis, although the first sharing services were implemented in medium-size cities like Ulm in Germany, Cambridge in the USA or the main Swiss cities.

The purpose of this study was to analyze the current motorcycle sharing systems deployed in Spain based on GIS tools. The research focused on several Spanish cities, the main characteristics of which are representative of the whole country. The study can therefore be useful for companies in the sharing sector interested in introducing the system in cities which do not yet have them, and for government administrations interested in this type of system. Furthermore, this research is a starting point for future comparative studies on Spain and other countries, or electric motorcycle and other e-vehicle-sharing systems.

1. INTRODUCTION AND OBJECTIVE

This study focused on several different Spanish cities. Therefore, its conclusions serve to establish the main characteristics defining *motosharing* systems in this geographic area, and are the starting point for evaluating possible future research that can compare it with the situation in other places. These conclusions may also be of interest to the companies in the sector themselves and also to cities that are considering introducing these services.

The recent growing concern for pollution in large cities and the current trend to urban rezoning promoting more pedestrian spaces (Cervero and Kockelman, 1997; Madanipour, 2019; Plasencia-Lozano, 2014), are generating policies directed at reducing the presence of private vehicles in streets in the city center, especially, polluting vehicles (Mackett, 2001; Tomassetti et al., 2020). Sometimes the number of lanes in the main streets are reduced, causing an increase in the level of service, and thus, an increase in travel time.

It also reduces parking spaces or limits their availability to hybrid or electric vehicles, less used now (Szarata et al., 2017; Yan et al., 2019). This reality can be observed in several countries (Fitzgerald, 2020; Hooi and Pojani, 2020; Mandeli, 2019; Mozos-Blanco et al., 2018).

At the same time, in the last decade, society has been profoundly transformed due to the surge in smartphones and apps. All of this leads to the idea of mobility through per-minute rentals known as sharing, in which the facility offered is supported by mobile devices for geolocation, immediate payment, etc. Thus, companies have started up that offer riders per-minute rental in main cities of electric vehicles such as cars (*carsharing*) (Derikx and van Lierop, 2021; Guirao et al., 2018), bicycles (*bikesharing*) (Barberan and Monzon, 2016; Shaheen et al., 2012) or scooters (Fitt and Curl, 2020; Hardt and Bogenberger, 2019).

One of these options is known as *motosharing* (Spanish common word for describing the sharing of e-mopeds), now available in cities in several different countries, also in Spanish cities (Aguilera-García et al., 2020). The operator distributes a certain number of electric e-mopeds within the area for a rental time rate (usually per minute) which includes the right to the necessary safety equipment and accident insurance.

This is done by downloading the company app and searching for the closest vehicle. All of them have three different modes: (1) Rent, which causes the e-moped to appear as available on the app's map and shows the vehicle battery and autonomy. (2) Ride, which is activated when the rider begins to use it and ends when finished; in general, the rider pays a rate for the use of a e-moped that can reach speeds of 50 km/h, and some companies offer e-mopeds that reach speeds of up to 80 or 100 km/h. In this case, the rider can decide to reach those speeds, but has to pay a higher rate. (3) Repeat, reduced rate the rider can activate after having parked the vehicle to reserve it for further use.

Every company operates in a certain zone and the beginning and end of the journey should be inside that zone, although it may outside it as long as the battery and autonomy allow the vehicle to return to it. The company that offers the service is also responsible for recharging the vehicle and ensuring that all vehicles are in good condition.

The purpose of this study was to analyse the current *motosharing* services in Spain based on defining and determining a series of parameters that help to characterize the service by using QGIS open software for obtaining data.

Therefore, its conclusions serve to establish the main characteristics defining *motosharing* systems in this geographic area, and are the starting point for evaluating possible future research that can compare it with the situation in other places. These conclusions may also be of interest to the companies in the sector themselves and also to cities that are considering introducing these services.

2. METHODOLOGY

The methodology developed is based on finding parameters that characterize *motosharing* services by using two types of data: those related to the service offered by the companies, and those related to the area where the company offers the service (area covered, population density, etc.). The method is carried out in seven steps (Figure 1).

1.	**Sample definition**		Cities with mopeds; Companies in each city
2.	**Parameter definitions**		Number of companies; Prices; Speed; service area…
3.	**Sample characterization**	**Companies**	News on Company web sites; Calls; e-mails; Annual reports
		Cities	2020 census; City council websites; Urban sprawl
4.	**Lab work**		Data processing with QGIS
5.	**Parameter-based results**		Mopeds/km^2; Mopeds/100,000 pop.
6.	**Analysis of results**		
7.	**Conclusions**		

Figure 1: Method description

First, the sample (Spanish cities with a *motosharing* service) was defined. To find them, news items were searched for in local newspapers on this service being started up, increase in the city's fleet, and other published data. Data provided by the Spanish Metropolitan Mobility Observatory [*Observatorio de Movilidad Metropolitana*] were also included.

After finding the cities and the number of companies with permits to operate in each, the data that should be known about them to be able to arrive at the desired conclusions were defined. The following were chosen: number of companies, year *motosharing* began, service price range in each city, maximum e-moped speed, vehicles available, area of the zone covered for starting and ending the ride, population census in the zone, total area of urban sprawl.

Thus, the following parameters can also be determined: number of e-mopeds per 100,000 inhabitants, number of e-mopeds per km^2 and percentage of the total area occupied by urban sprawl of the zone offered for starting and ending the ride.

Once the parameters had been set, the sample was characterized. One part was characterization of the companies, for which their web pages were found and the section on news in some of them showed data of interest on the company's growth over the years (year started up in each city, growth of fleet, etc.); some data were not available on the internet and they had to be contacted or their annual reports searched. The other was the characterization of the zone available for starting and ending the ride. Using QGIS software, the area and population (data from 2020 census) were found for each of them. Finally, the results were analysed, and conclusions reached.

3. RESULTS

3.1. Cities with *motosharing*. Service characteristics.

Ten cities in Spain offer a *motosharing* service: A Coruña, Gijón, Barcelona, Zaragoza, Córdoba, Valencia, Seville, Cádiz, Málaga and Madrid (Table 1).

City	Number of companies	First year of service	Price range [€/min]	Maximum speed offered, combined [km/h]	Companies
Barcelona	5	2013	0.24 – 0.26	80	eCooltra; Yego; Movo; Acciona; Seat MÓ
Madrid	3	2013	0.24 – 0.26	100	eCooltra; Movo; Acciona
Seville	3	2017	0.26 – 0.27	80	Acciona; Muving; Yego
Málaga	2	2017	0.25 – 0.26	80	Acciona; Yego
Cádiz	1	2017	0.27	50	Muving
Valencia	4	2017	0.25 – 0.27	80	eCooltra; Muving; Yego; Acciona
Zaragoza	2	2017	0.26 – 0.27	80	Acciona; Muving
Córdoba	1	2017	0.27	70	Muving
Gijón	1	2019	0.29	50	HiMobility
A Coruña	1	2019	0.24	50	Motiños
Average	2	2016	0.26	72	

Table 1: Number of companies, year started up, prices and speed in each city.

Motosharing services were set up for a time in other cities, but were discontinued as unprofitable, and their vehicles were used to reinforce the fleets in other cities, or to start up a service where there was none yet. Murcia, Alicante, Granada and Palma de Mallorca are in this group.

Other cities have a seasonal *motosharing* service as in Gandía, where a fleet of 200 electric e-mopeds is deployed in the city every summer.

The characteristics and service conditions vary depending on the company that provides them. Some cities (Barcelona, Madrid) have had a satisfactory *motosharing* service for years, which makes the number companies operating in them larger than the Spanish average.

Another example is Valencia, where the service was begun only four years ago, but its popularity has made the number of companies operating in it grow rapidly. Other cities, such as A Coruña and Gijón, have recently begun the service and there is only one company currently operating in them.

3.2. Rates, speed

The highest rate is in the city of Gijón, which has only one company offering the service for 0.29/€/min. In the cities with more companies, the price is not over 0.27€/min, being A Coruña an exception as there is only one company operating for 0.24€/min, the minimum in the country. However, in all the cities, companies have lower rates for their regular customers, offering rides for 0.17-0.19€/min.

The maximum speed riders can reach depends on the model offered by the company. Two points should be emphasized: the users in the three smallest cities, Gijón, Cádiz and A Coruña, have e-mopeds available that can go no faster than 45-50 km/h, while in other cities there is at least one operator offering services with speeds of at least 70 km/h. This may be due to these cities having urban highways. Furthermore, Acciona offers the possibility of reaching 80 or 100 km/h, but at an added cost of 0.03 and 0.09€/min, respectively, over the original rate (Table 1).

Figure 2: Motosharing vehicles. eCooltra, HiMobility, Muving, Yego, Movo, Acciona, Motiños and Seat MO. Source: companies webpages.

3.3. Operating zone

The zone available for starting and ending the ride varies with the operator. The percentage of the urban sprawl occupied by the *motosharing* service zone varies depending on the city, although in all cases is over 40% (Figure 3, Table 2). The minimum is in Seville, where 43.76% of the total urban sprawl is zoned for *motosharing*, and the highest is in Cádiz: 100.81%. This is because the customers, in addition to the city center, can use it at the university campus, outside of the city itself. The mean of the total area is 72.31% of the urban sprawl zoned for *motosharing*.

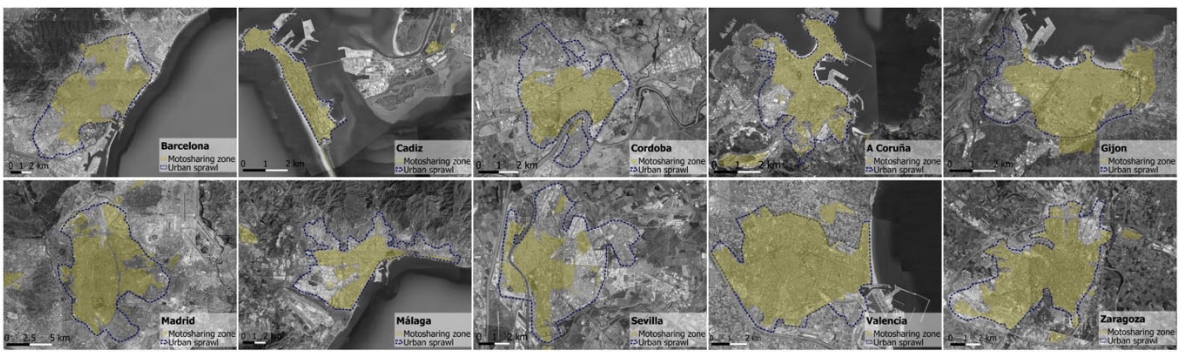

Figure 3: Motosharing operating zones and urban sprawl. Note that urban sprawl does not coincide with the municipal limits, but with homogeneity and continuity of total urbanized or partly residential space.

City	Area urban sprawl [km^2]	Area *motosharing* zone [km^2]	Percent urban area zoned for *motosharing* [%]	Autonomy [km]
Barcelona	67.57	45.06	66.68	80
Madrid	105.92	82.58	77.96	80
Seville	42.86	18.76	43.76	70
Málaga	47.24	23.13	48.95	70
Cádiz	5.37	5.61	104.42	70
Valencia	47.09	36.64	77.80	80
Zaragoza	42.79	37.18	86.88	70
Córdoba	21.44	11.38	53.08	70
Gijón	18.86	16.41	86.99	50
A Coruña	13.56	10.88	80.21	60
Average			72,7	

Table 1: Comparison of areas in different cities in Spain. The area of the *motosharing* zone includes the urban area where there is at least one operator.

3.4. Potential users

The 2020 census was used to calculate the residents in the zones set up by the operators (potential users), and also in the urban sprawl area (Table 3). Potential users have been compared with the total population of each urban area for evaluating the percentage of the population benefited by the service. In this case, the lowest percentage is in Seville, 51.17%, being Málaga the next with 71.55%. On the contrary, Cádiz, Valencia, Zaragoza and Gijón all have motosharing zones affecting over 95% of the population. Concerning the population density in each area, it has been set that the areas served by at least one motosharing company are in the same population density range of 14,455 pop/km^2 to 20,876 pop/km^2, except Barcelona, with a density of 29,152 pop/km^2. These figures are also higher than the population densities observed in the urban sprawl.

City	Urban sprawl population (2020 census)	Potential users [pop]	Percentage city population [%]	City population density [pop/km^2]	Population density in motosharing zone [pop/km^2]
Barcelona	1,725,977	1,313,629	76.11	25,542.27	29,152.89
Madrid	1,990,323	1,611,612	80.97	18,789.43	19,515.77
Seville	545,348	279,067	51.17	12,722.27	14,875.64
Málaga	467,304	334,363	71.55	9,890.53	14,455.82
Cádiz	107,253	106,922	99.44	19,514.88	18,524.42
Valencia	792,527	764,918	96.52	16,828.30	20,876.58
Zaragoza	586,055	575,617	98.22	13,694.92	15,481.90
Córdoba	267,004	201,251	75.37	12,453.42	17,684.62
Gijón	241,227	238,914	99.04	12,787.73	14,559.05
A Coruña	206,200	192,810	93.51	15,202.05	17,721.51
Average			84.19	15,742.58	18,284,82

Table 2: Population and potential users in the cities

3.5. Fleet

The fleet of e-mopeds available was defined by adding up all the companies that operate in each city. The Spanish cites with the most e-mopeds are Madrid (3,620), Barcelona (3,176) and Valencia (1,635). By contrast, Gijón and A Coruña services only offer 50. Analyzing the number of e-mopeds in each city per km^2, and keeping in mind the area zoned for *motosharing*, Barcelona is in first place, with 70 e-mopeds/km^2 followed by Valencia and Madrid with 44 e-mopeds/km^2 (Table 4). Last place is again held by A Coruña and Gijón: 4 and 3 e-mopeds per km^2 respectively.

City	Number of e-mopeds [Units]	E-mopeds/km^2	E-mopeds per 100,000 inhabitants
Barcelona	3,176	70.48	242
Madrid	3,620	43.84	225
Seville	440	23.45	158
Málaga	500	21.62	150
Cádiz	100	17.83	96
Valencia	1,635	44.62	214
Zaragoza	575	15.46	100
Córdoba	115	10.11	57
Gijón	50	3.04	21
A Coruña	50	4.59	26
Average		25,50	128,9

Table 3: Number of e-mopeds, zone for starting and ending rides, and potential users in each city.

The fleet in each city was also compared with the number of potential users in each zone by calculating the number of e-mopeds per 100,000 inhabitants. In this case Barcelona, Madrid and Valencia have over 200 e-mopeds/100,000, while Seville, Málaga and Zaragoza have over 100 e-mopeds/100,000. The rest of the cities have fewer than 100 e-mopeds/100,000, with Gijón and A Coruña at the tail with fewer than 30 e-mopeds/100,000.

4. DISCUSSION

This study analyzed some data related to the existing e-moped sharing systems in Spain (generally denominated motosharing in Spanish) in order to characterize them. Some parameters linked to the companies have been chosen, and also some data from the operating areas have been taken in account. After that, some ratios have emerged linked to the number of vehicles per inhabitant or the number of vehicles per km2.

The motosharing service was shown to be linked to large cities: the six largest cities in Spain were include here, and the seventh (Murcia) and eighth (Palma) at one time had motosharing services. It would be interesting to know the reason why in cities like Las Palmas de Gran Canaria or Bilbao, ninth and tenth in size, still do not have this service, and the reason why middle-sized cities, such as Gijón (15th place) or A Coruña (18th place), do.

It was also observed that the minimum population limit for this type of services is around 250,000 inhabitants. Rates were found to be rather homogeneous, although somewhat more economical in the cities with several operators.

Concerning the speed of e-mopeds, the larger number of operators is also linked to vehicles with higher top speeds. In general, the feeling is that competition between companies contributes to some of them wanting to be differentiated from the rest in this parameter. It has been also observed that cities with a smaller motosharing zone also offered e-mopeds with lower top speeds.

For example, Gijón, Cádiz and A Coruña, are the three cities with the smallest motosharing zone and also those with the lowest top speeds (50 km/h). On the contrary, Madrid, which has the largest zone, offers e-mopeds with top speeds of up to 100 km/h.

Another interesting fact is the percentage of urban sprawl that is covered by the different companies. Furthermore, the presence of more companies in the same city does not ensure wider coverage. One suggestive result is related to the population density in the companies' sharing zones.

This, as demonstrated, is in no case under 14,000 pop/km2. Therefore, it may be inferred that for the service to be profitable in a city, the population density in the sharing zone has to be extremely high. However, this population density is not related to the number of operators in the city.

The reason why the motosharing service is only available in areas where the population density is over 14,000 pop/km2 could be the lack of profitability of the service in areas below this density, so this cipher can be set as the minimum population density which makes attractive a central area for companies. It could be thought that although a city has a very small population, if it is a touristic city, the motosharing service would make sense there, but apparently it does not. In the end, the regular service customers are those who determine its triumph or failure in a city, so that motosharing in a touristic city would only make sense in the high season, as is the case in Palma de Mallorca.

Along this line, it is observed that the sharing zones have a much higher population density than urban sprawl as a whole. However, it is surprising that urban sprawl outside of sharing zones in Barcelona and Madrid have a population density over the 14,000 pop/km2 mentioned above, but the operators have not widened the service offered to the entire sprawl.

In percentage, the difference between the population densities in the sharing zone and the non-sharing zone is considerable in many cities, and shows that operators select the more heavily populated zones as (Table 5).

City	Density in urban sprawl [pop/km^2]	Density in sharing zone [pop/km^2]	Density in non-sharing zone [pop/km^2]	% difference in densities between sharing and non-sharing zones
Barcelona	25,543.54	29,15.89	18,318.44	63%
Madrid	18,790.81	19,515.77	16,22.84	83%
Seville	12,723.94	14,875.64	11,049.00	74%
Málaga	9,892.13	14,455.81	5,513.94	38%
Cádiz	19,514.88	18,524.42	-	-
Valencia	16,830.05	20,876.58	2,642.01	13%
Zaragoza	13,696.07	15,481.90	1,860.61	12%
Córdoba	12,453.54	17,684.62	6,536.08	37%
Gijón	12,790.40	14,559.05	944.08	6%
A Coruña	15,206.49	17,721.51	4,996.27	28%
Average	15,744.18	15,661.12	5,942.59	39%

Table 5: **Comparison of population densities in the urban sprawl and in the sharing zones**

It is worth mentioning that the rates are not related to a significant parameter a priori, the ratio which compares the e-mopeds per 100,000 pop and the *motosharing* zone, which determines the quality of the service offered (Table 6). However, this ratio may be related to the rotation of the e-mopeds, which in turn could be related to the area of the sharing zone: it seems logical that a smaller *motosharing* zone would be paired with a shorter distance to be covered by the ride, and therefore, length of time in use. This ratio was evaluated, and various groups appeared: one group is around 5.01 to 8.42, another in the fork between 1.28 and 2.72, and Cádiz with 17.11. This last is justified because the distance between the city center and the university campus, where it also provides the service, is quite long. The cities with lower ratios could be smaller, or metropolises where public transportation is easily available or transportation alternatives are high. In any case, it would be interesting to find relationships of this type in future research.

City	*Motosharing* zone [km^2]	E-mopeds per 100,000 inhabitants	Ratio
Barcelona	45.06	242	5.37
Madrid	82.58	225	2.72
Seville	18.76	158	8.42
Málaga	23.13	150	6.49
Cádiz	5.61	96	17.11
Valencia	36.64	214	5.84
Zaragoza	37.18	100	2.69
Córdoba	11.38	57	5.01
Gijón	16.41	21	1.28
A Coruña	10.88	26	2.39
Average	28.76	128.9	6.37

Table 6: **Ratio which compares the e-mopeds per 100,000 inhabitants and the *motosharing* zone**

There are some limitations and biases in this study. The data handled are rather reliable and objective, except perhaps the size of the urban sprawl, although there are metropolitan areas where the separation between the urbanized and unurbanized zones is clear, while in others, the definition could be somewhat more subjective. Thus, in Cádiz, it was decided to define the city itself as an island. However, Puerto Real or even San Fernando could have been included. Another question that could vary is the number of e-mopeds the companies offer in a city, as they fit the e-mopeds offered to the needs detected and better or worse reception of the service by citizens.

With a view to future studies of the *motosharing* service in Spanish cities, other factors could be considered in evaluating the service's feasibility, such as traffic inside the city, the percentage of the city that is pedestrianized, the city's motorization rate, the city's shape or alternative services offered, both sharing and public transportation. Another of the factors that could directly affect the use of this service is the climate, as the number rainy days per year or the mean annual temperature could influence users when making the decision to use the service or not. Another possible future study coming out of this one is of those *motosharing* services that have failed in recent times, such as in Murcia, Alicante or Granada, quantifying the parameters determined in this text, and comparing the differences in values of the cities analysed here. Furthermore, this method could be replicated for the study of other e-moped systems in other countries, and for comparing them with the Spanish system. Finally, the ciphers stated here could be used by companies and municipal administrations for planning futures services or for planning urban expansions (it is clear, for example, that low density cities are not interesting for e-mopeds sharing companies).

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EL SARS-COV-2 Y SU IMPACTO EN LA OBTENCIÓN DE DATOS SOBRE MOVILIDAD. LA EXPERIENCIA DEL PROYECTO TRAVELWELL+

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RESUMEN

La irrupción del virus SARS-CoV-2 y su propagación ha afectado a todos los campos imaginables de la vida. La ciencia no es ajena a ello: la situación derivada plantea desafíos en la obtención de datos. Las tradicionales encuestas in situ, los grupos de discusión y las entrevistas personales se han visto afectados por los nuevos comportamientos sociales y de movilidad, requiriendo introducir cambios en los métodos de obtención de datos.

El proyecto de investigación Travelwell+ – sobre nuevas formas de movilidad, bienestar y espacio público – aplica un enfoque mixto, utilizando métodos cualitativos y cuantitativos de recogida y análisis de información de movilidad de personas. La presente ponencia describe la adaptación del proyecto a las circunstancias de la pandemia, presenta los retos que la situación plantea, explica qué adaptación se ha llevado a cabo en la recogida de datos, y se concluye con una valoración preliminar de los resultados.

1. INTRODUCCIÓN

El 11 de marzo de 2020 la Organización Mundial de la Salud declaró la situación de pandemia por la expansión del virus SARS-CoV 2. La situación de emergencia sanitaria se ha extendido hasta la presente fecha, habiendo introducido cambios notables en la interacción entre personas, en los hábitos de movilidad y, como consecuencia, en las estrategias de obtención de datos para proyectos de investigación como los referidos a la movilidad, que se basan en muchas ocasiones en el contacto directo con los encuestados.

En un contexto de constante cambio en la movilidad urbana, con la aparición de nuevos modos de movilidad y la promoción de políticas de redistribución del espacio público, el proyecto Travelwell+ pretende estudiar los efectos de estos cambios haciendo énfasis en el aspecto psicológico y del bienestar de las personas.

El proyecto Travelwell+ se divide en dos fases, como se especifica en la figura 1. En una primera fase se pretende aportar conocimiento acerca de cómo las nuevas formas de movilidad (servicios de movilidad compartida y vehículos de movilidad personal, VMP) están alterando los patrones de movilidad e influyendo en el bienestar de sus usuarios. La segunda fase pretende estudiar cómo diferentes elementos del entorno urbano afectan al comportamiento y bienestar del usuario. Esta segunda fase pretende centrarse en el estudio de peatones, ciclistas y personas usuarias de VMP.

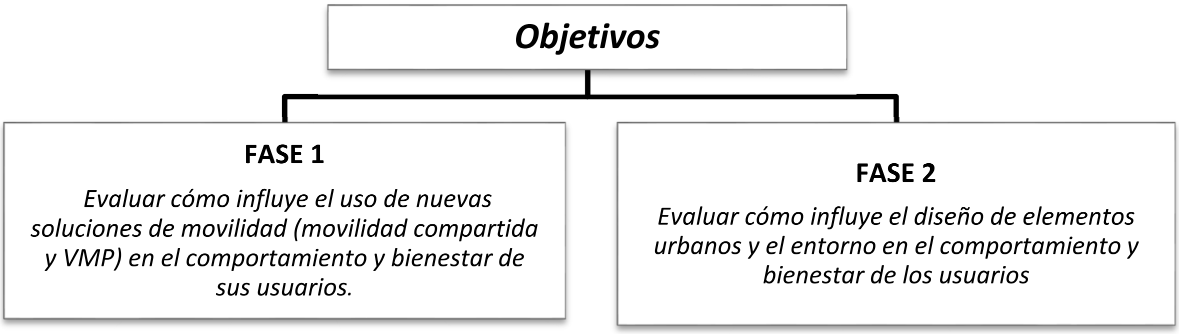

Figura 1: Fases del proyecto Travelwell+

Lejos del enfoque tradicional del estudio del transporte y los hábitos de movilidad según variables como el tiempo o coste mediante el criterio de maximización de la utilidad (Mcfadden, 2000; Ettema, 2010), este proyecto se suma a la creciente preocupación por el estudio de variables psicológicas, especialmente estudiadas en las últimas dos décadas, haciendo énfasis en las nuevas soluciones de movilidad.

Mientras que investigaciones previas (Friman et.al. 2013 o Ruiz et.al 2020) parecen concluir que la mayor satisfacción se alcanza en los desplazamientos a pie y en bicicleta, frente a los menores índices de satisfacción alcanzados en el transporte público, aún queda por analizar la posición que ocuparían los nuevos modos de movilidad: VMP y movilidad compartida como coches o motos. La satisfacción y bienestar con un medio de transporte están estrechamente ligados con las experiencias de los usuarios en ellos, así como con rasgos personales como sus percepciones, hábitos o carácter (Gao et.al. 2017).

Todos ellos pueden ser factores relevantes de la elección modal (Ettema et.al. 2010; Singleton et.al. 2019). El bienestar de una persona se compone de dos: el bienestar hedónico o subjetivo (SWB, de sus siglas en ingles *Subjective Wellbeing*) y el bienestar eudaemónico o psicológico (PWB, de sus siglas en inglés *Psychological Wellbeing*) (de Vos et. al., 2013). El conjunto de teorías sobre el SWB y PWB se ha materializado en una serie de escalas psicométricas que, de forma normalizada, analizan cuantitativamente factores relacionados con el bienestar. En Travelwell+ se complementan estas teorías con la consideración de la Teoría de la Autodeterminación (SDT, de sus siglas en inglés *Self-Determination Theory*) (Deci, 2000).

Una de las subteorías de la misma es la Teoría de las Necesidades Psicológicas Básicas, BPNT (de sus siglas en inglés *Basic Psychological Needs Theory*), que afirma que existen tres vertientes psicológicas innatas, básicas y universales: competencia, autonomía y relación con los demás. Las tres condiciones son esenciales para el bienestar personal, según afirman los autores. Dicha teoría se incorpora, a su vez, en todas las modalidades de recogidas de la información del proyecto Travelwell+.

Esta ponencia se organiza de la siguiente manera. Después de introducir el objeto del proyecto de investigación Travelwell+, a continuación, el apartado 2 presenta los desafíos que la pandemia supone en la obtención de información, tanto respecto a la forma de recopilarla, como respecto a los posibles sesgos que la situación puede inducir en los encuestados.

Se incide, a continuación, en el caso de los grupos de discusión, la fase de la investigación que, por el momento, ha tenido lugar en este contexto. Se realiza un análisis DAFO de los grupos de discusión online en este contexto de pandemia y se concluye en el apartado 3 con unas consideraciones finales.

2. RECOGIDA DE DATOS

El proyecto Travelwell+ se concibe como un proyecto de recogida mixta de información, combinando la información cuantitativa y cualitativa tanto en la fase 1 como en la fase 2, como se describe en la figura 2. Respecto a la información cuantitativa, se prevén en la fase 1 encuestas in situ y en línea que contengan escalas psicométricas que aborden la SWB, PWB y la BPNS (analizando las tres vertientes contenidas en la teoría: autonomía, competencia y relación). Respecto a la información cualitativa, se prevé la realización de grupos de discusión y entrevistas en profundidad en ambas fases.

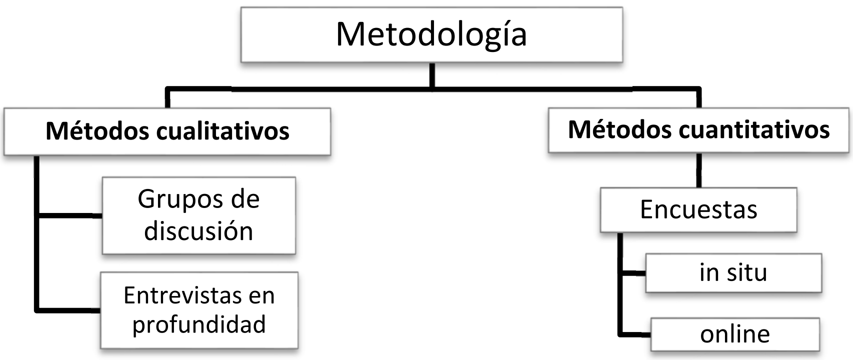

Figura 2: Métodos de obtención de información en el proyecto Travelwell+

Se pretende obtener información preferentemente de la ciudad de València, desde donde se lidera el proyecto, siendo el público empleado para la muestra la población general.

Se pretende, eso sí, obtener una sobrerrepresentación de las cohortes de edad correspondientes con el grupo de *millennials* (nacidos entre 1981 y 1996) y seniors (nacidos antes de 1950). El objetivo es evaluar especialmente en esos grupos de edad la influencia de estos cambios y su flexibilidad o rigidez al cambio de hábitos y las nuevas soluciones de movilidad.

2.1 La influencia de la pandemia en la recogida de información

A la fecha de entrega del presente artículo (abril de 2021), las tareas llevadas a cabo se han circunscrito al desarrollo de pruebas piloto relacionadas con la fase 1, empleando de muestra para ello miembros de la comunidad universitaria de la *Universitat Politècnica de València*, que aceptaron participar sin presentación de incentivo. En diciembre de 2019 se llevaron a cabo las pruebas piloto de las encuestas in situ (ver Ruiz et.al. 2020), antes de la irrupción de la pandemia por SARS-CoV 2. Los primeros grupos de discusión, pertenecientes a la fase 1 del proyecto, se desarrollaron en el mes de marzo de 2021.

La afección de la pandemia no solo se circunscribe a la forma de recogida de la información, sino también a la propia información que los usuarios puedan dar. A las esperadas reticencias al contacto social, cabe esperar que los datos recopilados muestren, al menos en parte, los cambios que la movilidad ha experimentado durante estos meses de pandemia, a saber, un menor índice de movilidad, una mayor reticencia al uso del transporte público y un trasvase de la mayoría de esos usuarios a medios de transporte activos (pie y bicicleta) (sirvan de constatación de esas tendencias los datos diarios de movilidad de la ciudad de València, publicados en su web coronavirus.valencia.es/pages/quadres-de-ciutat).

En el caso de los grupos de discusión, es de esperar que los participantes basen sus intervenciones en la utilidad recordada (Oliver 2017). Las preguntas que se les han formulado a los participantes en los grupos ya celebrados inciden en esa utilidad recordada siguiendo la recomendación de Kanehman y Dolan (2007), que asumen, aplicado al campo de la salud, que es preferible el análisis del bienestar mediante la utilidad experimentada –aquello que el usuario ya ha vivido y recuerda– y no mediante la utilidad esperada, basada en predicciones de los individuos sobre eventos futuros.

Los retos en la recogida de información son diversos y se ven afectados principalmente por las reticencias al contacto en un mismo espacio de personas desconocidas. En el caso de las encuestas in situ, planteadas como encuestas cara a cara en las que un entrevistador realiza preguntas en voz alta y las registra en un dispositivo electrónico, se obtuvo en la prueba piloto (previa a la pandemia) una baja tasa de respuesta, sobre todo, cuando se pretendió captar a usuarios durante sus desplazamientos. Desde marzo de 2020 no se han llevado a cabo nuevas encuestas in situ. Estas se habrán retomado en mayo de 2021 considerando las conclusiones de la evaluación piloto, esto es, priorizando puntos de encuesta en los que se realicen actividades estacionarias –de descanso o tiempo libre–, donde la predisposición a la participación parece mayor que durante los desplazamientos.

Las encuestas se realizarán en puntos al aire libre, respetando las distancias de seguridad y llevando los equipos de protección individual que las autoridades sanitarias recomiendan. Ello nos lleva a pensar que la tasa de respuesta de la gente no será muy diferente a la que puedan dar en circunstancias normales. No obstante, sí que se presenta la duda acerca de cómo conseguir una sobrerrepresentatividad del grupo de edad senior. La disminución de sus desplazamientos y vida social puede dificultar la obtención de datos en esa cohorte de edad.

2.2 Los grupos de discusión, modalidad presencial y online

La gran incógnita se nos presenta en la realización de las entrevistas en profundidad y, sobre todo, en los grupos de discusión. Los grupos de discusión suponen, en el caso de Travelwell+, la reunión de un total de 9 personas (7 participantes, un moderador y un observador) en un espacio que habitualmente es cerrado, ya que al aire libre pueden producirse interferencias y ruido en la grabación y mayores distracciones en los participantes.

Aun guardando las distancias de seguridad, portando mascarilla y tratando de garantizar una buena ventilación del habitáculo, la propia recomendación de las autoridades sanitarias de evitar lugares cerrados, el obligado desplazamiento de los participantes al lugar de reunión, así como su desconocimiento del resto de participantes y de las características del lugar de la reunión, hacen que sea esperable un alto rechazo a la celebración de estos eventos presencialmente. Siendo conscientes de este aspecto, el equipo investigador planteó la posibilidad de realizar los grupos de discusión de forma telemática. El profesorado y alumnado de la UPV ya tenían experiencia a este respecto mediante la plataforma TEAMS, de Microsoft, por lo que se valoró esa opción.

Los grupos de discusión por internet en sus diferentes modalidades (mediante grupos de chat o webcams, generalmente) son una herramienta que permite reunir a participantes que se encuentran geográficamente dispersos, aunque presentan la desventaja de limitar el potencial de participación y depender de las limitaciones tecnológicas (Guest et.al. 2017). En la investigación se trató de analizar previamente qué riesgos podían suponer ambas modalidades. Se entendía que la interacción entre participantes, la dinámica grupal, así como el estudio de la comunicación verbal y no verbal, eran esenciales en el análisis de un grupo de discusión, por lo que la principal amenaza en los grupos online era que estas condiciones se vieran mermadas por la distancia y desapego entre participantes. Por otra parte, más allá de las pruebas piloto, la muestra final se corresponde con la población general de la ciudad de València, a los que no se les presupone un conocimiento de las aplicaciones de videollamada. Los posibles problemas informáticos añaden mayor incertidumbre al correcto funcionamiento de las discusiones. Para los moderadores del grupo de discusión, la modalidad online también era una novedad, para lo cual se empleó, además de la lectura y visualización de diferentes fuentes bibliográficas, la colaboración estrecha de Lidón Mars Aicart, doctora en Psicología e investigadora del proyecto.

Se acordó finalmente la realización de tres grupos de discusión piloto para la fase 1, detallados en la tabla 1. El grupo de discusión se planteó con una duración de 90 minutos y pretendía cubrir los tres elementos básicos de la BPNT: competencia, autonomía y relación. Se organizaba en los bloques temáticos de bienestar (percepciones e interacciones entre usuarios), seguridad, organización de actividades (tiempo, destinos y cadena de desplazamientos), género y elección de ruta.

GRUPOS DE DISCUSIÓN				
FECHA	**MODALIDAD**	**MEDIO DE TRANSPORTE**	**PARTICIPANTES**	**OBJETIVO**
09-03-21	En línea	Bicicletas	Estudiantes	Familiarizarse con la aplicación informática y el control de las dinámicas de grupo telemáticamente. Compañeros de clase con sesgo por amistad previa.
23-03-21	Presencial	Patinetes	Estudiantes	Comprobar dinámicas de grupo de forma presencial en tiempos de pandemia y funcionamiento del guion
30-03-21	En línea	Patinetes	Trabajadores de la universidad	Comprobar dinámicas de grupo de forma telemática y funcionamiento del guion

Tabla 1: Listado de grupos de discusión piloto celebrados

La experiencia adquirida es breve y deben asumirse las limitaciones de muestra y características de los participantes. No obstante, ya pueden apuntarse de forma preliminar aspectos positivos y negativos de los grupos de discusión online, reflejados en la tabla 2.

ANÁLISIS DAFO GRUPOS DE DISCUSIÓN ONLINE	
Debilidades	**Amenazas**
- Carencia de experiencia previa en la conducción de grupos de discusión online	- Mayor incertidumbre acerca del comportamiento de los participantes: dinámica y atención durante el grupo y motivación a participación previamente - Necesidad de equipos informáticos para la correcta grabación (micrófono y cámara) que cada participante debe tener - Desconocimiento de los programas informáticos - Posibles problemas de conexión de los participantes - Comunicación no verbal limitada: reduce la capacidad de control de la discusión, interrupción o reparto de los turnos de palabra
Fortalezas	**Oportunidades**
- Conocimiento y experiencia con aplicaciones para llevar a cabo reuniones telemáticas - Mayor facilidad de grabación de las reuniones	- Predisposición entre la población al uso de herramientas online - Se amplía el abanico de posibles participantes, incluso de diferentes poblaciones (se elimina la necesidad de movilidad) - La pandemia ha supuesto la potenciación de los medios de transporte objeto del análisis. Mayor facilidad de captación de usuarios.

Tabla 2: Celebración de grupos de discusión online. Análisis DAFO

Respecto a las dinámicas de grupo e interacción entre participantes, el grupo presencial tuvo una dinámica muy positiva. Es de mencionar, no obstante, que los estudiantes participantes acuden diariamente a las clases de la universidad y en condiciones parecidas a las del grupo de discusión celebrado. Ello explica, en buena manera, su predisposición a participar. Esa circunstancia no es común a otros grupos de edad, probablemente no tan acostumbrados a reuniones con personas desconocidas bajo las presentes circunstancias, por lo que no es directamente extrapolable. Respecto a los grupos de discusión online, en el celebrado el 30 de marzo la dinámica fue altamente satisfactoria.

Los participantes, trabajadores de la UPV, tenían ya conocimiento de la aplicación y hacían uso habitual de la misma en reuniones internas. Por otra parte, los participantes no tenían amistad previa, y se comprobó la utilidad de una adecuada ronda inicial para ganar confianza y complicidad entre ellos y sentar las bases de una mejor interacción. Se comprobó que es posible entablar una dinámica de grupo adecuada de forma online, aun asumiendo las interferencias y distracciones que a los participantes se les presentan ocasionalmente. Se les pidió, además, tener en todo momento la cámara encendida, lo cual ayudó a involucrarlos en la discusión. La tarea de moderación y control de los tiempos es también compleja. La comunicación no verbal, que en encuentros presenciales juega un papel relevante en el control y reparto de los turnos de palabra, en la modalidad online apenas se advierte por parte de los participantes y obliga al uso de otras técnicas que pueden ser peor percibidas por los participantes.

El incentivo no se planteó en esta prueba piloto, aunque sí se contempla para los grupos definitivos. La tasa de no aparición de los participantes fue considerable (entre un 35-40% de los que en un principio aceptaron). La mayoría o no se excusaron o lo hicieron tras consultas por nuestra parte de última hora. Las causas no parecen estar relacionadas con la situación de pandemia, sino más bien por la ausencia de un incentivo que anime a la participación cuando surgen otros quehaceres de mayor interés a última hora.

Organizativamente, las reuniones telemáticas se han demostrado más sencillas: no es necesaria la reserva de espacios, el desplazamiento de los participantes o la preparación de los dispositivos de grabación, lo cual puede suponer un ahorro de tiempo y dinero tanto a organizadores como a participantes. La grabación mediante la aplicación online es muy sencilla de ejecutar y ofrece buena calidad de audio y vídeo, siempre que los participantes dispongan de cámara y micrófono adecuados, incluso superior a la que podría obtenerse in situ. La no necesidad de desplazamiento abre, a su vez, nuevas posibilidades de recopilación de información más allá de la población en la que se lidera el proyecto. Conocidas las limitaciones en cuanto a servicios de movilidad compartida en València, el equipo del proyecto Travelwell+ se plantea aprovechar esta tesitura para organizar grupos de discusión online con población de la Comunidad de Madrid, donde los servicios de movilidad compartida son más variados y están más extendidos. Se presenta esta situación, por tanto, también como una oportunidad.

3. CONCLUSIONES

La situación derivada de la emergencia sanitaria por SARS-CoV 2 tiene como consecuencia un cambio en los datos y en la forma de obtenerlos. En cuanto a los datos, el cambio en los hábitos de desplazamiento y reparto modal que la situación acarrea deberá ser reflejado y considerado en las investigaciones que tengan lugar durante este contexto. En nuestra investigación puede suponer una oportunidad, ya que el uso de nuevas formas de movilidad personal, como el patinete, parece estar viéndose incrementado. Por otra parte, la toma de datos se ve alterada, especialmente si implica una mayor interacción social, como es el caso de los grupos de discusión.

La investigación Travelwell+, con un enfoque mixto de recogida de datos cuantitativos y cualitativos, ha tenido que adaptarse a esta situación, especialmente en la realización de los grupos de discusión. Aunque los grupos celebrados son escasos en número y se circunscriben a la fase de preparación, se puede concluir que la celebración de los mismos de manera online no supone necesariamente una desventaja en la obtención de resultados. La predisposición de la población a la participación mediante estas tecnologías y las facilidades de organización juegan a favor de esta técnica. Además se eliminan los límites geográficos y surgen nuevas oportunidades de captación de información sin necesidad de movilidad.

El éxito de las dinámicas de grupo recae, aún más si cabe, en los moderadores y su capacidad de animar a la participación y crear el ambiente propicio para ello. Si este se da, la participación no parece verse afectada sobremanera. Entre los desafíos, eso sí, se encuentran la gestión de los turnos de palabra y las estrategias de interrupción a los participantes. Dado que la comunicación no verbal, usual en la modalidad presencial, se ve restringida en la modalidad no presencial, este aspecto se plantea como una dificultad añadida. Como riesgos cabe destacar el posible desconocimiento de las aplicaciones de videollamada, que puede dificultar encuestar a colectivos no acostumbrados a ellas. La logística previa parece más sencilla, aunque son de esperar mayores problemas durante los grupos de discusión (problemas de conexión, interrupciones, problemas de sonido o audio).

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BIENESTAR, TRANSPORTE Y MOVILIDAD SOSTENIBLE

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RESUMEN

El bienestar, asociado a los sentimientos de felicidad, emociones positivas o la autorrealización, es un aspecto relacionado con el comportamiento humano que se estudia por los psicólogos sociales desde hace décadas. El bienestar también se aplica en la planificación del transporte como un factor explicativo de las características de la movilidad de las personas.

Esta ponencia presenta en primer lugar, las teorías psicológicas y métodos de estudio más importantes relacionados con el bienestar. Además, se describen las principales escalas de medición del bienestar subjetivo y psicológico, y las variables que se utilizan.

Posteriormente, se revisa su aplicación en el área del transporte; se plasman los resultados más relevantes, obtenidos en algunos estudios de movilidad de personas que incluyen el bienestar, para transporte público, privado y modos activos. Finalmente, se identifican líneas de trabajo futuro, y su importancia.

1. INTRODUCCIÓN

Tradicionalmente se ha estudiado el bienestar desde dos corrientes (Keyes, Ryff y Shmothkin, 2002), la tradición hedónica o el estudio del bienestar subjetivo (SWB, de sus siglas en ingles *Subjective Wellbeing*) y la tradición eudaimónica o el estudio del bienestar psicológico (PWB, de sus siglas en inglés *Psychological Wellbeing*) (De Vos, Schwanen, Van Acker y Witlox, 2013).

El bienestar subjetivo persigue maximizar las experiencias de felicidad y placer, evitando así las que conllevan malestar o dolor. (Ryan y Deci 2001), que consta tanto de elementos afectivos como cognitivos. Este tipo de bienestar se ha medido en numerosos estudios a través de variables como la satisfacción con la vida, el afecto positivo y el afecto negativo (Lucas, Diener y Suh, 1996; Diener 2000).

Por otra parte, el bienestar psicológico estudia la consecución del bienestar a través del desarrollo del potencial humano, del propósito y significado de la vida, el crecimiento personal y el pleno desarrollo de las propias capacidades y potencialidades (Ryan y Deci, 2001). Ryff (1989), sugirió un modelo de bienestar psicológico compuesto por seis dimensiones: la autoaceptación, el crecimiento personal, el propósito vital, la autonomía, el dominio del entorno y el mantenimiento de relaciones positivas.

A partir de esta concepción del bienestar psicológico, se ha desarrollado una teoría evolutiva del bienestar (Ryff y Keyes, 1995; Ryff y Singer, 2001) basada en la búsqueda de la realización del propio potencial. Este tipo de bienestar se ha medido a través de variables como la autoestima, autoeficacia, o la vitalidad subjetiva.

En ocasiones, se habla de estas dos concepciones como si estuvieran en conflicto o fueran contrapuestas, sin embargo, en realidad son complementarias y abordar el bienestar desde ambas hará que las personas alcancen mayor bienestar (Huta, 2015).

Trasladando estos conceptos al área del transporte de personas, Singleton y Clifton (2019) afirman que hay beneficios más allá del simple hecho de alcanzar un destino, de hecho, cuando una persona se traslada de un lugar a otro experimenta una serie de sentimientos y emociones, positivas o negativas, que inciden en la satisfacción de dicho viaje.

Por otro lado, viajar también puede influir en el bienestar gracias a la satisfacción de diversas necesidades, el fortalecimiento de lazos sociales o el alcance de determinadas metas personales.

Sin embargo, las primeras evaluaciones de satisfacción con los viajes, estaban basadas en la teoría de la utilidad, es decir, el análisis de la relación costo-beneficio, restando así importancia a otros aspectos emocionales y psicológicos influyentes como la calidad de vida o el bienestar de las personas, que eran considerados un objetivo secundario (Ettema et al, 2012)

De esta forma, es importante conocer en qué grado, la satisfacción con los viajes diarios contribuye a la satisfacción con la vida y el bienestar emocional; así como, los factores que inciden en la satisfacción de las personas y la forma de medirlos o entender cómo las personas evalúan cognitivamente sus viajes.

Además, establecer diferencias en el bienestar experimentado en diversos modos de transporte. (Redman, Friman, Gärling y Hartig, 2013; Gärling, Ettema, Fors Connolly, Friman y Olsson, 2020).

2. MEDICIÓN DEL BIENESTAR

La evaluación del bienestar, ya sea subjetivo o psicológico, se ha venido realizando a través de diferentes instrumentos o escalas psicométricas. Para la medición del bienestar subjetivo se pueden destacar: la Escala de Satisfacción con la Vida SWLS (del inglés *Satisfaction with Life Scale*) (Diener, Emmons, Larsen y Griffin, 1985), la Escala de Afecto Positivo y Negativo (PANAS, del inglés *Positive and Negative Affect Scale*, Watson, Clark y Tellegen, 1988), la escala de medición de la Intensidad Afectiva de Larsen, (AIM; del inglés *Affect Intensity Measure*, Larsen, 1987); la escala SCAS (*Swedish Core Affect Scale*, Västfjäll y Gärling, 2007) y la Escala de Satisfacción con los Viajes STS. (*Satisfaction with Travel Scale*, Ettema y colaboradores, 2011).

A continuación, se describen algunas de estas escalas utilizadas en los estudios que describe la presente ponencia. En cuanto al bienestar psicológico, se destaca la teoría de necesidades psicológicas básicas BPNT y la escala de medición de la Satisfacción y Frustración de estas Necesidades Psicológicas Básicas, BPNSF.

Diener et al (1985), consideraron que, aunque los individuos pudieran tener diferentes estándares de éxito para cada una de las áreas de su vida, podrían tener al mismo tiempo un criterio global de evaluación de la vida en general, que podía ser evaluado de forma independiente. Por lo tanto, la SWLS consta de cinco ítems que evalúan un juicio global de satisfacción con la vida. La escala de respuesta es de tipo Likert de siete pasos desde “1, completamente en desacuerdo” hasta “7, completamente de acuerdo”.

El inventario PANAS se compone de 20 ítems y consta de dos subescalas, afecto positivo y afecto negativo, con 10 ítems cada una. Los encuestados deben responder siguiendo la consigna de cómo se sintieron durante los pasados días o semanas y la escala de respuesta es de tipo Likert de cinco pasos, desde 1 “nada” a 5 “extremadamente” en la que deben evaluar su estado de ánimo durante ese período de tiempo específico (Watson et al, 1988).

La Escala de Intensidad Afectiva (AIM), desarrollada por Larsen (1987), es un instrumento de medida del constructo unidimensional que describe la intensidad con que se experimentan las emociones (Martínez y Ortiz, 2000). Larsen desarrolla el concepto de intensidad afectiva, para delimitar las diferencias individuales en la intensidad con que las personas experimentan subjetivamente los distintos estados afectivos (Larsen y Diener, 1987). Esta escala está compuesta por 40 ítems en una escala tipo Likert desde “1, nunca” hasta “6, siempre” y los encuestados deben valorar cómo reaccionarían ante las diferentes situaciones que se proponen.

En 2010 Ettema, Gärling, Olsson y Friman propusieron un marco teórico para aplicar el concepto de bienestar en el análisis del comportamiento de los usuarios de transporte. Para ellos el bienestar subjetivo se puede medir a través de la evaluación de la satisfacción con la vida de forma global y la evaluación del bienestar emocional.

Ettema y colaboradores (2011) desarrollaron un instrumento para medir el bienestar subjetivo relacionado con los viajes, la Escala de Satisfacción con el Viaje (STS) que consta de 9 ítems. Esta escala proporciona una medida de la satisfacción general de viajes realizados y está basada en dos dimensiones, cognitiva y afectiva, del bienestar subjetivo, y se refiere al viaje en general y no para cada etapa del mismo. (Ettema et al, 2012).

Los ítems de la STS (Ettema y colaboradores, 2011) que miden el bienestar afectivo se basan en la Escala Sueca de Afecto Central (SCAS; Gärling, 2007) y la Escala de Afecto Central del modelo de Russell (1980; 2003). Según este enfoque, el afecto se compone de dos dimensiones: la activación y la valencia. La activación se refiere al grado de estimulación del individuo, por las señales del entorno, y que fluctúa desde el polo de activación al de desactivación y la valencia se refiere a la evaluación del individuo sobre esos afectos en términos de positivos a negativos. Se parte del principio que la satisfacción con el viaje puede ser una medida de bienestar subjetivo perteneciente a un dominio específico (viaje).

Los 6 ítems que miden el afecto, relacionados con el viaje, se basan en SCAS. (Ettema et al, 2013). Cada ítem, consta de pares adjetivos que representan dimensiones de activación-valencia. Los 3 primeros ítems constan de pares adjetivos que van desde activación negativa a desactivación positiva. Los siguientes 3 ítems van desde desactivación negativa a activación `positiva. Y los 3 últimos ítems son descripciones que van de evaluaciones cognitivas de los viajes negativas a positivas. La escala de respuesta es de tipo Likert de 9 puntos que van de -4 a 4 pasando por cero y la escala se aplica a viajes en general (Ettema et al, 2012).

Con respecto a la corriente eudaimónica o de bienestar psicológico, en sus postulados se encuentra la Teoría de la Autodeterminación, SDT (del inglés *Self Determination Theory*. Esta es una macroteoría de motivación humana, que consta de 6 miniteorías, entre las cuales se destaca Una de estas miniteorías es la de las necesidades psicológicas básicas (BPN, del inglés *Basic Psychological Needs*), Ryan y Deci, 2017; 2019) en ella se plantea que existen 3 necesidades psicológicas básicas y necesarias para el bienestar: autonomía, competencia y relación.

La necesidad de autonomía se refiere al sentimiento de las personas de ser el origen de la propia toma de decisiones o capacidad de escoger las propias acciones y de no ser controladas por otros. La satisfacción de la autonomía conlleva un comportamiento autodeterminado y acorde con la voluntad y los deseos de los individuos, por lo tanto, se genera una sensación de plenitud y placer.

En contraste, cuando las personas sienten que su autonomía es frustrada experimentan que alguien o algo activamente impide que tomen sus propias decisiones y se encuentran en el polo controlado de la conducta por lo que se dan experiencias no placenteras. El término competencia se refiere a la necesidad de los individuos de sentirse eficaces y en control.

De ahí que la satisfacción de la competencia se dará cuando el individuo sienta que puede interactuar de forma eficaz con el ambiente y tiene la capacidad de lograr sus objetivos; por el contrario, la frustración de la competencia se dará cuando el individuo sienta que se le impide ser eficaz y por tanto dude de sus capacidades para interactuar con el ambiente. Por último, la necesidad de relación se refiere a la necesidad inherente del ser humano, como ser social, a ser contactado por otros y tener buenas relaciones con ellos. Así, la satisfacción de esta necesidad consiste en conectar con otros de forma positiva y sentirse unido a ellos; la frustración de esta necesidad se refiere a sentimientos de aislamiento, soledad o no sentir que no se tienen relaciones positivas con los demás (Castro, 2009).

En la teoría de la autodeterminación, un instrumento desarrollado para evaluar la satisfacción de estas necesidades es la escala BPNS, Escala de Necesidades Psicológicas Básicas.

Consiste en 12 ítems, divididos en tres factores compuestos por cuatro ítems por factor para medir la satisfacción de cada una de estas tres necesidades psicológicas básicas: autonomía, competencia y relación. Las respuestas son recogidas en una escala tipo Likert del 1 (totalmente en desacuerdo) al 7 (totalmente de acuerdo). (Nishimura y Suzuki, 2016).

Con respecto a la Escala de satisfacción y frustración de las necesidades psicológicas básicas BPNSFS (Del inglés *Basic Psychological needs Satisfaction and Frustration Scale*, Chen et al, 2015); Está compuesta de 6 factores satisfacción y frustración de las tres necesidades psicológicas básicas postuladas desde la teoría de la autodeterminación, con cuatro ítems en cada factor. La escala de respuesta es de tipo Likert de 5 pasos desde totalmente falso a totalmente verdadero.

3. BIENESTAR Y MOVILIDAD

3.1 Bienestar y transporte público

Ettema y colaboradores en 2011, realizaron un estudio con 155 estudiantes universitarios de la Universidad de Karlstad en Suecia, a quienes por grupos se les pidió que evaluaran cinco escenarios hipotéticos usando el STS que mide bienestar afectivo y cognitivo, la escala de satisfacción con el día (una modificación de la escala SWLS para evaluar un único día) que mide bienestar cognitivo y el SCAS que mide bienestar afectivo. Las diferentes versiones presentadas diferían en el modo de transporte (autobús vs coche), el tiempo de viaje y el acceso a la parada del autobús. En todas ellas los encuestados debían evaluar tres días hipotéticos con tres agendas de actividades determinadas que diferían en la cantidad de actividades que hipotéticamente realizarían en ese día.

Para evaluar las diferencias entre los distintos escenarios hipotéticos, se realizaron análisis de varianza (ANOVA) de medidas repetidas y pruebas *t*, de diferencia de medias. Los resultados concluyeron que tanto el modo de transporte utilizado, como el tiempo de viaje y el acceso a la parada de bus influía sobre el STS y por tanto el bienestar.

En cuanto a los resultados del STS, fueron más bajos para el modo autobús que automóvil; para los viajes en autobús, los encuestados sentían menor bienestar a mayores tiempos de viaje y si era menor el acceso a las paradas de autobús.

Un año más tarde, en 2012, otro estudio realizado por Ettema, Friman, Gärling, Olsson y Fuji pone a prueba la escala STS, el objetivo era evaluar cómo incidía en el bienestar subjetivo, el desarrollo de otras actividades realizadas durante un viaje en transporte público. Se aplicaron cuestionarios a usuarios de transporte público en Suecia que se dirigían hacia el trabajo. A través de análisis de regresión, sus resultados indicaron que las actividades que se realizaban durante el viaje impactaban en la satisfacción del mismo, por ejemplo actividades que implicaran una interacción con otros (ej. hablar con otros pasajeros), tenían efectos más positivos que actividades cuyo fin era el entretenimiento o relajación (ej. escuchar música, o utilizar el teléfono móvil) que por el contrario implicaban una satisfacción con el viaje más baja; se concluyó además que el destino incidía así mismo en la satisfacción con el viaje, ya que encontraron un mayor efecto de las actividades durante el viaje de regreso al hogar que hacia el lugar de trabajo.

Por su parte, Friman, Fujii, Ettema, Gärling y Olsson (2013), realizaron un estudio enfocado en medir el bienestar subjetivo de los usuarios en diferentes modos: transporte público, vehículo privado y modos activos. Aplicaron encuestas STS a muestras aleatorias de residentes de las tres zonas urbanas más grandes de Suecia preguntándoles sobre su viaje de ida al trabajo y de vuelta a sus hogares, posteriormente hicieron análisis factoriales confirmatorios, y pruebas de invarianza sobre las diferentes zonas urbanas y los distintos modos de transporte. Obteniendo como resultado que existían diferencias en el bienestar subjetivo de las personas dependiendo del área en la que viajaran y también del modo de transporte, aquellos que viajaban a pie o en bicicleta sentían mayor satisfacción con el viaje que aquellos que viajaban en otro modo de transporte, además para usuarios de transporte público, la satisfacción con el viaje fue significativamente menor que para usuarios de automóvil y modos activos.

De Vos, Schwanen, Van Acker y Witlox (2015) también realizaron un estudio enfocado en analizar viajes de ocio en diferentes modos de transporte: transporte público, transporte privado y bicicleta, en la ciudad de Gante (Bélgica). Para cada modo de transporte, se calificaron los 9 ítems de la escala STS, y se compararon los promedios de estos valores con las medias de los otros modos combinados, mediante pruebas *t*. La satisfacción del viaje para las evaluaciones tanto afectivas como cognitivas, resultó menor para los viajes de ocio en transporte público que para los otros modos (automóvil y modos activos).

En otro estudio sobre bienestar subjetivo (Friman, Ettema y Olsson, 2017), el objetivo era establecer si la satisfacción con los viajes (diarios, de ocio, escolares y viajes de compras) estaba relacionada con la satisfacción con la vida y el bienestar emocional.

Para ello se aplicó la encuesta STS a una muestra aleatoria de 367 participantes que fue reclutada de tres áreas urbanas en Suecia (Karlstad, Gotemburgo y Estocolmo). Los resultados obtenidos fueron analizados, aplicando la teoría de mínimos cuadrados y modelos de ecuaciones estructurales.

Se reafirmó que, la satisfacción con los viajes diarios influía directamente en el bienestar emocional y directa e indirectamente en la satisfacción con la vida. Los resultados mostraron que los viajes en transporte público eran menos satisfactorios que en automóvil y modos activos.

Más recientemente, Singleton y Clifton (2019) desarrollan mediciones multidimensionales de bienestar tanto subjetivo como psicológico asociados a un viaje. La muestra correspondió a adultos que trabajan y viajan diariamente en el área metropolitana de Portland, Oregón, que se desplazaban, a pie, en bicicleta, automóvil o transporte público; y se aplicaron encuestas on-line. Para la realización de las encuestas, se utilizó el formato corto de PANAS (I-PANAS-SF), el cual ha sido validado psicométricamente (Thompson, 2007).

Para medir aspectos eudaimónicos del bienestar referido a los viajes de ida y vuelta del trabajo crearon diversos ítems basados en otros cuestionarios anteriores que aplicaban a la vida en general. Se realizaron análisis factoriales exploratorios y confirmatorios, para evaluar los diferentes tipos de bienestar; y el trabajo concluye proponiendo una nueva escala de medición de factores que inciden en el bienestar subjetivo y bienestar psicológico.

3.2 Bienestar y transporte privado

En cuanto a las evaluaciones de bienestar para el transporte privado. En el estudio de Ettema et al (2011), se obtuvieron mayores valores de satisfacción con el viaje (usando el cuestionario STS) para los viajes en automóvil, en comparación con los viajes en autobús; al tener este último, aspectos desfavorables como mayores tiempos de viaje y depender mucho del acceso a las paradas.

Ettema, Gärling, Olsson, Friman y Moerdiik (2013) también desarrollaron una investigación para medir la satisfacción con el viaje de una muestra de usuarios de vehículo privado utilizando la escala STS en cuatro autopistas diferentes de Países Bajos. Como resultado demostraron que diversos factores influían sobre la satisfacción con el viaje: la seguridad vial, el nivel de enfado con los otros usuarios de la autopista, cansancio, distraerse con las señales, y falta de capacidad para decidir la velocidad y el carril, así como el propósito del viaje y las propias características del conductor.

Como se ha comentado anteriormente en el trabajo de Friman y colaboradores (2013) a través de la aplicación de la encuesta STS, observaron que la escala global de la satisfacción con el viaje para usuarios de automóvil fue significativamente mayor que para usuarios de transporte público.

En el análisis de De Vos y colaboradores (2015), en el que aplicaron la escala STS, para viajes de ocio en diferentes modos de transporte de la ciudad de Gante (Bélgica); la satisfacción del viaje para las evaluaciones tanto afectivas como cognitivas, resultó mayor para los viajes de ocio en automóvil, que en transporte público.

Friman y colaboradores (2017) en su estudio para determinar la relación entre satisfacción con los viajes y satisfacción con la vida, observaron que la satisfacción con los viajes diarios influía en el bienestar emocional y en la satisfacción con la vida. Los resultados mostraron que los viajes en vehículo privado eran más satisfactorios que en transporte público; debido a las variables como interrupciones en el transporte público por baja capacidad de infraestructura; accesibilidad a aparcamientos de vehículos vs paradas de autobús alejadas, o que el vehículo privado fuera considerado más cómodo que el transporte público. Además de antiguas políticas de vivienda que han favorecido el uso del vehículo privado.

3.3 Bienestar y movilidad activa

Algunos de los estudios anteriormente descritos, además de evaluar el bienestar en el transporte público y el vehículo privado, incluían modos activos como bicicleta o a caminar; en nuestra revisión aparecen otros estudios que se enfocan específicamente en algunas de estas modalidades.

Como se ha descrito anteriormente en Friman y colaboradores (2013), en la medición del bienestar subjetivo experimentado por usuarios de diferentes modos de transporte, los resultados revelaron que, viajar en bicicleta o a pie, era más satisfactorio que viajar en otros modos de transporte público o privado.

Jones, Harms y Heinen (2016) realizaron una investigación enfocada a usuarios de bicicletas eléctricas, de Holanda y Reino Unido, con el fin de determinar su bienestar psicológico, experiencias y percepciones. Esta se centró en 3 aspectos:

- motivos de compra
- percepción del impacto en el comportamiento de viaje
- experiencia del usuario.

Los resultados arrojaron que la principal motivación que tienen las personas para viajar en bicicletas eléctricas es superar viajes largos o complicados o reemplazan viajes personales que normalmente hacían en automóvil.

Los resultados del estudio de Friman et al (2017), confirman la relación entre bienestar y modo de transporte. Para el caso específico de modos activos, los viajes en modos activos son más satisfactorios que en transporte público.

Se destaca también, el estudio realizado en China por Ma y colaboradores (2018), quienes desarrollaron un modelo para determinar los factores que afectaban el bienestar subjetivo de los usuarios de bicicletas compartidas, aplicando encuestas on-line a 908 usuarios, y encontraron que el valor percibido por los usuarios, la influencia social y las características del sistema de bicicletas compartidas son factores importantes que inciden en el bienestar subjetivo de los usuarios; además, el bienestar subjetivo puede verse afectado por factores psicológicos como la realización personal. Concluyendo que el valor hedónico tiene el mayor impacto en el bienestar subjetivo, seguido por el valor social y por el valor utilitario, y por tal razón, los usuarios de bicicletas compartidas valoran más el placer sobre los demás factores. Adicionalmente, ofrecían recomendaciones para los operadores, encaminadas a mejorar el placer de los usuarios, tales como, mejorar aún más el diseño visual de las bicicletas; reforzar la imagen de utilidad, placer y felicidad del servicio, a través de campañas; y aplicar la teoría de la influencia social para atraer más usuarios.

En el estudio de Handy y Thigpen (2019), realizado con estudiantes y empleados de la Universidad de California, se utilizó un modelo de regresión lineal bayesiano. Al evaluarse los resultados de las encuestas, en las que se utilizó una escala de Likert, y se tomó el promedio de la evaluación de 6 aspectos relacionados con sentimientos generales sobre el viaje, resultó que los caminantes estaban más satisfechos seguidos de cerca por los ciclistas.

En el estudio de Burgueño et al (2020) se adapta la versión española de la Escala de Necesidades Psicológicas Básicas en el ejercicio a los desplazamientos activos desde y hacia la escuela, en niños y jóvenes utilizando la escala BPNS, y se considera que la escala para medir la satisfacción de las necesidades básicas psicológicas es el primer instrumento válido para medir las 3 necesidades en los desplazamientos activos desde y hacia la escuela de los jóvenes españoles (a pie y en bicicleta).

4. CONCLUSIONES

El concepto de bienestar en el transporte ha adquirido importancia en las últimas décadas. Se han venido desarrollando y adaptando teorías psicológicas y herramientas de medición, que buscan evaluar de la manera más fiable posible, los componentes afectivos del bienestar, que anteriormente se dejaban de lado, cuando se prestaba más atención a las relaciones costo – beneficio. Se ha demostrado que la satisfacción con los viajes diarios influye en la satisfacción con la vida y en el bienestar emocional; es importante que las políticas públicas se alineen en ese sentido, buscando impactar la calidad de vida de las personas, a través de las mejores experiencias en sus viajes.

La satisfacción y las emociones experimentadas por los usuarios está ligada al modo de viaje, por consiguiente, la implementación de nuevas soluciones de movilidad urbana, afectarán el comportamiento. Se debe estudiar los cambios que se producen, e inciden ya sea positiva o negativamente en el bienestar psicológico y subjetivo de las personas.

Por ejemplo, evaluar el uso de modos de transporte compartidos vs formas convencionales de moverse. Estas nuevas formas de movilidad incluso, han incidido en cambios en el diseño urbano, y aún no se han hecho estudios en cuanto al comportamiento; por ello, es importante, desarrollar investigaciones al respecto. Al realizarse una revisión de literatura, estos estudios son escasos, especialmente, donde se aborden nuevos modos de movilidad, como patinetes o modos compartidos (*carsharing, motosharing*). Por lo tanto, el estudio del bienestar psicológico o eudaimónico, enfocado a analizar estos nuevos modos de movilidad, permitiría obtener conclusiones importantes con respecto a los factores que influyen en el bienestar de los usuarios.

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LA REGULACIÓN DE LOS PATINETES ELÉCTRICOS COMPARTIDOS EN LAS CIUDADES ESPAÑOLAS

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RESUMEN

El uso del patinete eléctrico se está extendiendo cada vez más por distintos países del mundo. Recientemente se han publicado algunos artículos sobre su implantación en algunas ciudades, sobre todo de Estados Unidos. Sin embargo, todavía hay poca investigación sobre aspectos regulatorios. Este trabajo estudia la regulación de esta nueva forma de movilidad en España. Tras analizar la normativa aprobada en las ciudades con más de medio millón de habitantes, se han determinado los factores regulatorios diferenciadores entre ellas. Empleando un análisis clúster, se han establecido grupos de ciudades en función de su similitud normativa. Los resultados obtenidos pueden contribuir a que el uso de esta nueva forma de movilidad sea más eficiente y sostenible.

1. INTRODUCCIÓN

Las políticas de transporte dirigidas a impulsar la sostenibilidad urbana en las ciudades tienen en estos momentos una gran importancia. La División de Transporte Sostenible de la Comisión Económica para Europa considera que apostar por la planificación urbana orientada a la movilidad puede impactar en trece de los diecisiete Objetivos de Desarrollo Sostenible de la Agenda 2030, establecidos por Naciones Unidas. Además, la movilidad sostenible es esencial para cumplir con el Objetivo 11 sobre ciudades y comunidades sostenibles que, dentro de sus metas, establece la de proporcionar acceso a sistemas de transporte seguros, asequibles, accesibles y sostenibles para todos, así como la de mejorar la seguridad vial mediante la ampliación del transporte público.

Desde el año 2017, el patinete eléctrico se ha convertido en una alternativa para moverse por la ciudad, y su uso compartido es cada vez más habitual porque ofrece una alternativa al automóvil privado y reduce la contaminación del aire y el ruido. Se trata de un medio de transporte que sirve para recorrer distancias cortas y se engloba dentro de la micromovilidad.

Sin embargo, la aparición de los patinetes eléctricos en las ciudades no ha estado exenta de problemas. Desde un principio las dificultades más importantes en el desarrollo de esta actividad han estado relacionadas con la convivencia en la acera de peatones y patinetes, así como el su incorrecto estacionamiento.

Todo ello ha dado lugar a un intenso debate sobre la seguridad vial y la protección de los peatones.

En España, la implantación de patinetes eléctricos compartidos está siendo heterogénea, puesto que depende de la política de movilidad de cada Ayuntamiento. Éstos se han visto obligados a aprobar regulaciones específicas sobre esta actividad económica, ya que el vacío legal existente hasta este momento tanto a nivel local como estatal, así como la implantación de empresas para satisfacer una demanda real, han forzado a los Ayuntamientos a aprobar Ordenanzas nuevas que regulen la movilidad o a modificar las vigentes.

El objetivo de este artículo es identificar las tendencias regulatorias del patinete eléctrico en España. Para ello, se analiza la convergencia o divergencia de las decisiones tomadas por los diferentes Ayuntamientos en relación con aspectos clave de la normativa implantada. Para ese fin, se han estudiado las ciudades españolas con una población superior a medio millón de habitantes en 2020 y cuyas Administraciones han establecido medidas regulatorias para los patinetes eléctricos, esto es, Madrid, Barcelona, Valencia, Sevilla, Zaragoza y Málaga.
El análisis realizado permite conocer cuáles son los aspectos regulatorios más importantes en el ámbito del patinete compartido, cuáles son las tendencias normativas que más se han implantado en las ciudades, así como las diferencias más significativas entre unas y otras. Finalmente, se indica por dónde está avanzando la regulación a nivel estatal para homogeneizar la regulación.

Los resultados obtenidos en este trabajo de investigación ayudarán a los Ayuntamientos a generar normativa que regularice el uso del patinete eléctrico compartido de forma homogénea en todo el territorio nacional, promoviendo el uso de nuevas formas de movilidad.

2. LA REGULACIÓN DEL PATINETE EN LAS CIUDADES

El uso del patinete eléctrico compartido como una nueva forma de movilidad se está extendiendo cada vez más a lo largo de distintas ciudades del mundo. Sin embargo, a las empresas operadoras no les está resultando fácil su implantación debido a los vacíos normativos sobre la explotación de este tipo de negocio en unos casos, y a la heterogénea normativa municipal en otros. Son muy escasos los estudios existentes sobre esta cuestión, y los publicados recientemente se centran en ciudades de Estados Unidos (Caspi et al., 2020; Portland Bureau of Transportation, 2018; Wood el al., 2019). Así, NACTO ha elaborado guías de regulación y gestión de la micromovilidad (NACTO, 2018).

En España, el Estado es competente para regular los aspectos básicos en materia de tráfico, circulación y seguridad vial, mientras que los Ayuntamientos gozan de autonomía para regular la ordenación del tráfico de vehículos y personas en las vías urbanas, así como el transporte público de viajeros.

Cada Ayuntamiento, por tanto, es competente en la implantación de medidas que fomenten una movilidad urbana sostenible en su término municipal.

La primera Ordenanza de patinetes eléctricos que se publicó en España corresponde al Ayuntamiento de Barcelona, en junio de 2017, pero en ella no se desarrolló la regulación específica para el alquiler de patinetes. En octubre de 2018, el Ayuntamiento de Madrid publicó su Ordenanza de patinetes eléctricos, desarrollando las especificaciones que deben cumplir las empresas de alquiler de patinetes, y en febrero del año siguiente se otorgaron las primeras licencias. En mayo de 2019 los Ayuntamientos de Valencia y Zaragoza publicaron sus propias Ordenanzas. En Valencia se estableció una política similar a la de Barcelona, en cuanto a no desarrollar en su Ordenanza el servicio de patinetes compartidos. Sin embargo, el Ayuntamiento de Zaragoza sí definió las condiciones en las que se debe operar dicha actividad y otorgó las primeras licencias a empresas de alquiler en mayo de 2019. El Ayuntamiento de Sevilla publicó su Ordenanza de patinetes en octubre de 2019 y en enero de 2021 otorgó las primeras licencias de operación. Por último, la Ordenanza de patinetes eléctricos del Ayuntamiento de Málaga se publicó en agosto de 2019 y, aunque todavía no ha otorgado licencias a empresas de alquiler, desarrolla en su Ordenanza algunos aspectos de esta actividad.

Una vez identificada la regulación en materia de patinetes eléctricos compartidos de las ciudades españolas con más de medio millón de habitantes, se han identificado los aspectos más relevantes de dicha regulación. La Tabla 1 recoge una comparativa entre las ciudades. Para facilitar su presentación, se han agrupado los factores regulatorios en cuatro bloques atendiendo al orden de aparición en normativa:

- acceso al mercado, competencia y distribución en la ciudad
- características técnicas y operacionales
- estacionamiento, circulación y seguridad
- supervisión del servicio.

2.1 Acceso al mercado, competencia y distribución en la ciudad.

Para que las empresas puedan estacionar los patinetes compartidos en zonas de dominio público, se precisa de una autorización demanial o una concesión administrativa otorgada por el Ayuntamiento. A la autorización demanial tienen acceso en cualquier momento todas las empresas que cumplan los requisitos establecidos por dicho Ayuntamiento, mientras que la concesión administrativa se otorga a un número limitado de empresas seleccionadas a través de un procedimiento de concurrencia en un periodo determinado.

Estas dos formas que tienen las empresas de acceder al mercado tienen importantes implicaciones a efectos de limitación de la competencia. Si se accede mediante concesión administrativa, el número de empresas operadoras es más reducido que si se precisa de una autorización demanial.

El Ayuntamiento de Madrid ha optado por autorizar la actividad a todos los operadores económicos que cumplan con una serie de condiciones fijadas previamente; inicialmente se concedieron licencias de operación a 14 empresas de alquiler. Los Ayuntamientos de Sevilla y Zaragoza han otorgado concesiones administrativas para adjudicar la operación a dos empresas en cada uno de sus términos municipales. Por otro lado, los Ayuntamientos de Barcelona, Valencia y Málaga no han dado autorizaciones demaniales ni han otorgado concesiones administrativas.

Tanto las autorizaciones demaniales como las concesiones administrativas son temporales, oscilando su duración entre uno y dos años, con posibilidad de prórroga en algunos casos, como ocurre en Zaragoza. El Ayuntamiento de Madrid optó por las autorizaciones demaniales, no obstante, se reserva la posibilidad de revocarlas en caso de que se saque a concurso público la prestación del servicio mediante concesión administrativa.

Algunas ciudades han establecido un número máximo de patinetes para operar. En Madrid operaron en el año 2020 alrededor de 4.800 patinetes de los 10.000 permitidos. El estricto reparto de vehículos por áreas en la ciudad y la escasa rentabilidad generada ha hecho que algunas de las empresas operadoras del servicio se hayan retirado.

Por su parte, en Sevilla y Zaragoza se ha fijado el límite de patinetes compartidos en 3.000 y 1.700 respectivamente. A diferencia de Madrid, estas dos ciudades exigen en los pliegos de sus concesiones mantener operativas todas las licencias de patinetes otorgadas.

Respecto a la distribución geográfica de los patinetes, tanto Madrid como Zaragoza han establecido unos límites de patinetes de alquiler en cada área concreta de la ciudad. En Madrid, se fijó primero el número máximo de patinetes compartidos autorizables en cada barrio, y posteriormente se concedieron las licencias de forma equitativa en cada barrio a las empresas que solicitaron licencia. Por otro lado, Sevilla tan solo establece en los pliegos de la concesión que los patinetes compartidos se distribuyan de forma equilibrada por la ciudad.

2.2 Características técnicas y operacionales.

La determinación a nivel estatal de las características técnicas y operacionales que deben cumplir los patinetes eléctricos ha ido evolucionando. La aparición de estos vehículos de movilidad personal (VMP) supuso un problema regulatorio para las Administraciones debido a que este tipo de vehículos no venían recogidos en el Reglamento General de Vehículos.

En el año 2016 la Dirección General de Tráfico publicó la Instrucción 16/V-124. Ésta distinguió entre dos tipos de patinetes eléctricos: por un lado, los denominados de tipo A, que son más pequeños y más ligeros; por otro lado, los denominados de tipo B, que son patinetes eléctricos de mayor tamaño. Esta clasificación fue establecida en las Ordenanzas de Madrid, Barcelona, Valencia y Zaragoza.

Con la aprobación del Real Decreto 970/2020, en vigor desde el 2 de enero de 2021, se pone fin al vacío legal en el que se encontraba el patinete eléctrico, incluyéndolo formalmente en el grupo de VMP. Esta norma establece que los patinetes eléctricos no pueden alcanzar una velocidad superior a 25 km/h, no pueden circular por la acera ni zonas peatonales, y no pueden contar con sillín.

La Instrucción 2019/S-149 TV-108 de diciembre de 2019 ya adelantaba que la velocidad máxima de los patinetes eléctricos se fijaría en 25 km/h. De esta forma, las últimas Ordenanzas aprobadas, la de Sevilla y la de Málaga, no establecieron la distinción entre patinetes eléctricos tipo A y tipo B, y fijaron la velocidad máxima de circulación en 25 km/h.

En el Real Decreto 970/2020 también se establece que a partir de los dos años desde que se publique el Manual de Características de los VMP, éstos estarán obligados a disponer de un certificado para la circulación en el que se acredite que dicho vehículo cumple con los requisitos técnicos exigidos por la normativa nacional e internacional, así como de su identificación.

En cuanto a las condiciones operacionales, cabe destacar que tanto Sevilla como Zaragoza establecen restricciones acerca de la recarga de los vehículos. Ambos Ayuntamientos exigen garantizar el uso de toda la flota activa en horario diurno, sin permitir a los operadores subcontratar las actividades de recarga o mantenimiento.

En todas las ciudades se exige que los operadores tengan contratado un seguro de responsabilidad civil ante terceros. En Sevilla y Zaragoza se obliga a que su importe sea superior a 300.000 euros.

2.3 Estacionamiento, circulación y seguridad vial.

El estacionamiento de los patinetes compartidos en Madrid se realiza mediante free floating (aparcamiento libre en la acera), mientras que en Málaga y Sevilla es exclusivamente en base fija (aparcamiento de patinetes en pequeñas áreas establecidas por el Ayuntamiento). Aunque el Ayuntamiento de Málaga todavía no ha otorgado licencias de operación a empresas de alquiler, debido a la proliferación de estos vehículos, han decidido habilitar espacios para el estacionamiento en la vía pública.

Zaragoza ha optado por un sistema mixto, prohibiendo el estacionamiento fuera de las bases fijas en algunas partes del centro, y permitiendo en el resto de la ciudad free floating, aunque recomendando estacionar en bases fijas si existen. Se exige a los operadores establecer mecanismos que premien con incentivos tarifarios a los usuarios cuando estacionen en bases fijas. Además, el Ayuntamiento puede obligar a los operadores a efectuar algunas penalizaciones concretas. Por ejemplo, Málaga exige mantener activa la tarificación si el usuario estaciona fuera de las bases fijas.

En cualquier caso, la responsabilidad por el correcto estacionamiento de los patinetes corresponde a la empresa, sin perjuicio de las sanciones que ésta pueda repercutir a los usuarios.

Las bases fijas pueden disponerse de dos maneras: de uso general o específicas para patinetes. Mientras Zaragoza otorga el uso de estas bases fijas únicamente a vehículos de movilidad compartida, Sevilla reserva al menos un tercio de su capacidad a vehículos privados. Sevilla cuenta con 249 bases fijas con capacidad para 2.650 patinetes eléctricos. Zaragoza cuenta con 38 bases fijas y permite también estacionar en ellas a bicicletas compartidas. Málaga presenta 29 bases fijas a lo largo de la ciudad.

Barcelona y Valencia no permiten a ninguna empresa de alquiler estacionar en dominio público. En algunos casos, las empresas han empleado bases privadas para poder prestar el servicio, por ejemplo, realizando acuerdos con otras empresas que les proporcionen un espacio en sus locales para poder estacionar los patinetes.

En general, el orden de prioridades de estacionamiento de los patinetes es el siguiente: como primera opción se debe hacer uso de estacionamientos específicos para patinetes; la segunda opción es el empleo de reservas de estacionamiento para bicicletas; la tercera opción es hacer uso de la banda de estacionamiento de la calzada; y en último lugar, se permite estacionar en la acera. Es importante resaltar que, aunque la normativa de Barcelona establece que el estacionamiento de los patinetes debe realizarse en los espacios habilitados, en el momento en el que se redactó este artículo el Ayuntamiento no había habilitado ninguno.

Respecto a la circulación de los VMP, el Real Decreto 970/2020 prohíbe de forma general su uso en las aceras. Es habitual que los Ayuntamientos, como el de Málaga, exijan que la circulación se realice por carril bici si éste está disponible. En cuanto a la calzada, los seis Ayuntamientos limitan la circulación de los patinetes eléctricos en carriles de 30 km/h. La diferencia reside en que Barcelona y Málaga permiten circular en cualquier calle de varios carriles por el carril limitado a 30 km/h. Madrid y Valencia permiten circular en calles de varios carriles, pero solo en el caso de estar todos ellos limitados a 30 km/h. Sevilla y Zaragoza sólo permiten circular por calles de un solo carril limitado a 30 km/h. Algunos Ayuntamientos han especificado que la circulación deberá hacerse por la parte central del carril, mientras que Zaragoza tan solo lo recomienda.

En cuanto a las velocidades máximas de circulación, los Ayuntamientos diferencian las siguientes vías: calzada, carril bici, aceras bici y sendas ciclables compartidas con el peatón. Inicialmente, las Ordenanzas de Madrid, Barcelona y Valencia establecieron las velocidades máximas en la calzada según la clasificación de la Instrucción 16/V-124: 20 km/h los patinetes Tipo A y 30 km/h los Tipo B. Posteriormente, con la publicación de la Instrucción 2019/S-149 TV-108, las Ordenanzas de Sevilla, Zaragoza y Málaga ya incluyeron la velocidad máxima en calzada de 25 km/h.

Tan solo en las ciudades que no han desarrollado la regulación de alquiler de patinetes (Barcelona y Valencia) se exige el uso del casco de protección a patinetes de velocidades superiores a 20 km/h.

2.4 Supervisión del servicio.

Los Ayuntamientos han establecido la obligación de que los patinetes de las empresas de alquiler estén identificados. Así, en Sevilla se exige que el VMP sea identificable de forma inequívoca con la documentación, bien con un número de serie o bastidor, o bien mediante la identificación de la marca y el modelo.

Algunos Ayuntamientos han incluido exigencias en cuanto al control remoto que las operadoras de patinetes deben realizar sobre sus vehículos. Málaga exige a los operadores la capacidad de desactivar el vehículo al penetrar en Zonas de Acceso Restringido al Tráfico Rodado. También Sevilla establece este tipo de requerimientos para casos donde el usuario sobrepase los límites de velocidad o estacione en áreas no permitidas.

3. DATOS Y METODOLOGÍA

Una vez seleccionadas las ciudades y recopilada la información regulatoria, se han asociados los factores regulatorios más destacados a variables de tipo cualitativo ordenado y no ordenado. Los factores se clasifican en dos grupos: (a) aspectos que afectan al patinete eléctrico en general y (b) factores que afectan sólo al servicio compartido de patinetes eléctricos (Tabla 2).

Tan solo se incluirán en el análisis los factores regulatorios más destacados que presenten diferencias en alguna de las ciudades. Estos factores son los recogidos en la Tabla 1 y se incluirán como en ella vienen establecidos, salvo la siguiente consideración para extraer mayor información: el factor “Estacionamiento permitido (ordenado por prioridad)” se divide en 3 factores para el análisis clúster, en función de si permite estacionar en calzada, anclado en la acera y en reservas de bicicletas. Todos los factores regulatorios se han considerado cualitativos. Cuando en la Tabla 1 no aparece opción para un factor regulatorio, ello implica que no ha sido recogida en la normativa municipal. Puesto que la Tabla 1 muestra la regulación definida por los Ayuntamientos previa al Real Decreto 970/2020, el análisis clúster incluye los factores “Dimensiones máximas (masa, anchura y longitud)” y “Velocidad máxima en calzada”.

Con el fin de cumplir con el objetivo establecido, se ha realizado un análisis clúster, agrupando las ciudades en función de sus semejanzas. El análisis clúster jerárquico es una técnica estadística multivariante que agrupa elementos tratando de lograr la máxima homogeneidad en cada grupo y la mayor diferencia entre los grupos (Edwards et al, 1965). En este caso los elementos a agrupar son las seis ciudades del caso de estudio, y los factores en función de los cuales se agrupan son cada uno de los factores regulatorios estudiados.

La clasificación se realiza mediante un algoritmo que se basa en la semejanza o diferencia del conjunto de los factores regulatorios comparando los diferentes individuos (Lee et al., 2013). En este estudio se ha medido la semejanza o diferencia de los individuos mediante la distancia de Gower, siendo ésta un valor comprendido entre 0, máximo parecido; y 1, máxima diferencia (Gower, 1967).

$$d(i,j) = (\sum_k \delta_{ijk}\, d_{ijk}) / \sum_k \delta_{ijk} \qquad (1)$$

Donde, i y j, corresponden a los individuos que se comparan; k es el factor de análisis; d_ijk toma el valor de 0 si el factor k de los individuos i y j coinciden, y toma el valor 1 en caso contrario. δ descarta los factores donde los individuos no presentan esa característica. La distancia de Gower entre dos individuos que se establece para cada factor depende de si dicho factor se ha considerado como cualitativo ordenado o no ordenado. En este artículo se han ordenado los factores de una regulación más restrictiva a menos restrictiva. En el caso de factores cualitativos no ordenados, el valor establecido será 0 si ambos individuos coinciden, o 1 en caso contrario. En cambio, para los factores cualitativos ordenados se fijan puntos equidistantes entre 0 y 1 en función del número de opciones del factor, estableciendo la distancia de Gower como la distancia comprendida entre la opción de cada una de las dos ciudades.

Posteriormente, se procede a aplicar el algoritmo de agrupación. Este algoritmo agrupa los individuos (ciudades) por niveles, separando aquellos que más se diferencian del resto (Lee et al., 2013). Cada subgrupo resultante se sitúa en la vertical en función de la diferencia entre los dos individuos más diferentes del subgrupo. Cuanto más parecido hay entre los individuos de un subgrupo, más abajo en el eje vertical aparece. A partir de ese árbol se ha definido el clúster resultado del análisis (Petchey & Gaston, 2007; Akay, & Yüksel, 2018).

Con el objetivo de validar los agrupamientos definidos en el procedimiento anterior, se debe evaluar la bondad de ajuste para evitar la búsqueda de patrones en un dato aleatorio (CHOUIKHI ET AL., 2015). Para evaluar la calidad de los clústeres resultantes se hace uso del índice Dunn, que se estima como la relación entre la mínima separación entre los grupos y el diámetro máximo entre ellos. Se busca que el diámetro de los clústeres sea pequeño y que la distancia entre los clústeres sea grande.

4. RESULTADOS

Se emplea el análisis clúster jerárquico para agrupar a las seis ciudades de estudio en función de la similitud de sus tendencias regulatorias referidas al patinete eléctrico. Se ha establecido previamente que se agruparán las ciudades hasta encontrar los 3 grupos de ciudades con mayor similitud de acuerdo con el óptimo de grupos establecido por la metodología de la silueta media (Rousseeuw, 1987).

El primer análisis clúster compara las seis ciudades en función de los factores del patinete eléctrico en general. Los tres clústeres resultantes son: Málaga; Valencia y Barcelona; Madrid, Zaragoza y Sevilla (Figura 1a).

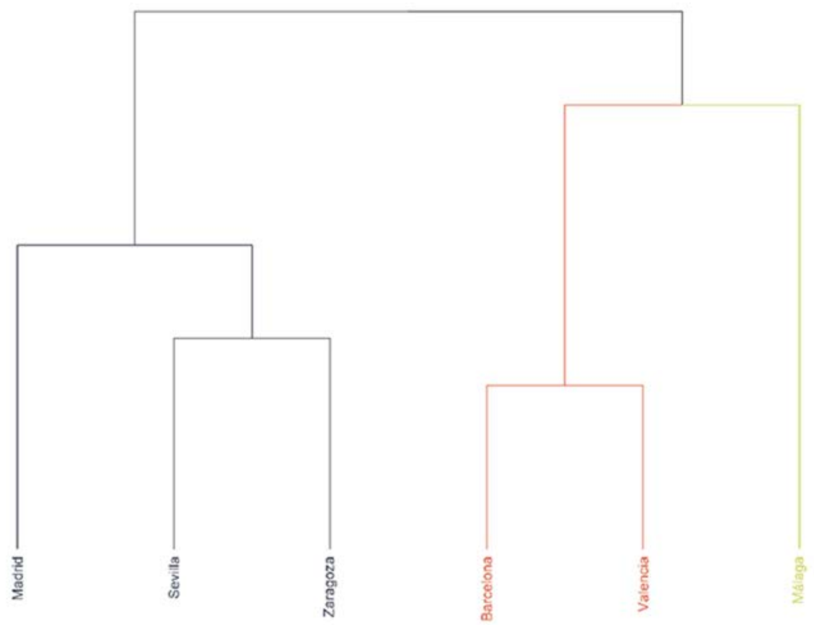

Figura 1a: Patinete eléctrico en general

En este caso, el índice de Dunn resulta un valor de 1,96, lo que significa que los clústeres son compactos y están bien separados de otros clústeres. Málaga forma en solitario el primer clúster, siendo la ciudad que menos se parece al resto en la regulación del patinete en general. La razón se explica en que su Ordenanza ha sido la última en aprobarse, pudiendo estudiar las experiencias en el resto de las ciudades y generar una mezcla de las distintas opciones.El segundo clúster lo forman Valencia y Barcelona. Tan solo se diferencian en algún factor de poca importancia como la velocidad máxima en carriles bici. Esto se puede explicar en que la Ordenanza de Valencias se basó en la de Barcelona.

El último clúster lo forman Madrid, Zaragoza y Sevilla. Son ciudades cuyas Ordenanzas muestran una tendencia a facilitar la circulación en patinete eléctrico. Lo demuestran en varios de los factores en los que coinciden, como son la no obligación en el uso del casco de protección, en permitir estacionar en reservas de bicicletas, o en establecer la circulación del patinete eléctrico por el centro de la calzada. Cabe destacar que dentro de este último clúster Zaragoza y Sevilla acentúan su parecido respecto a Madrid. Esto se debe en parte a que sus Ordenanzas sí fueron establecidas con posterioridad a la Instrucción 2019/S-149 TV-108.

El segundo análisis clúster compara los factores específicos del patinete eléctrico compartido definidos en la Tabla 2. Los tres clústeres resultantes son: Madrid; Sevilla y Zaragoza; Barcelona, Valencia y Málaga (Figura 1b).

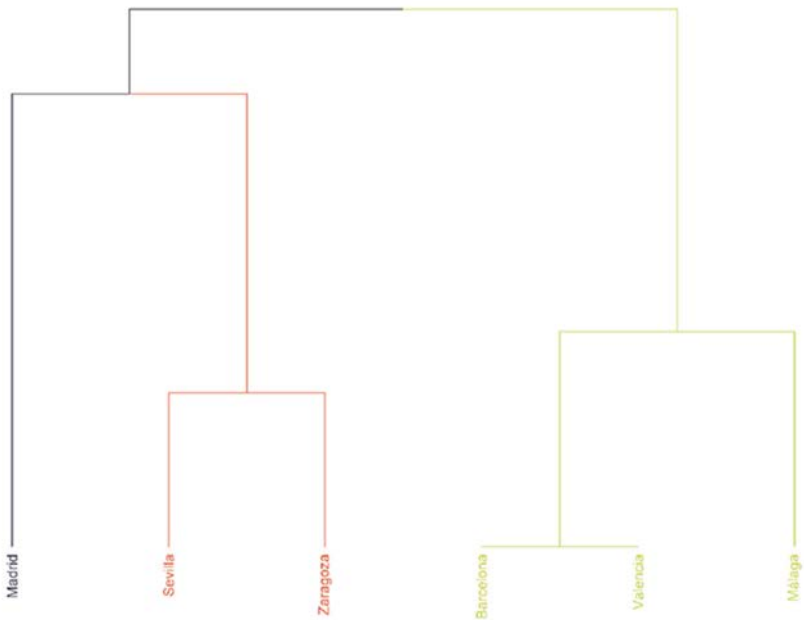

Figura 1b: Patinete eléctrico de uso compartido (alquiler)

En este caso, el índice Dunn tiene un valor de 2,95. Barcelona y Valencia son dos ciudades que casi no han establecido regulación para el patinete de alquiler, por ello no es de extrañar que resulten las dos ciudades más parecidas en este segundo análisis. Málaga completa el primero de los 3 clústeres, aunque manteniendo una cierta diferencia con las dos ciudades anteriores. Esto se debe a que Málaga sí ha adelantado cierta regulación en materia de alquiler de patinetes, como la tipología de alquiler, qué capacidad de control remoto debe tener la empresa de alquiler, y la interacción del usuario con ésta. El segundo clúster está formado por Sevilla y Zaragoza, ciudades muy similares en materia de alquiler de patinetes, donde se optó por restringir la competencia mediante un modelo de concesión administrativa. Por último, Madrid forma en solitario el tercer clúster. Las peculiaridades de Madrid se explican en tanto que fue la primera ciudad en regular y otorgar autorizaciones de alquiler de patinetes.

5. CONCLUSIONES

Ante el incremento de patinetes eléctricos en las ciudades españolas en los últimos cinco años y el vacío legal existente a nivel estatal en cuanto a su uso, los Ayuntamientos se han visto obligados a aprobar Ordenanzas municipales que los regulen.

El resultado es que actualmente existe un abanico de normativas distintas que recogen la voluntad de cada ciudad respecto a su interés en impulsar esta nueva forma de movilidad, y cómo consideran que debe afrontarse. Los factores objeto de regulación más relevantes han sido los requisitos que deben reunir las empresas operadoras de patinetes eléctricos compartidos para prestar su servicio, los requerimientos técnicos y operacionales exigidos a los patinetes, el estacionamiento y la circulación de los mismos, y la supervisión del servicio prestado por las empresas operadoras.

Las primeras ciudades que aprobaron Ordenanzas sobre patinetes eléctricos fueron las de mayor tamaño, Barcelona (2017) y Madrid (2018). En el año 2019 esta nueva forma movilidad compartida se extendió a otros municipios, como son Valencia, Zaragoza, Sevilla y Málaga.

Respecto a la regulación del patinete eléctrico, la normativa de Málaga es la que menos se parece al resto, ya que ha sido la última en aprobarse y esto le ha permitido enriquecerse de las experiencias anteriores. Las normativas de Barcelona y Valencia son similares, puesto que la segunda se basó en la primera. Las normativas de Madrid, Zaragoza y Sevilla muestran una tendencia a facilitar la circulación de los VMP, no obligando a usar casco de protección, permitiendo estacionar en reservas de bicicletas, y permitiendo su circulación por el centro de la calzada.

Respecto a la regulación del patinete eléctrico compartido, se concluye que Barcelona y Valencia no la han regulado. Málaga sí ha regulado algunas cuestiones como la tipología de alquiler, la capacidad de control remoto que debe tener la empresa operadora, y la interacción con el usuario. Zaragoza y Sevilla optaron por restringir la competencia mediante un modelo de concesión administrativa, aunque difieren en cuanto a la duración de las licencias, el número máximo de patinetes, su distribución en la ciudad, y la capacidad de control remoto. Por último, Madrid fue la primera ciudad en regular y otorgar autorizaciones de alquiler de patinetes, estableciendo un sistema de free floating sin limitación en el número de operadores.

Los resultados obtenidos en este trabajo demuestran que, aun cuando se pueden caracterizar grupos de ciudades por su regulación, existen muchas dudas en cuanto al mejor modo de regular esta nueva forma de movilidad compartida. Indudablemente, la regulación debería estar marcada por el logro de objetivos de sostenibilidad y calidad de vida en las ciudades que conduzca a criterios homogéneos.

El desarrollo de nuevas disposiciones normativas más homogéneas debe venir marcado por resultados de futuras investigaciones sobre la eficacia de las medidas normativas adoptadas desde una perspectiva económica, social y medioambiental, que contribuyan a la toma de decisiones de los técnicos y políticos que quieren implantar o mejorar este sistema en las ciudades.

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COLLABORATIVE MOBILITY: COMMON FEATURES IN A NEW GENERATION OF MOBILITY BUSINESS MODELS

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ABSTRACT

Mobility has been massively disrupted by new-generation telecoms and mobile apps, which allow an optimised utilisation of both transport means and infrastructures. When it comes to this kind of mobility, transport authorities and 'traditional' transport planning can only do little. Citizens step in and fill in the gaps at neighbourhood level by co-creating mobility solutions, as they already own or have at their disposal enough assets to work with: private and commercial vehicles, tracking and geo-location capabilities, smart communication devices, a transportation infrastructure grid and so on.

Without additional investment in physical assets for marginal uses of the infrastructure, and without adding more vehicles to the streets, it becomes possible to 'kick start' a new mobility 'metabolism' through collaborative solutions that concatenate several 'sharing' approaches: car-pooling, car-sharing, crowd-parking, bike-sharing, cargo-pooling, data-sharing.

In sum, crowd-sourcing and shared-economy ideas are turbo-charged by new technologies. Such technologies can bridge social capital and citizen power with the valuable aspects of free market economics. In addition, crowd-sourcing mobility solutions seem to make economic sense and bring democratic thinking and environmental conscience. But are they financially sustainable?

1. A NEW MOBILITY PARADIGM?

The idea of sharing things and using them together has worked perfectly well for hundreds of years. In fact, sharing economy ancestors are not Uber or Airbnb. Yet sharing behaviour is being revolutionised and facilitated nowadays by an easy and widespread access to digital information and communication technologies (Papí, 2016).

As a consequence, the shared economy is in the process of evolving into a significant element of the economic cycle -if it is not already-. The idea of sharing things and using them together has worked perfectly well for hundreds of years. All of a sudden, however, it has begun to spawn disruptive business models with spiralling customer numbers and revenues to match (Uber, Airbnb, BlaBlaCar, Deliveroo, etc.)

'Traditional' logistics require centralised planning and thinking; much research has been performed on learning from ant colony and beehive analysis in order to create learning systems. Yet there is a limit on how much we can learn from ants and bees. It is better to design systems to help people interact in better and smarter manner (Papí, 2018). This is the philosophy behind crowd-sourced mobility.

Shared (or collaborative) mobility is arguably the most rapidly growing and evolving sector of the sharing economy. When it comes to this kind of mobility, transport authorities and 'traditional' transport planning can do only little. Citizens step in and fill in gaps where mobility demand is inefficiently met at neighbourhood (or any other) level by co-creating mobility solutions. For example, focus group studies carried out by the ITF show that citizens in Finland's capital Helsinki are specifically looking for services that connect different outer areas of the city with each other (ITF, 2017). In the Irish capital, Dublin, shared services could be useful as feeder services to public transport for residents in suburban areas (ITF, 2018). (Papí, 2016). In this regard, citizens already own enough assets to work with: private and commercial vehicles, tracking and geo-location capabilities, smart communication devices, a transportation infrastructure grid at their disposal, and so on.

Without additional investment in physical assets (obviously in the case of marginal uses of the existing infrastructure, as a widespread commercial roll-out of new solutions would require additional infrastructural investments), and without adding more vehicles to the streets, it seems possible to 'kick start' a new mobility 'metabolism' through sharing and collaborative solutions. These solutions allow changing urban metabolism by concatenating several 'sharing' approaches: car-pooling, car-sharing (car-pooling and car-sharing are often referred indistinctly as 'ride-sharing'), crowd-parking, bike-sharing, cargo-pooling (such as the one proposed by the DynaHUBs project https://www.dynahubs.com) and data-sharing (Such as the traffic data shared by Waze users www.waze.com).

Mobility has been massively disrupted (in a positive manner) by new-generation telecoms and mobile apps, which today are allowing an optimised utilisation of both transport means – public and private – and infrastructures (Papí, 2016). Young professionals living in cities increasingly invest in smartphones to hail a ride rather than in their own set of wheels.

For instance, the International Transport Forum (ITF) has recently stated that both passenger and freight transport demand is set to nearly triple in the next three decades, at the same time highlighting that potential disruptions from within and without could significantly change the transport sector (ITF, 2019). In particular the ITF has examined several disruption scenarios and concluded that:

- A massive uptake of shared mobility could halve vehicle-kilometres travelled in cities and reduce urban transport CO2 by 30% by 2050;
- The combination of shared mobility services, autonomous vehicles, and restrictions on private cars could cut urban transport CO2 by 73%.

Crowd-sourcing and shared-economy ideas are obviously turbo-charged by new technologies. With the proper solutions, such technologies can provide for the European way of bridging social capital and citizen power with the valuable aspects of free market economics. Crowd-sourcing mobility solutions seem to have economic sense and bring democratic thinking and environmental conscience. But are they financially sustainable? (Papí, 2016).

2. LET'S START BY THE BASICS: WHAT DO WE UNDERSTAND AS SHARING ECONOMY?

In 2015 the term 'sharing economy' was introduced into the Oxford English Dictionary. But it seems there is a growing confusion of what the sharing economy actually means. In this context, terms like 'sharing economy', 'peer economy', 'collaborative economy', 'on-demand economy', 'collaborative consumption' are often used interchangeably, though they mean very diverse things.

Today many terms are being used to describe a broad band of start-ups and models that in some way use digital technologies to directly match service and goods providers with customers, bypassing traditional middlemen. The following categorisation (Botsman, 2015) provides much-useful to-the-point definitions:

- Collaborative Economy: An economic system of decentralised networks and marketplaces that unlocks the value of underused assets by matching needs and haves, in ways that bypass traditional middlemen.
- Sharing Economy: An economic system based on sharing underused assets or services, for free or for a fee, directly from individuals.
- Collaborative Consumption: The reinvention of traditional market behaviours — renting, lending, swapping, sharing, bartering, gifting— through technology, taking place in ways and on a scale not possible before the Internet.
- On-Demand Services: Platforms that directly match customer needs with providers to immediately deliver goods and services.

In addition, it is important to highlight the existence of two collaborative economies: one for profit - ridesharing, private accommodation, collaborative food markets, etc. -, which can be considered as an alternative to traditional business models, and one non-for-profit related to barter-like sharing and exchange of goods - home swapping, clothes swapping, services exchange, etc. (Beaumont, 2016).

Another categorisation suggests four categories of activities in the collaborative economy: i) recirculation of goods, ii) increased utilization of durable assets, iii) exchange of services, and iv) sharing of productive assets (Gruszka, 2016; Schor, 2014).

There are authors (Beaumont, 2016) that also connect the rise of the collaborative economy with the economic crisis and the widespread utilization of smartphone applications across the population. Likewise, many of the new sharing and collaborative consumption organisations benefitted from the 2008 economic collapse, which "caused some consumers to lose their homes, cars, and investments and made most everyone more price sensitive" (Belk, 2014).

From a Marxist perspective, collaborative consumption could be viewed as an economic resistance to global capitalism that has born out of its inherent contradictions, signalling a dialectic relationship between capitalism and the sharing economy, which is seen to be more democratic (Rifkin, 2014). Along this line of thought, we could label collaborative consumption as "a form of resistance", a countermovement to the economic violence of the free-market, aimed at self-protection by using the Internet in order to create or engage in alternative to free market-exchange models allowing access to a greater diversity of goods at lower prices (Viba, 2014).

Collaborative consumption can also be labelled as a shift "from a world where we're organised around ownership to one organised around access to assets" (Gansky, 2014). In a way, "the so-called 'sharing economy' has turned traditionally underused assets into competitors to established industries" (Beckmann, 2013). This shift in consumer values from ownership to access is fundamental to understand the on-going emergence of a global network for entrepreneurs, businesses and governments which holds the potential to transform business, consumerism and the way we live.

We can also distinguish between three different constituents in the collaborative economy ecosystem (Sundararajan, 2014):

- Platforms (marketplaces),
- Entrepreneurs (small businesses, micro-entrepreneurs), and
- Consumers.

While the platforms are the person-to-person marketplaces that facilitate the exchange of goods and services between peers, entrepreneurs are the individuals or small businesses that supply goods and services in these marketplaces. In this context, consumers are the individuals who drive demand: buy, rent, consume (both entrepreneurs and consumers are often referred to as ‘peers’). To close the circle, typically the payment from the consumer to the entrepreneur is mediated by the platform, which often charges a commission to one or the other trading party.

From another perspective, we could note five key ingredients to truly collaborative, sharing-driven companies (Botsman, 2015):

- The core business idea involves unlocking the value of unused or under-utilized assets (‘idling capacity’) whether it is for monetary or non-monetary benefits.
- The company should have a clear values-driven mission and be built on meaningful principles including transparency, humanness, and authenticity that inform short and long-term strategic decisions.
- The providers on the supply-side should be valued, respected, and empowered and the companies committed to making the lives of these providers economically and socially better.
- The customers on the demand side of the platforms should benefit from the ability to get goods and services in more efficient ways that mean they pay for access instead of ownership.
- The business should be built on distributed marketplaces or decentralised networks that create a sense of belonging, collective accountability and mutual benefit through the community they build.

Now the issue is to review how the new economic paradigm briefly reviewed above has made its way to mobility and transportation.

3. A DEEPER LOOK INTO COLLABORATIVE MOBILITY

Sharing routine objects seems to make social and economic sense. Such economic sense becomes immediately apparent in the case of automobiles, which are simply left standing instead of being driven for most of the time (Beckmann, 2013).

In recent years, the success story of car-pooling and car-sharing platforms such as BlaBlacar, together with the expansion of transportation network companies (TNC; the TNC acronym designates companies providing transportation services that resort to online platforms (website or mobile apps) to connect passengers with drivers using their personal vehicles. They are also called PHV (Private Hire Vehicles) in the UK. Well-known examples include Uber and Lyft) such as Uber, has marked the onset of a new mode of transport that we could label as 'collaborative transport'.

Beyond the classical motorised individual transport and collective public transport by rail or road, this new transportation option is moving beyond the status of a simple niche demand. A non-exhaustive glance at successful collaborative mobility solutions at the global level brings up platforms as the following:

Uber (www.uber.com) was launched in 2009 as a luxury service providing drivers in black cars to people who needed a ride (https://growthhackers.com/growth-studies/uber. Retrieved on 8 May 2019). A TNC platform, requests and payments are made through the mobile app, and reviews allow building trust between users. Uber is estimated to have 110 million worldwide users (https://www.statista.com/statistics/833743/us-users-ride-sharing-services. Retrieved on 8 May 2019) and has operations in 750+ metropolitan areas worldwide (https://www.uber.com/en-BE/cities. Retrieved on 8 May 2019). Many different services are now available under different brands, including economic options (UberX, Uber XL, UberSelect), premium cars (UberBlack, UberSUV, UberLux), electric cars (Uber Green) and delivery services (UberRush, UberEats). Some Uber services are provided by professional drivers with a TNC licence, while others are provided by peers.

Lyft (www.lyft.com) is a transportation network company (TNC) operating in 600+ cities in the United States and 9 cities in Canada (https://www.lyft.com/driver/cities. Retrieved on 8 May 2019). It develops, markets, and operates the Lyft mobile app, offering car rides, scooters, and a bicycle-sharing system.

Waze (www.waze.com) is an app for smartphones that enables step-by-step navigation and real-time traffic information (RTTI). Traffic information is based on crowd-sourced data regrouping movement data of Waze users (100+ million worldwide) in certain areas as well as their manually supplied additional data such as traffic density, road construction works, or police/radar controls. By utilising this data, Waze detects congestions on the route and suggests alternatives. Waze users can also register themselves as map editors to add missing information and rectify altered design and layout of roads. Additionally, Waze provides traffic data to public entities and broadcasters.

Moovit (www.company.moovit.com) provides an app for smartphones that intends to improve the use of public transportation. Currently it is present in 2,700+ cities in 90 countries and counts on 400+ million users. Users can plan their travel with public transportation and other selected mobility services. Similar to Waze, Moovit relies on crowd-sourced data to add real-time information about delays, cancellations, and other characteristics of individual trains or buses, e.g. crowdedness or cleanliness. Moovit also enables users to register as editors in order to alter or add lines, routes, and timetables.

BlaBlaCar (www.blablacar.com) is an online marketplace for carpooling. Its website and mobile apps connect drivers and passengers willing to travel together between cities and share the cost of the journey. The platform has 70 million users in 2019 and is available in 22 countries (https://thenextweb.com/adobe-fundamentals/2019/02/19/why-french-unicorn-blablacar-still-believes-in-done-is-better-than-perfect/. Retrieved on 7 May 2019).

Zipcar (www.zipcar.com) is the world's leading car-sharing network operating in over 500 cities and towns. Zipcar provides over one million members on-demand access to more than 12,000 vehicles in urban areas and college campuses (https://www.zipcar.com/press/overview. Retrieved on 7 May 2019).

The World Collaborative Mobility Congress (Organised annually by Wocomoco Mobility Academy, a subsidiary of the Touring Club of Switzerland. Flyer downloadable from https://www.wocomoco.org/assets/docs/Publikationen/WOCOMOCO-Brand-Flyer-2014v6_engl-version-webseite.pdf. Retrieved on 22 March 2019) highlighted that "collaborative mobility focuses on sharing journeys, modes of transport and infrastructure. In between collective and individual transport new peer-to-peer based networks are emerging, boosting new types of individual mobility beyond private car-ownership. We are increasingly freeing ourselves from the costly constraints of having to purchase and possess our means of transportation and at the same time are making us independent of large-scale public transport providers to serve our mobility needs. Private bicycle and car sharers, carpooling services, long-distance bus service providers and shared parking providers are as much a part of this new mobility paradigm as the numerous websites and apps where new mobility products and services can be purchased, rented or shared – ranging from cars to public transport tickets to cargo bikes".

A high-level review of the collaborative mobility alternatives listed above (car-pooling, car-sharing, crowd-parking, bike-sharing, plus two additional alternatives suggested by the authors, cargo-pooling and data-sharing) reveals several common features:

- Use is favoured over private ownership (for instance, co-mobility apps launched by cars manufacturers).
- Sharing is often a strategy for investment optimisation (i.e. overhead costs of maintenance minimised in shared fleets).
- Moving is privileged over standing still (i.e. sharing parking reduces costs for parking owners, and at the same time decreases the external costs caused by 'parking search' traffic).
- Pay-per-use is favoured over long-term investment (i.e. the costs of private ownership of a vehicle are passed onto others while the user still enjoys the benefits he sees in possessing a private car).
- Networking and socialisation are preferred over individual ownership (i.e. ride-sharing as a smart form of hitch-hiking and meeting other people).

- A citizen-driven, ‘uncontrolled’ mobility confronting politicians with new challenges (i.e. car-poolers increasing traffic volumes).

Research (Project Consortium TUM Living Lab Connected Mobility, 2016) shows that the attractiveness of the mobility ecosystem depends on a balanced participation (and integration) of service users and services provided. In such a mobility ecosystem, end-users are not only data evaluators as participants but also data sources, as they may contribute to the ecosystem by providing own traveling data and views regarding their mobility preferences. In this context, crowdsourcing in the mobility context often involves:

- Navigation applications, providing the fastest, shortest or nicest driving route from point A to B, or the route with least emissions, to name just a few.
- Intermodal traffic recommendation applications, offering all possible routes from point A to point B providing combinations of different mobility services, such as public transportation, bike sharing or car sharing
- Mobility sharing applications, enabling two or more users to share a ride from point A to B.
- Mapping applications, offering indoor and outdoor maps for special purposes and based on crowd-sourced data.

The availability of Peer-to-Peer (P2P) networks connecting collective and individual transport open new doors, as they apparently free the citizen from the (previously almost-compulsory) private purchase of a mobility tool. In this sense, P2P networks allow people to avoid buying a vehicle of their own and instead hiring a car when they need one; as a consequence, “their mobility is guaranteed without the financial burden of private car ownership” (Beckmann, 2013).

Some authors highlight that collaborative transport benefits from idle, unused transport capacity, therefore offering a low-cost and environmentally friendly mobility with little capital investment in the case of marginal uses of the infrastructure. Taking the example of car-sharing, the potential environmental advantages operate through two channels (Firnkorn and Shaheen, 2015). First, fewer cars have to be produced to satisfy the same overall demand for auto-mobility. Second, with car sharing people use cars more selectively because the marginal costs loom larger than when they own their car (and the fixed costs thus dominate the marginal costs). Along this line, the use of electric or hybrid vehicles in car sharing schemes could have a multiplier effect in terms of these environmental benefits.

This school of thought makes collaborative mobility equivalent to sustainable mobility, highlighting that “it is economically sustainable because it makes better use of existing capacities and requires no additional investments in infrastructures. It is ecologically sustainable because, by making better use of existing capacities, it spares finite resources;

then again, it is socially sustainable because it promotes new forms of communal mobility organisation" (Beckmann, 2013).

To the contrary, other authors challenge the above, as they are indications that shared mobility may not only replace some forms of private travel but may also facilitate other forms of private travel; hence, the net environmental and transport impacts remain contentious (Franckx, 2015).

The authors are of the opinion that the impact of shared mobility on traditional forms of transport has not been studied sufficiently. According to the ITF (ITF, 2019), "bike-sharing and micromobility-sharing may lead to a switch from certain short-distance car trips in some contexts, especially where car use dominates". The IFT further reflects that, in the case of high-quality and cost-effective public transport being available, preliminary findings show that bike-sharing and micromobility-sharing can serve as feeders to public transport, but often replacing walking, while where public transport is infrequent or of low quality, these modes may substitute for public transport.

Today scholars and public policy makers increasingly promote the sustainable mobility paradigm (Banister, 2008) based on 'optimal congestion' and not on 'minimal congestion' (Urry and Lyons, 2005). This is to be achieved through four key objectives: fewer trips, modal shift, distance reduction, and increased efficiency (Cohen, Kietzmann, 2014).

Fewer trips are associated with a reduction in total trips required or taken by a citizen which can be achieved through solutions such as the ability to make online purchases for locally and regionally produced goods and services. Modal shift is the idea of altering the transportation hierarchy from single occupancy vehicles to walking, public, and shared transit alternatives. Through increased densities and better mixed-use development, cities can achieve a reduction in aggregate distances travelled by residents. Finally, increased transport efficiency is associated with reduced environmental impacts of the transportation system through more energy efficient public transportation services and the encouragement of lower footprint personal vehicles (Banister, 2008).

4. COLLABORATIVE MOBILITY: A CHALLENGE TO TRADITIONAL TRANSPORT PLANNING?

Transportation planning is commonly defined as a collaborative process that defines future policies, goals and investments for the mobility of goods and persons in a given territory. Generally speaking, transportation-planning practitioners apply a multi-modal and/or comprehensive approach incorporating the input of public and private stakeholders assessing a range of alternatives and forecasting impacts on the transportation system as a whole.

The second half of the twentieth century saw an increasing sophistication in the methods and techniques associated with transport planning. Increased computer modelling capability, better information technology and improved educational standards all drove up the quality of inputs to planning processes.

Yet we could claim that little change has taken place in the basic transport planning models over the last four decades with the four-stage aggregate model (trip generation, trip distribution, modal split, trip assignment) acting as the bedrock upon transport planning takes place. Since the 1960s transport planners have developed a strong tradition of scientific method for solving urban transport problems, using the classic deductive approach: data collection, defining goals and objectives, and forecasting future demands (Banister, 2002).

Methods and techniques used have been increasingly called in to question in terms of how well they were able to predict long-term futures and help inform policy-making processes (see Timms, 2008 and Næss and Strand, 2012 for lively critiques). Many were associated with practices of ‘predict and provide’ whereby travel demands were predicted using ever more sophisticated models that were then provided for through increased supply (Owens, 1995).

Where mature transport networks exist, the idea of ‘predict and provide’ has been increasingly questioned. Significantly it took no account of the aims of other policy sectors, this at a time when policy integration and sustainability have increasingly become recognised as an important governmental challenge (Te Brommelstreot and Bertolini, 2010). For instance, drawing upon an analysis of 210 projects across 14 countries, Flyvbjerg et al. found that ‘‘forecasters generally do a poor job of estimating the demand for transportation infrastructure projects” (Flyvbjerg et al., 2006: 1).

It therefore seems that current transport demand forecasting and strategic policy-making tools are not sufficient for the change and uncertainty we currently face in the 21st century (Walker et al., 2010, Lyons, Davidson, 2016). On the one hand, physical mobility systems appear ever more crucial in granting individuals and organizations access to the spatially and temporally disjointed resources they need to thrive, or even just to survive. On the other hand, because of a heterogeneous mix of mounting financial and fiscal constraints on infrastructure expansion, and growing awareness of and social resistance to the negative impacts of mobility, the traditional `predict and provide' approach to planning is no longer an option (Bertolini, 2007).

In this context, we could be witnessing an evolution from a rigid transportation ‘monoculture’ that forces people to adapt to the system rather than a flexible, responsive and user-friendly transportation ‘poly-culture’ that can adapt more easily to people and their activities. By transportation monoculture, we refer to inelastic and inflexible systems where there are few mobility options and people must adapt their activities based on the limited mobility options available. In contrast, a transportation polyculture refers to a more robust and flexible transportation system with a wide range of mobility options, involving a wider spectrum of mobility technologies, and in addition requiring a much greater degree of coordination among modes and travellers. In such context, the public sector would have a multifaceted role – not only as a regulator of private transportation and a provider of public transportation, but also a facilitator of shared transportation (Miller, 2011).

Two avenues are of interest here (Vigar, 2017). First, there is increasing recognition in academic circles that disciplinary boundaries often perpetuate approaches not suited to contemporary, complex problems. Inter-disciplinary work is thus often proposed to bring together experts from different disciplines to provide new perspectives. It reflects the idea that innovation frequently arises from interactions outside the immediate policy community. Second, there is increasing attention to involving ‘non-experts’ in such practices, to generate information and ‘co-produce’ solutions. These two elements can be brought together in a ‘trans-disciplinary’ approach, which encompasses experts from across disciplines but also non-experts (Hirsch Hadorn et al., 2008).

The contentious nature of much transport planning in an era of greater citizen activism and less trust in experts also suggest that planning is unlikely to succeed if conducted in a top-down, autocratic way (Vigar, 2017).

In a context where there are opportunities for collecting user preferences at the convergence of three technologies - sensor technologies, geographic information systems, social computing -, collaborative mobility allows participants sharing information and resources, collaborating on solving local and operational transportation challenges (“How do I get to work today?”), and in addition making joint decisions that take the total system costs into considerations (Miller, 2011).

Greater user involvement improves the flow of information, of situated knowledge, to a strategy. And one way of overcoming implementation deficits is by giving people ownership of strategies through participation. The collaborative platforms that ‘match’ services and clients have huge amounts of data available - for instance on accidents, driving patterns, real-time trip data, driver availability. If these data were shared with transportation authorities, this could lead to improvements in the transportation network and the identification of areas that are poorly served by transport services (Franckx, 2015).

Yet at present comparatively little attention is paid to this bottom-up, cooperative approach to transport planning with rather more attention devoted to adjusting demand models for example (Vigar 2017).

The above clearly points out to a principal challenge for transport planners in the years to come: figuring out how to take advantage of the choices of individual transport users in the practice of transport planning and policy development.

5. NEW BUSINESS MODELS FOR THE SHARING ECONOMY

The business model is a broadly discussed concept in academia and practice. It represents a company's money-earning logic (Osterwalder & Pigneur, 2010). Within the architecture of the company, a business model is located between the strategic and operational layer (e.g. Osterwalder, 2004). The meaning of business models underwent strong changes; from a technological to an organisational, and then to a strategic approach (Wirtz, 2011). Still, literature does not agree upon one single understanding.

As noted by Abdelkafi and Makhotin (2013) there are two major streams: an activity-based and a value-based stream. The *activity-based view* describes the business model as the way activities and resources are used to do the business and achieve growth (Baden-Fuller & Morgan, 2010). The *value-based view* defines the business model as a "representation of how a business creates and delivers value, both for the customer and the company" (Johnson, 2010), or as "the way organizations or individuals communicate, create, deliver, and capture value out of a value proposition" (Abdelkafi, 2012).

Staying on the latter perspective, a business model can be defined as a concept describing what value a company proposes to existing and potential customers (*value proposition*), how the business is organized to create the value (*value creation*), with which resources and infrastructure (*value creation infrastructure*), under which circumstances (*value creation conditions*), and how financial value is retained for the company (*value capture*; e.g. Mäkinen & Seppänen, 2007; Johnson, 2010; Osterwalder & Pigneur, 2010; Osterwalder, Pigneur, & Tucci, 2005; Teece, 2010; Zott et al., 2011).

In this sense, a business model defines the product a company provides and the way it interacts with customers and suppliers (Ovans, 2015). It relies on few founding pillars: a superior *value proposition*, a *profit formula* that outlines how to convert value into revenue and the *key resources and processes* to deliver the proposition (Johnson, Christensen, & Kagermann, 2008). These key resources are among others brand, people, technology, partnerships and data (Seiberth & Gruendinger, 2018).

Information technology offers extensive strategic and economic possibilities and decision makers have to consider new technological solutions that re-shape existing business models (Beutel et al, 2014; Teece, 2010). New business model concepts are being explored these days, motivated by the need to describe and analyse new forms of business, such as e-businesses or virtual organizations (Mahadevan, 2000; Timmers, 1998). For instance, today seven in ten of the world's most valuable brands are digital platforms (Seiberth & Gruendinger, 2018).

'E-business' refers to the application of information and communication technologies (ICT) in support of business activities (Beynon-Davies, 2012). The advent of the ICT has caused organisational transformations incorporations and industries (Timmers, 1998; Tapscott et al., 2000; Dubosson-Torbay et al., 2002; Martinez, 2000); in a way, we could say that the concept of a 'business model' has become almost synonymous with e-business and the emergence of the new economy.

Researchers have further created the concept of 'platform business models' to refer to transactions occurring in a two-sided market (Rochet and Tirole, 2003b, 2006) in which various stakeholders can join the platform as part of the supply or demand side (Rochet and Tirole, 2003b; Rochet and Tirole, 2006; Armstrong and Wright, 2007; Evans and Schmalensee, 2008; Rysman, 2009). A two-sided market is an environment established to allow multiple groups such as suppliers and consumers to participate in order to exchange the values that each group desires to obtain through fair 'transactions'. The 'network effect' emerges from these 'transactions' because transactions in two-sided markets create value by facilitating interactions between the different sides (Parker and Van Alstyne, 2005, Eisenmann et al., 2006).

Platforms evolve through the connection and interaction of platform participants as an ecosystem of coexistence that can provide new values and benefits to all participants (Ceccagnoli et al., 2011). And it is at the heart of a business ecosystem that consists of mutually-dependent business communities, producers and consumers, all of which have a complementary and symbiotic relationship with the platform (Evans et al., 2006). Therefore, the nature of platform business models can be characterised by three keywords: 'two-sided market', 'network effect', and 'business ecosystem' (Junic, 2015).

A specific category of platform business models are the ones operating in "sharing economies" of collaborative consumption (Botsman & Rogers, 2010), where people offer and share underutilized resources in creative, new ways. For instance, Airbnb lets people rent out part or all of their homes for short stays, and Uber allows for real-time, location-based ride-sharing. As a consequence, an increasing number of individuals who may not have considered ridesharing or renting a room in private residence as their vacation domicile a few years ago now prefer such sharing models to mainstream alternatives.

Some scholars, however, believe that the 'classical' activity-based and the value-based views presented above do not factor in the resulting complexities when companies deliberately aim for ecological and social value creation beyond financial profits (Schaltegger et al, 2016) and they are therefore increasingly exploring if and how modified and completely new business models can help achieve economic prosperity by either radically reducing negative external effects or creating positive external effects for the natural environment and society (e.g., Boons Montalvo, Quist & Wagner, 2013). Their work has attempted to define the so-called "business models for sustainability" (BMfS), also referred to as "sustainable business models" or "sustainability business models".

The potential sustainability benefits associated with such sharing economies are interesting from an organisational and environmental perspective, but they are not the subject of this research. BMfSs consists of four business model building blocks: a value proposition, supply chain, customer interface, and financial model. Their operationalization of the four elements of a BMfS is provided below (Boons & Lüdeke-Freund, 2013):

1. Value proposition: provides measureable ecological and/or social value in concert with economic value.
2. Supply chain: involves suppliers who take responsibility toward their own as well as the focal company's stakeholders.
3. Customer interface: motivates customers to take responsibility for their consumption as well as for the focal company's stakeholders.
4. Financial model: reflects an appropriate distribution of economic costs and benefits among actors involved in the business model.

The authors consider the BMfSs framework as a viable alternative to start building a taxonomy of the key business models present nowadays in the shared mobility arena.

6. CONCLUSIONS AND THE WAY AHEAD

Only few of the emerging mobile innovations have reached commercial viability backed by real customers, and not just by institutional investors and/or government grants. In short, there seems to be a gap between solutions brought by people and the 'commercial reality'. This gap is like an underwater passage most great innovations fail to cross.

The public perception of shared goods has changed substantially in the past few years. While co-owning properties has been widely accepted for a while (e.g., timeshares), the notion of sharing bikes, cars, or even rides on an on-demand basis is just now starting to gain widespread popularity. The emerging 'sharing economy' is particularly interesting in the context of cities that struggle with population growth and increasing density.

New technologies are enabling the crowd-sourcing of transport data and the emergence of business ideas linked to shared mobility, and this in a society that progressively demands overcoming 'traditional' mobility, at the same requesting i) a flexible and adaptive transport supply with ii) greater respect for environmental considerations.

While sharing vehicles promises to reduce inner-city traffic, congestion, and pollution problems, the associated business models are not without problems themselves.

Many of the collaborative mobility platforms have a hard time finding their way to practical, large-scale exploitation. One of the reasons behind this is that the business model view on this exploitation is lacking. Many of these developments have a technology-push character, where things are developed inside out, with a focus on the concepts and the technologies involved from the very start, and with little attention for actual business deployment at the end of the day. Consequently, a clear, explicit view on commercial exploitation is often missing in these developments. This situation is made worse by the fact that complex mobility scenarios involve a multitude of stakeholders, each of which has its own business interests. Consequently, such business models with a great potential to address mobility and transportation challenges are hardly realised.

Today, TNC (transportation network company) services such as Uber seem to determine their pricing by introducing a reduction to the price of the substitute product (e.g. taxi). At the same time, we can observe that the financial results of this type of companies show losses year after year (for the Uber case: https://techcrunch.com/2019/02/15/uber-reports-3b-in-q4-revenue-rising-operating-losses/?guccounter=1&guce_referrer_us=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_cs=PLetZWiCOB-DyCnVQV004A. Retrieved on 18 March 2019), and that their survival strategy seems to be 'burning the cash' received from venture capital investors, with the hope of expelling their competition from the market.

Little research has been conducted on the issue of pricing the new collaborative mobility solutions, and hence this paper proposes calls for further research on the modelling the pricing of collaborative mobility solutions taking into consideration a combination of variables among which we should consider, a priori and for the case of a TNC service, the existing degree of traffic congestion, the cost of living, the cost of fuel, the price of the substitute product (e.g. taxi, public transport) and the recovery of the costs incurred by the vehicle owner (the driver or his employer).

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FROM URBAN CONGESTION PRICING TO TRADABLE MOBILITY CREDITS: A REVIEW

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ABSTRACT

Congestion is still a big challenge for urban mobility while vehicle sharing, eCommerce and autonomous vehicles will likely increase the unit veh-km of each vehicle and the density of vehicles moving on the streets. Urban vehicle congestion pricing schemes have been taken as effective solutions to this problem. This paper first reviews the research and application cases of urban congestion pricing through recent years, although with the well-developed theoretical basis and successful practices in Singapore, London, Stockholm, Milan, etc., public acceptance and equity concerns are still the main issues for such policies' implementation. To circumvent this shortcomings of congestion pricing, a scheme of tradable mobility credits is proposed as an alternative. As travellers are distributed mobility credits within a specific urban area, which are allowed to be traded, those with low vehicle-using demands can sell their credits to those with more demands. Therefore with this scheme, people have the incentive to reduce the using of vehicles. This paper reviews the studies on this new urban mobility management strategy and compared it with ordinary congestion pricing schemes. Finally, we conclude the gap and possible directions for future work in this area.

1. INTRODUCTION

Congestion has been the major problem that troubles cities around the world. As a strategy of Transportation System Management, urban congestion pricing (CP) was carried out as the approach to solve it. Since the early introduction by Pigou (1920) and Knight (1924), it has long been taken as the most socially optimal strategy for the allocation of road capacity (Hau, 2005). For road bottlenecks or urban restriction area, vehicles enter or travel within the area will be levied. Especially in recent decades, theories and technologies have been well developed and several cities have practised their urban charge schemes.

However, although there are existences of successful applications, arguments on the implementation of CP schemes never stop. Public acceptance is the main obstacle while the equity problem is often considered the core. Thus, the tradable mobility credits (TMC) scheme is introduced to make up for this shortcoming. It is seen as an alternative to the CP but allow travellers to drive for free with limited quotas. Such schemes of tradable credits or tradable permits are found studies and implementations in various fields like forestry regulation (Tripp & Dudek, 1989), water pollution control (Dales, 1968), automobile emission control (Goddard, 1997; Raux & Marlot, 2005) and the well-known Emission Trading Scheme (ETS) of EU, etc.

Both CP and TMC have gained enough attention, there are still difficulties and unresolved issues. Especially the newer TMC, though theoretical works have been carried out, practical experiences are not seen. This paper aims to present, via a case study of urban congestion pricing and an overview of TMC, valuable insights on the further development of TMC to make it more applicable for future implementation.

The paper is structured as follows. Section 2 reviews the implementation cases of urban congestion pricing in Singapore, London, Stockholm and Milan. Then this part also discusses the arguments on acceptance of CP. Section 3 reviews the development, theory and recent works of TMC schemes. Finally, section 4 concludes the paper and proposes further research direction on this area.

2. URBAN CONGESTION PRICING

The main principle of CP is to charge the externalities that are imposed on other users by a new driver entering the network (Knight, 1924; Pigou, 1920). In this case, the equilibrium will achieve when the charging price is equal to the marginal cost of other users. After decades of development, the research of CP has already been well developed. Detailed reviews on theories and methodologies have been concluded (de Palma & Lindsey, 2011; Tsekeris & Voß, 2009; Yang & Huang, 2005). As a transportation demand management policy, CP leads travellers to change their travel behaviours (including route choice, travel time, mode choice, et al.), reallocate the road to travellers who are willing to pay for the externalities. Besides, CP can raise revenues to fund transport projects like road maintenance and the improvement of public transport. Therefore it is approved by most economists (Lindsey, 2006) to achieve social optimum. With sufficient theoretical support, various CP schemes have been considered or already implemented worldwide.

2.1 Implementation cases

Several urban areas around the world have implemented urban congestion schemes to alleviate congestion in the city centres, including Singapore (1975), several Norwegian cities (Bergen, Oslo, Trondheim, etc.), London (2003), Stockholm (2006), Milan (2012) and Gothenburg (2013). The charging schemes vary among those cities with their unique features. All those practices show efficient consequences on congestion control.

Here, based on literature, we selected Singapore, London, Stockholm and Milan to investigate their CP schemes and impacts.

2.1.1 Singapore

As the first practice, Singapore implemented the Area Licensing Scheme (ALS) in 1975. This is a manual-enforced cordon toll system based on gantries at entry points of Restricted Zone (RZ) of the city centre. Drivers needed to buy licenses in advance to enter and travel within the central area, during morning peak hours from 7:30 to 9:30 am. Then three weeks after the introduction, the morning charging hours were extended to 10:15 am to response to the occurring traffic just after 9:30 am (Fan et al., 1992). And initially, they thought that the restriction of morning peak hours would show a ‘mirror image’ on the evening outbound traffic, so there was not charging for evening peak hours. However, as such image did not materialize, ALS is added to the evening peak from 4:30 pm to 7:30 pm (Phang & Toh, 2004) in 1989. Finally in 1994, in order to make the traffic more even throughout the day, ALS was extended to the inter-peak period (10:15 am to 4:30 pm) but with a lower charging rate. In addition, another Road Pricing Scheme (RPS) was implemented to three expressways.

However, the effect of ALS was far above expectation and was considered to make the road network underutilized (Santos, 2005). After the introduction of ALS, the average speeds within the RZ increased to 36 km/h while the expectation was 20-30 km/h (Phang & Toh, 1997). And the peak-hour traffic flow reduced by 45-50% while the original target of reduction was 20-30% (Phang & Toh, 2004). In that case, McCarthy & Tay (1993) argued that the charging rate of ALS was about 50% above the optimal level. Similar conclusions were made after the implementation of the new Electronic Road Pricing scheme (Li, 1999; Willoughby, 2000).

In 1998, ALS and RPS were replaced by Electronic Road Pricing (ERP). This new system made the charging scheme more convenient for both drivers and the administration department. Drivers do not need to buy various licenses in advance, instead, an In-vehicle Unit (IU) is installed on the windscreen of each vehicle with a stored-value card. With sensors on the gantries at each entrance of RZ and IUs on vehicles, ERP charges vehicles when they pass the gantries. The ERP system based on the rationale of optimal average speeds. The optimal average speed for expressway should be 45-65 km/h while 20-30 km/h for arterial roads. The rates and charges are reviewed every quarter and set in 30-minute blocks which means that the rates can be differentiated regarding the real-time congestion level. That means the charge will be reduced if the average road speeds are higher than the optimal level and vice versa (Goh, 2002; Yap, 2005).

On the other hand, alongside the ALS and ERP, Singapore was also developing its public transit services as the alternative for mobility (Santos, 2005). Commuters shifted from private vehicles to public transport modes. The share of public transport increased from 33% to 69% (Phang & Toh, 2004).

2.1.2 London

Following Singapore and several Norwegian cities, London introduced its Congestion Charge scheme in February 2003. It's a kind of area licensing scheme (Santos & Shaffer, 2004). During weekdays between 7:00 am and 6:30 pm, drivers needed to pay a fee (£5 initially) in advance to travel within the central area delimited by the Inner Ring Road. Once paid, drivers can pass the cordon with unlimited journeys in a single day. Although the heavy goods vehicles were charged three times the normal charge (£15) at the beginning, now the price is the same, regardless of the vehicle types and entry time. Meanwhile, there are exemptions and discounts for several specific kinds of vehicles. For example, vehicles belonging to the residents of the central area enjoy a 90 percent discount. Then in 2007, the Congestion Charge zone was extended, making the total Congestion Charge zone covers 39 km^2. Now the congestion charge has been extended to the entire week, a £15 daily charge is asked from 7:00 am to 10:00 pm to travel within the Congestion Charge zone (except Christmas Day).

Before the implementation of Congestion Charge, traffic within the charging zone was expected to reduce by 20 to 30 percent (TfL, 2003) and average speeds would increase by 10 to 15 percent (Santos, 2008). Several months after, the number of private cars, vans and trucks in the central area dropped by 27 percent (Leape, 2006). In terms of average speeds in central London, it was around 14 km/h in 2002 (TfL, 2003), in comparison with 16 to 17 km/h after the implementation (TfL, 2004).

Alongside the Congestion Charge scheme, London has put investment in public transport sectors, promoting the network, convenience and the level of service (Givoni, 2012; Santos, 2008). This reuse of revenues helped it to increase public acceptance and attracted 50 percent of the former vehicle users to shift to public transportation.

2.1.3 Stockholm

In 2016, Stockholm carried out its CP scheme as a seven-month trial from January to July. It was a time-differentiated charge scheme with the cordon around the inner city of Stockholm. Like ERP of Singapore, charges are made once vehicles pass the border. Then after evaluation of the trial and a referendum, the scheme has been permanently implemented since August 2007.

Vehicles would be levied SEK 10, 15 or 20 (depending on the time of day) when passed the cordon on weekdays from 6:30 am to 18:30 pm. There were not levies in evenings and holidays as well as free for vehicles to cross the charging area through the Essinge Bypass. Meanwhile, around 30% of vehicles were exemptions including buses and alternative-fuel cars (Eliasson, 2008). The target was a reduction of 10 to 15 percent of traffic across the cordon. As a result, compared with the corresponding months of 2005, every month the number of vehicles that passed the border decreased 20 to 30 percent in the trial period (Eliasson et al., 2009).

The most interesting point of Stockholm is the change of public acceptance. Before the trial, only 36 percent of Stockholm citizens were in favour of the CP scheme. Then public acceptance increased gradually after the implementation. Later in September 2006, the referendum showed that 53 percent of voters supported to remain the charging scheme (Borjesson et al., 2012; Eliasson, 2014). However, the oppositions of the citizens live in the suburban areas outside Stockholm did not gained enough consideration.

The revenues collected were dedicated to public transport during the trial. As Menon & Guttikunda (2010) pointed out, like Singapore and London, the success of the implementations of CP in Stockholm is partly attributed to their well-developed public transit systems. Similarly, Kottenhoff & Brundell Freij (2009) pointed out that, the successful implantation of CP in Stockholm is closely linked to the expansion of the public transport system.

2.1.4 Milan

Milan first implemented an urban vehicle charge scheme called Ecopass in 2008. But the difference from other cases is that it was a traffic pollution charge while congestion reduction just a side-goal. The charge was set based on the Euro emission standards. A daily charge was imposed on vehicles enter the traffic restricted zone between 7:30 am and 7:30 pm. The maximum fee was €10 while different levels of discounts were granted to low-emission vehicles and frequent users (Rotaris et al., 2010). This scheme made owners of Euro 0-3 vehicles shift to other low-emission vehicles and led to a substantial increase in motorbikes (Percoco, 2014).

The Ecopass program terminated by the end of 2011 and then, was replaced by a new congestion control scheme (Area C) from January 2012. The new Area C scheme has the same charging zone, technology and time period as former Ecopass. As Area C is a congestion charge instead of a pollution charge, vehicles are imposed the same €5 daily charge regardless of their emission standard. And in order to increase acceptance, residents who live within the area have 40 free entrance per month and need to pay €2 for every extra entrance while commercial vehicles also benefit from discounts (Beria, 2016).

After the implementation of Ecopass, commercial and private traffic showed a reduction of 16.2 percent in 2010, compared to 2007. The daily average emission of PM10 decreased by 25 percent within the area. However, in four years, the environmental-friendly vehicles entering increased by 478 percent and commercial vehicles increased by 1400 percent. Then as the impacts of Area C, traffic volume reduced by 36 percent while PM 10 emission reduced by 27 percent (Martino, 2011).

In terms of the use of revenues collected by the schemes, unlike the Ecopass was criticized for its lack of transparency on the revenue reinvestment, in Area C they reinvested the revenues to improve public transport and sustainable mobility modes (Beria, 2016).

2.1.5 Cases summary

These cases prove the effectiveness of such CP schemes on urban congestion control and the successful result gained the endorsement of citizens. One thing that needs to point out is that, although all four cases of CP schemes charge vehicles at the entrance of charging areas, they are different (Croci, 2016; Gu et al., 2018). Singapore and Stockholm use cordon-based schemes that make charges as long as vehicles pass the borders. London and Milan use the kind of area-licensing scheme or called zonal schemes that collect daily charge that vehicles can enter the area with unlimited times.

These four successful cases have a common feature is that the approach of CP is just one of a basket of policies to manage congestion. Another important point is the investment in alternative transport modes, especially public transport. Kottenhoff & Brundell Freij (2009) concluded that public transport may serve very necessary roles in CP policy package. Sole CP schemes will change the drivers' route and travel time to show the reduction of traffic during peak-hour windows (Santos, 2005) while The development of public transport system can help reduce the use of vehicles and attract the mode shifting. The reinvestment of revenues on public transport can benefit the equity issue as well (Eliasson & Mattsson, 2006). Revenue distribution is considered as one of the auxiliary amendments of CP to deal with inequality and make the policy more acceptable (Tian, 2015).

Furthermore, discounts and exemptions are important. For instance, in London citizens living in the city centre enjoy a 90 percent of discount and in Singapore vehicles with more than three passengers also have a discount. And disabled people are considered exemptions in implementations. Moreover, Gu et al. (2018) stated that, in order to achieve a theoretically efficient pricing scheme, the simplicity of the policies is important. The failure in Edinburgh and the greater Manchester showed people's dislike of complicated mechanisms. The ERP is much more simple than ALS that drivers do not need to buy tickets in advance any more. While in Milan, the replacement of Ecopass by the single-rate Area C helped it to raise public acceptance (Hensher & Li, 2013).

2.2 Public acceptance

However, although with sufficient theoretical studies, urban congestion pricing schemes can only find limited practical applications across the world. The main obstacle to the implementation of CP is public acceptance (Albalate & Bel, 2009; Banister, 2003; Glazer & Niskanen, 2000; Schade & Schlag, 2003). Citizens have long taken the free use of roads for granted. Naturally, it is difficult to gain public acceptance to charge a good which is always for free. Cities including Hong Kong, New York, Edinburg and Manchester are the cases that failed to introduce CP schemes (Albalate & Bel, 2009; Gu et al., 2018). Even in

Stockholm's referendum, they ignored the opposition from suburban areas where residents rely more on vehicles to commute to the urban centre.

On the other hand, equity is greatly concerned by stakeholders (Perera & Thompson, 2020) and is taken as the core of acceptance (Langmyhr, 1997; Viegas, 2001), as this is strongly related to the perception of fairness. People tend to take CP as an extra tax on drivers. And it makes low-income drivers gave the roads to those with higher income or have high value of time (VOT). Meanwhile, if the revenues are not used to improve the public transport system, those low-income drivers would be the victims of CP.

In the context of out-of-pocket charges, low-income drivers and people with reduced mobility are faced with more severe travelling burden and further limitations on the travel options (Gu, et al., 2018; Weinstein & Sciara, 2006). Therefore, in London, Stockholm and Milan there are various discounts for some specific groups. Referring to a review article focusing on public acceptance (Gu. Et al., 2018), it concludes that all of the selected key references mention that in Hong Kong, New York and Edinburg, the design of CP policies ignored the equity problem and therefore the concerns of inequity became the main reason for people's opposition (Larson & Sasanuma, 2010; Pretty, 1988; Ryley & Gjersoe, 2006). Accordingly, a more acceptable and fairer approach is needed.

3. TRADABLE MOBILITY CREDITS

3.1 Early works

In order to tackle the most concerned equity problem of CP, a kind of schemes based on tradable mobility credits are proposed as an alternative (Fiorello, 2010; Gulipalli et al., 2008; Raux, 2004; Zhang et al., 2021). The general concept is simple. Drivers are allocated with a limited amount of mobility credits during a certain period (e.g. one month). When travelling within a charging area or go through a charge cordon, drivers will be charged the credits rather than out-of-pocket monetary. Those who exhaust the credits need to buy from authorities or from other drivers. Tian (2015) described it as a stick-carrot mixed approach while traditional CP was seen as the stick. In this situation, drivers with low VOTs have the incentive to reduce their use of vehicles and get a bonus by selling their surplus credits while those with higher VOTs will pay for the congestion externalities.

In the field of congestion control, mobility credits or mobility rights are not a new concept. Daganzo (1995) proposed a hybrid scheme of rationing and pricing. This scheme can be seen as the allocation of mobility quotas without tradability. Viegas (2001) used the concept of "mobility rights" to deliberate over the quota scheme. He described that, at present, drivers get unlimited quotas of mobility rights to drive and the free allocation of limited quotas could be seen as a reduction of the current situation.

Early research mainly focused on concept development, policy design, qualitative analysis and discuss the potential of implementation and reactions from stakeholders. To tackle congestion externalities, Verhoef et al. (1997) proposed several different types of tradable permits schemes which are based on ownership, distance, fuel consumption or parking, respectively.

Then the idea of TMC is proposed more definitely. Raux (2004) discussed the applications of transferable permits in the field of transport policy. He stated that such transferable permits could be an intermediate solution for congestion problems. Later he further defined the tradable driving rights (TDR) scheme with which that urban inhabitants are allocated certain quotas of driving rights and allowed to trade their unused quotas with those who need excessive trips (Raux, 2007). In parallel, Kockelman & Kalmanje (2005) designed a revenue-neutral credit-based congestion pricing (CBCP) policy. Registered vehicle owners get a monthly monetary allowance of travel credits. Drivers do not need to pay money unless they use out of the credits and those who with unused credits can stock up for next month or exchange for cash. And the further work based on expert surveys gave a more detailed refinement of CBCP policy (Gulipalli et al., 2008). From the user’s point of view, CBCP is a very simple scheme since users only need to interact with the authority. Studies on public acceptance have shown that the simplicity of CP policies is another key factor (Gu et al., 2018), which gains proof from the rejection of Edinburgh and Manchester (Hensher & Li, 2013). Ch’ng (2010) hypothesized a tradable credits system with a two-sided auction market where the price of mobility credits is determined by demand and supply. Based on an experiment of tradable credits auction, he explored that trading in the auction market allows revenues to be returned to drivers who shift to other alternative modes and the equilibrium of utility among both sellers and buyers will be achieved.

In general, the TMC schemes have the features as below:
1) the administration department determines the total amount of credits and allocates them to eligible individuals;
2) the exchange of credits is allowed: individuals that travel less can sell their credits to those who exhaust the credits;
3) like congestion pricing schemes, the charging rates of mobility credits may vary depending on the time, location, route or vehicle type.

3.2 Quantitative studies and development

The idea of such a scheme is simple but deeper works more than conceptual discussions are needed. In the recent decade with the well-developed concepts, investigations started to concentrate more on quantitative studies.

Fiorello et al. (2010) took Genoa as a case study, developed a system dynamic model of Genoa Mobility Rights (GMR) to estimate the impact of TMC on individuals with a sequential procedure. Yang & Wang (2011) introduced a system of tradable travel credits and developed the quantitative analysis as well as modelling of the scheme. They assumed a situation with homogeneous travellers to trade their travel credits in a free and competitive market without the interference of the government. After that, they further investigated the complicated situation of heterogeneous drivers that have different VOTs (Wang et al., 2012). Then more following works contribute to the scenario of heterogeneous users. In order to promote a more equitable TMC scheme, Wu et al. (2012) developed a modelling framework to reckon the impacts of the distribution of credits on travellers with different income and geographic features. He et al. (2013) state that the authority needs to deal with not only individual travellers but also transportation firms (such as logistic companies and transit agencies). They take individual travellers as Wardrop-equilibrium (WE) players while transportation firms as Cournot-Nash (CN) players. The differentiated scheme will allocate different numbers of credits to these kinds of users and also charge them differently. Zhu et al. (2014) assumed travellers with continuously distributed VOTs and established a scheme that can decentralize a given target network flow pattern into a user equilibrium link flow pattern. They stated that a proper credits distribution regulation can make every heterogeneous traveller better off.

In the recent years, the increasing number of articles are seen in this field. Nie & Yin (2013) designed a new TMC scheme that rewards credits to travellers who avoid peak-hour window or choose other alternative modes. Their work assigns that not only the new scheme but even a very simple TMC scheme can achieve substantial efficiency. Miralinaghi & Peeta (2016) proposed a multi-period TMC scheme that travellers are allowed to use or sell the credits in the current period or transfer to future periods. They argue that this scheme can stabilize the price of credits. Xiao et al. (2019) proposed a link-based cyclic tradable credit scheme (CTCS) in which the compensatory credits could be charged from or subsidized to the travellers. In terms of sustainable-oriented transport, Wang et al. (2020) combined the TMC scheme with a link capacity improvement measure and proposed a bi-objective bi-level model to balance economic growth and environmental management.

In addition, the efficiency and effectiveness of TMC for alleviating bottleneck congestion are discussed (Tian et al., 2013; Xiao et al., 2013). Nie (2015) carried out a tradable credit scheme of road bottleneck during the morning peak period. He assumed that vehicles passing the bottleneck within the morning-peak time window would be charged with credits and on the contrary, off-peak travellers would be rewarded with tradable credits.

Meanwhile, as a transportation system management policy, participants' reaction and behaviour are important. Ye & Yang (2013) established a continuous dynamic model to depict travellers' learning behaviour. Bao et al. (2014) adopted a disutility function to study travellers' loss aversion behaviour for credit collection during route choice procedure. Xu & Grant-Muller (2016) captured simulation analysis for a case study of Beijing to appraise the TMC's influence on people's mode choice and travel pattern. Tian et al. (2019), based on an online experiment, studied people's interaction with each other as well as with intelligent virtual agents in the situations of credit trading and route choice. And a more detailed literature review on the behavioural impact of tradable credits is concluded by Dogterom et al. (2017).

And necessarily, in terms of the issue of public acceptance, TMC gains better support from the public. The work by Kockelman and Kalmanje (2005) in Austin, Texas proved TMC as a viable and competitive alternative. Likewise, a survey carried out in the UK revealed the better public acceptance of TMC than CP and participants approved its fairness (Harwatt et al., 2011). Dogterom et al. (2018) investigated the acceptability of a distance-based TMC scheme in the Netherlands and Beijing. They found that TMC gained a much higher acceptance in Beijing in comparison with the Netherlands and attributed it to the worse congestion problem.

3.3 Current problems

TMC is a new congestion management approach and there have not found practical implementations by now. Some issues still need more insights.

The administrative cost is a main issue that researchers concern about for TMC. Authorities need to work on the verification of eligible receivers, allocation of credits, monitoring the use and transaction, etc. Therefore, the administrative cost of TMC scheme will be higher than ordinary CP schemes (Dobes, 1998; Fan & Jiang, 2013; Nie, 2012; Verhoef et al., 1997). Especially the transaction cost is a new matter that needs to be taken into consideration but by now have not gained enough attention. Nie (2012) investigated the effects of transaction cost on auction market and negotiated market respectively. He assumed a brokerage service to assist the transaction procedures and a commission fee is charged. They concluded that the auction market can achieve the desired equilibrium allocation of mobility credits while in negotiated market transaction costs would influence the equilibrium. He et al. (2013) concluded that transaction costs will reduce the trading volume of mobility credits and change the price as well as the travellers' route choices. Zhang et al. (2021) found that transaction cost can lead negative influence on travel disutility for people with low VOT and suggested the imposition of equity constraint in TMC design.

Additionally, TMC is introduced as an alternative to CP. While the distribution of revenues on the development of alternative mobility modes is widely approbated in CP schemes, in TMC there are not enough insights. Revenues could be collected as a commission fee in the free-market schemes or collected directly in the schemes like CBCP. In fact, CBCP may be much convenient for the administration department to redistribute the bonus to drivers and to other transport projects. Authorities need to balance the proportion of revenues that rewarding drivers and investing in transport projects, as well as administrative cost should be considered.

Another issue is that researchers now have not reached a consensus about the credit receivers. In general, we can divide the objects into two groups. One is a more limited group that only referred to drivers or car owners (Ch'ng, 2010; Kockelman & Kalmanje, 2005; Verhoef, 1997). On the contrary, other researchers argue that mobility credits should be allocated to all taxpayers or local inhabitants (Fiorello, 2010; Raux, 2007; Viegas, 2001; Yang & Wang, 2011). A consensus is that credits should be allotted to individuals rather than vehicles. Viegas (2001) pointed out that allotting the credits to vehicles will induce rich drivers to own more cars. It is important to determine the appropriate TMC users which are highly relevant to the quantification of the total amount of credits. If the system adopts a free trade market or the auction scheme for transaction, the trading price will be influenced by the total amount. On the other hand, the number of participants in the system will partly determine the efficiency and cost of administration and trading.

4. CONCLUSIONS

In this article, starting from urban congestion pricing, we have reviewed the successful experience of the implantations in Singapore, London, Stockholm and Milan while the failure cases are also discussed. Sufficient research works and practical cases have shown that public acceptance is the main obstacle for the implementation of CP schemes and the core factor should be equity. Thus, we review the literature on TMC schemes, which was proposed as a fairer congestion management approach to circumvent the shortcoming of CP. Although plentiful conceptual, qualitative and quantitative works have been carried out, there are currently lack of implementation practices of TMC schemes. The TMC presents more complicated management and operation systems than traditional CP schemes. Taking the cases of CP as a reference, future research is recommended to improve TMC schemes more applicable.

First, more specific work can be done in terms of heterogeneous users. The feedbacks of those cases show that commercial, retail and delivery industries enjoy the smooth traffic in urban areas that benefit from the implementation of CP schemes. The abatement of congestion, especially during peak-hour windows, allows the delivery industry to arrange their schedule more flexible. More importantly, while with frequent trips and larger size, urban freight vehicles contribute more to urban congestion. Therefore, in the scenario of heterogeneous users, future works of TMC could draw more attention on urban freight delivery. Setting different regulation of credit consumption that vary from vehicles types to present the externalities caused by freight delivery vehicles.

Secondly, the reuse of revenues on the development of public transport system (Banister, 2003) or active transport modes is essential. As drivers shift from private vehicle to other means of transport like public transport (metro, commuter rail, bus, etc.) and active transport (bicycle, walking and PMDs), the services of these modes should be promoted. Hence, further research can focus on the balance of the bonus enjoyed by individuals and the revenues invested in transport projects.

Besides, researchers could also do further investigation on the allocation process of credits, including more insights on the determination of eligible receivers and the total number of credits. The quantitation of the total amount of credits in the urban area is crucial for the theory's implementation.

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PLANIFICACIÓN DEL TRANSPORTE
PLANNING OF TRANSPORT

ANÁLISIS DE EQUIDAD EN LA OFERTA DE TRANSPORTE PÚBLICO MEDIANTE UN MODELO LUTI (LAND-USE AND TRANSPORT INTERACTION). APLICACIÓN AL ÁREA METROPOLITANA DE BUCARAMANGA EN COLOMBIA.

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RESUMEN

La planificación y gestión del transporte debe fundamentarse en un conjunto de técnicas que permitan evaluar, de manera integral y dinámica, su funcionamiento en interacción con los usos del suelo. Para concretar esta idea, se plantea el desarrollo y estimación de un modelo LUTI (Land-Use and Transport Interaction), que incorpora cuatro sub-modelos: Transporte (MT), Localización Residencial (MLR), Localización de Actividades Económicas (MLAE) y Modelo de Indicadores de Accesibilidad (MIA). Además, los resultados de este modelo se han evaluado mediante la estimación de distintos indicadores: de equidad horizontal, mediante el uso del Índice de Servicio de Transporte Publico (ISTP), de equidad vertical, mediante el Índice de Necesidad Social del Transporte Publico (INSTP) y de igualdad mediante el coeficiente de Gini. Este modelo se ha aplicado al análisis de equidad espacial ofertada por el Sistema Integrado de Transporte Metrolinea (SITM) en el Área Metropolitana de Bucaramanga (AMB) en Colombia. Los resultados obtenidos ofrecen un cálculo de la equidad en la provisión del servicio de transporte público, considerando tanto la oferta como la necesidad social, entre las distintas zonas del AMB. Esto ha permitido detectar aquellas áreas con mayor necesidad de transporte público y aquellas que, en cambio, experimentan sobre-provisión del servicio.

1. INTRODUCCIÓN

En Colombia, la migración de población desde zonas rurales a las ciudades ha ocasionado un rápido crecimiento de éstas en términos de población, densidad y empleo. Esto ha impulsado un fuerte aumento de la demanda de suelo y, consecuente, de movilidad, una dinámica que ha obligado a implementar de manera urgente una planificación urbana y del transporte más sostenible, es decir, que fomente un crecimiento más equilibrado. Entre las ciudades que experimentan este crecimiento se encuentra el Área Metropolitana de Bucaramanga (AMB) con un desarrollo urbanístico típicamente determinado por los sectores residencial y comercial, mientras que la planificación del crecimiento en infraestructura y servicios de transporte ha sido mucho más lenta. Este proceso ha ido por lo tanto en dirección opuesta a la regla fundamental de sostenibilidad urbana, la cual propone un equilibrio entre los componentes de la movilidad y de uso del suelo (Cordera et al., 2018). La entidad de planificación del AMB ha aplicado distintas políticas para intentar articular transporte y territorio, y atenuar el impacto de la congestión derivada de un uso excesivo del vehículo privado. Dentro de las principales medidas, se implementó un sistema de transporte público tipo Bus Rapid Transit (BRT), denominado Sistema Integrado de Transporte Metrolinea (SITM), para incentivar el modo público frente al uso de transporte individual. Sin embargo, los resultados han sido limitados, gran proporción de usuarios prefieren un elevado tiempo de viaje con mayor confort antes que usar un transporte público, que parece ser cada vez más ineficiente (Ardila, 2019; Pineda, 2017). Por tanto, la falta de planificación y ausencia de técnicas que permitan una evaluación objetiva, han generado hasta ahora soluciones con una efectividad limitada.

En esta ponencia se propone una metodología para la modelización y la evaluación de la equidad espacial del transporte público, considerando la oferta y demanda (Currie, 2010), que ayude a mejorar la planificación del mismo. En el análisis de la oferta se usa el Índice de Servicio de Transporte Publico (ISTP), y en la demanda, el Índice de Necesidad Social del Transporte Publico (INSTP), con el objetivo de obtener una visión clara sobre la equidad en la provisión del servicio. Se entiende además por equidad horizontal, el equilibrio o desequilibrio entre la densidad de población y la oferta de transporte público, y por equidad vertical el nivel de equilibrio o desequilibrio entre la necesidad social y la oferta que provee cada zona del área de estudio. Finalmente, se ha establecido el nivel de disparidad entre oferta y demanda, resaltando las zonas con mayor necesidad de transporte y aquellas donde hay sobre-provisión del servicio. Para una visión global de la equidad y la igualdad en el servicio que provee el SITM, se utiliza el coeficiente de Gini y la curva de Lorenz (Delbosc & Currie, 2011). Este análisis espacial se ha basado en un modelo de interacción entre el transporte y los usos del suelo (modelo LUTI) que, adaptado al AMB, se redefine como AMB-LUTI. Este modelo se ha apoyado en los resultados obtenidos por Cordera et al. (2013), Barrett et al. (2002), John (2005), Salvini & Miller (2005), Strauch et al. (2005), Waddell (2002), Salas et al. (2017) y Guzmán et al. (2017), en este último caso con resultados de carácter más local. En concreto, la metodología interrelaciona los cuatro sub-modelos mediante programación Python, para la representación dinámica y versátil del comportamiento de la movilidad en un día laborable.

2. METODOLOGÍA

Para poder realizar el cálculo de los índices de equidad, se ha partido del desarrollo por etapas de un modelo LUTI, el cual proporcionará los datos de entrada. Este modelo presenta cuatro sub-modelos interrelacionados, procediendo posteriormente a integrar su funcionalidad mediante el lenguaje de programación Python.

2.1 Estructura del Modelo AMB-LUTI

Con el objeto de analizar el SITM, se ha considerado necesario estimar un modelo LUTI (Torrens, 2000) que simule el funcionamiento del sistema urbano. Este modelo debe ser capaz de representar la organización espacial del transporte y de las actividades humanas en el área metropolitana (Lowry, 1964), es decir, reproducir y estimar la movilidad y la localización residencial de la población y de sus actividades económicas. Los modelos LUTI pueden clasificarse en tres grandes grupos según Cordera et al. (2018): de *primera generación* basados en la teoría de la interacción espacial (Wilson, 1970; Andrews, 1953), en técnicas de programación matemática (Herbet & Stevens, 2006; Brotchie et al., 1980) o en matrices de input/output (Leontief, 1966; Echenique, 2011); los de *segunda generación* basados en la teoría de utilidad aleatoria (McFadden, 1974) para la simulación de los usos del suelo (Martínez, 1997; Anas, 1983); los de *tercera generación* basados en modelos desagregados llamados de micro-simulación (Iacono et al., 2007; Castiglione et al., 2015).

El modelo propuesto AMB-LUTI se fundamenta en técnicas tanto de primera como de segunda generación, bajo la premisa de establecer el equilibrio entre los cuatro sub-modelos que lo componen. Es decir, si ocurre un cambio en el uso del suelo, este repercute en el sistema de transporte, generando un nuevo equilibrio y nueva representación del sistema urbano. Este aspecto hace que se interactúe con escenarios hipotéticos mostrando sus posibles efectos. La estructura del modelo AMB-LUTI se puede ver en la Figura 1.

Los cuatro sub-modelos del AMB-LUTI son: modelo de transportes (MT) que funciona con la información proveniente del modelo de localización residencial (MLR) y de actividades económicas (MLAE), generando el equilibrio entre la oferta y demanda de transportes; el MLR que funciona con la información proporcionada por el MT y por el MLAE simulando un patrón de localización residencial de trabajadores por clase socioeconómica; el MLAE que funciona con la información dada por el modelo de accesibilidad (MIA) y MLR, simulando la distribución de las actividades económicas por sector económico; y el MIA que utiliza la información del MT y MLR, y proyecta el nivel de oportunidades que tiene cada zona para acceder al empleo. Además, hay una serie de supuestos del modelo que ayudan a simplificar la simulación, limitando o excluyendo aspectos secundarios difíciles de modelizar (Cordera et al., 2013): la zona de estudio se considera cerrada, es decir, la demanda laboral es satisfecha por la oferta de trabajadores internos al AMB, evitando simular la inmigración y emigración de trabajadores desde zonas colindantes; la ubicación de actividades económicas, como las industrias exportadoras, se considera fija, ya que no depende de la distribución poblacional, ni de la demanda interna de comercio y cuya ubicación está establecida por el Plan de Ordenamiento Territorial (POT); el modelo AMB-LUTI considera la restricción en cuanto a población residente y actividades económicas presentes en cada zona. Si esta capacidad es superada, el modelo reubica estas familias/empresas en su siguiente localización preferida.

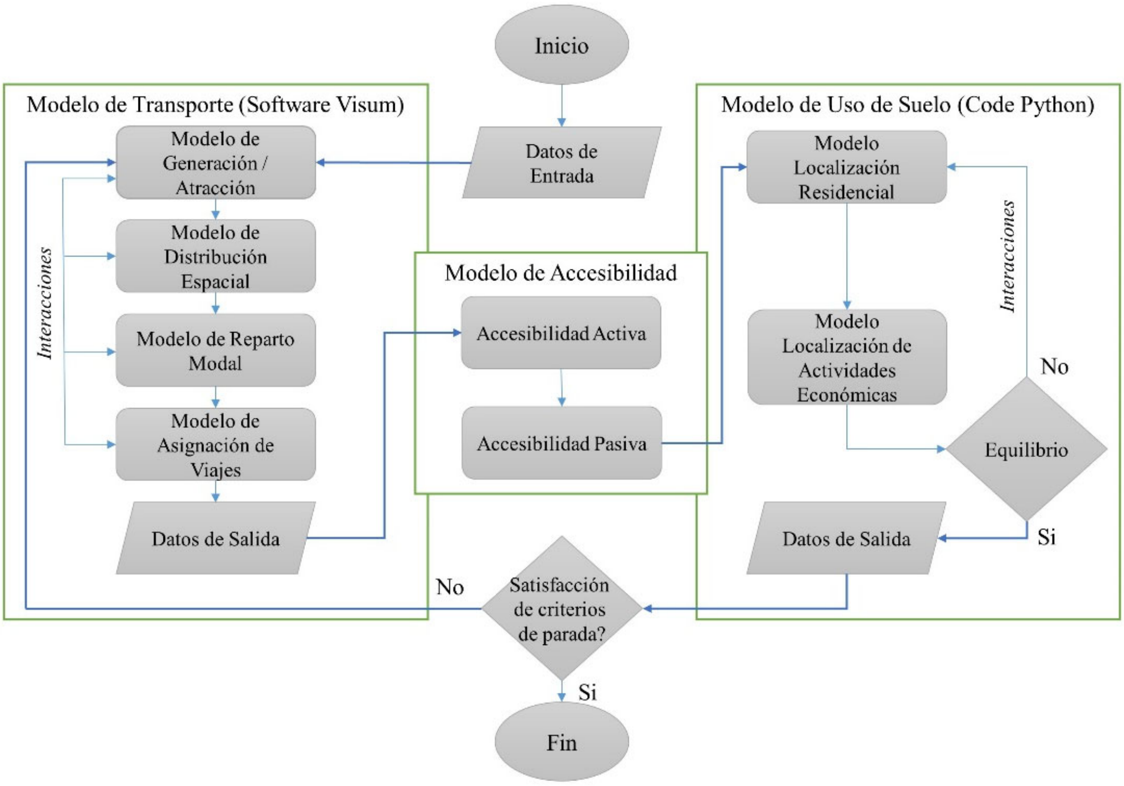

Figura 1:Estructura del modelo AMB-LUTI propuesto

2.1.1 Modelo de Transporte (MT)

El MT utilizado se ha basado en desarrollos anteriores. Tiene carácter estratégico con estructura propia del modelo clásico de 4-etapas (Ortuzar & Willumsen, 2011); *generación-atracción de viajes*, *distribución de viajes*, *elección modal* y *asignación*. La primera etapa está formulada bajo el concepto de ciclo de viaje, es decir, una cadena de viajes con origen en el hogar hacia un destino y respectivo retorno; considerado viaje basado en el hogar (Jovicic & Hansen, 2003). Cada hogar tiene un vector de datos de entrada con características socioeconómicas y elecciones de movilidad realizadas por las personas del hogar. Los viajes son modelizados mediante regresión lineal y posteriormente expandidos por la cantidad de hogares de cada zona. La segunda etapa constituye un modelo de maximización de entropía doblemente acotado basado en la analogía del modelo gravitacional (véase la Ecuación 1).

$$V_{ij} = A_i O_i B_j D_j f(C_{ij}) \qquad (1)$$

donde:

- Vij: viajes entre zonas i y j
- Ai: factor de balanceo en zona i; Oi: viajes originados desde zona i
- Bj: factor de balanceo en zona j
- Dj: viajes atraídos desde zona j
- f(Cij): función de coste entre zonas i y j

La función de coste f(C_{ij}) puede presentar distintas formas, entre ellas la forma combinada (Williams, 1976) de la Ecuación 2. Los costes entre zonas son calculados a partir del coste compuesto (Williams, 1977) mediante la Ecuación 3, el cual es a su vez generado a partir de los costes generalizados por modo de viaje de las Ecuaciones 4 y 5.

$$f\left(C_{ij}\right) = a * K_{ij}^{b} * \exp(-\beta * K_{ij}) \tag{2}$$

$$K_{ij} = 1/-\lambda \cdot ln \sum\nolimits_{n} \exp(-\lambda\left(C_{ij}^{n} + \delta_{ij}^{n}\right)) \tag{3}$$

$$C_{ij}^{Bus} = Coste1 + \theta_{tvp} Tviaje\ percibido \tag{4}$$

$$C_{ij}^{Car} = Coste2 + \theta_{tv}\ Tviaje \tag{5}$$

donde:

- f(Cij): función de coste de tipo combinada;
- Kij: coste compuesto del viaje entre zonas i y j
- a, b y β: parámetros de calibración
- Cnij: coste generalizado entre i y j en el modo n
- λ y δ: parámetros de calibración
- CBus: coste generalizado en transporte público
- Coste1: valor del ticket transformado a minutos
- θtvp: parámetro tiempo de viaje
- Tviaje percibido : tiempo de viaje percibido por usuario
- en vehículo, por trasbordo, entrada, salida y espera.
- CCar: coste generalizado en transporte privado
- Coste2: valor proporcional a la distancia recorrida (min)
- θtv: parámetro tiempo de viaje en transporte privado
- Tviaje: tiempo de viaje dentro del vehículo.

La tercera etapa está basada en la información de cada zona, y es modelo de tipo Logit Multinomial (MNL) que determina la probabilidad de elegir cada modo de transporte. El MNL se genera aceptando que los residuos aleatorios se distribuyen Gumbel independiente e idénticamente distribuidos entre alternativas (IID) (Domencich & McFadden, 1975). Esto permite deducir el modelo dado en la Ecuación 6.

$$P_n = (exp^{(-\lambda(C_n+\delta_n))})/(\sum_m exp^{(-\lambda(C_m+\delta_m))}) \quad (6)$$

donde:

- Pn: probabilidad de elegir un modo de desplazamiento n
- λ: parámetro de escala
- Cn: coste generalizado del modo
- δ: penalidad modal de cada modo.

La cuarta etapa consiste en simular los arcos de red más usados para los desplazamientos generados entre cada par origen-destino, cargándose posteriormente los flujos vehiculares estableciendo las condiciones de tránsito y volumen de pasajeros en las rutas del SITM por zona. Esta asignación es simulada usando el software de transporte Visum.

2.1.2 Modelo de Localización Residencial (MLR)

El MLR se basa en la probabilidad de que un trabajador elija su lugar de residencia dado que trabaja en la zona *d*. La elección se basa en un modelo de elección de zona donde el trabajador maximiza su utilidad de localización. El modelo es probabilístico, permitiendo la evaluación de cada zona de acuerdo a sus atributos socioeconómicos, ambientales e infraestructurales (Hsu & Guo, 2006).

$$P^i_{res-job}(o|d) = (\exp[U^i(o|d)])/(\sum^i_n \exp[U^i(o|d)]) \quad (8)$$

donde:

- Pi : probabilidad de residir en la zona o condicionado a trabajar en la zona d para un usuario de tipo i
- Ui : utilidad sistemática de cada zona o.

La utilidad asumida en cada zona puede descomponerse en dos partes: una sistemática o representativa, medida directamente por el modelador y otra aleatoria cuya distribución se supone Gumbel IID. La utilidad queda definida como:

$$U_i(o|d) = V_i(0|d) + \varepsilon_i(o|d) \quad (9)$$

donde:

- Vi (0|d): atributos cuantitativos de la zona y/o trabajador
- εi (o|d): residuo o utilidad aleatoria.

Dado que la primera hipótesis del modelo supone que el área de estudio es cerrada, es posible calcular el número de trabajadores de estrato *i* que residen en la zona *o* como:

$$W^i(o) = \sum_d P^i_{res-job}(o|d) * Job^i)(d) \quad (10)$$

donde $Job^i(d)$: Número de empleos disponibles en la zona *d* de estrato socioeconómico *i*.

Además, partiendo de la cantidad de trabajadores de estrato *i* residentes en la zona *o*, es posible determinar la población total de dicha zona, aplicando un coeficiente que representa la relación entre población y personas con trabajo.

$$Pop\ (o) = K(o) * \sum_i \sum_d W^i(o) \quad (11)$$

donde K(o): ratio entre población y trabajadores en la zona *o*.

En el MLR, la relación establecida entre la población residente en una zona y los trabajadores presentes en ella, está respaldada por la teoría urbana clásica (Alonso, 1964; Putman, 1979; Simmonds, 1999; Marinez & Donoso, 2001).

2.1.3 Modelo de Localización de Actividades Económicas (MLAE)

La estructura del MLAE es similar al MLR. Partiendo de la teoría de utilidad aleatoria, simula las decisiones de localización de las actividades económicas por medio de elecciones discretas donde se supone que las empresas asignan a cada zona una utilidad y eligen aquella que la maximiza. La probabilidad de localización está dada por la Ecuación 8, usando la Ecuación 9 para el cálculo de la utilidad sistemática. El modelo permite determinar la distribución de empleos por zona y por sectores de actividad según la Ecuación 12.

$$Job_a(d) = P_a(d) * Job_a \quad (12)$$

donde:

- Joba (d): número de empleos ubicados en la zona d pertenecientes al sector económico a;
- Pa (d): probabilidad de localización de empleos de tipo a en la zona d
- Joba: número de empleos totales pertenecientes al sector económico a en el área estudiada.

2.1.4 Modelo de Indicadores de Accesibilidad (MIA)

El MIA es el enlace fundamental en la modelización que relaciona el sistema de transporte y el sistema de usos del suelo. La accesibilidad es la capacidad que tiene un individuo, desde un lugar determinado, de participar en una actividad específica localizada en otro lugar (Hansen, 1959), o bien, la facilidad con la que se puede realizar una determinada actividad desde cualquier ubicación a través del sistema de transportes (Dalvi & Martin, 1976). El indicador de accesibilidad utilizado en este caso es de tipo gravitatorio basado en el concepto de Location–based asccessibility (Geurs & Van Wee, 2004). Además, se han considerado dos indicadores dentro de ese tipo: *accesibilidad activa* (Ecuación 13) u oportunidad potencial para acceder a múltiples actividades desde una zona específica (Cascetta, 2009) y *accesibilidad pasiva* (Ecuación 14), o potencial de oportunidades que tiene una zona de ser alcanzada por la población de diferentes lugares.

$$A(o) = \sum_i [\exp(\alpha_1 * Cost(o, d_i) * Job(d_i)^{\alpha_2}] \quad (13)$$

donde:

- Cost (o, di): coste de viaje entre zona de origen y zona de destino i
- Job(di): número de empleos presentes en la zona de destino i; α1: parámetro de calibración
- α2: parámetro de calibración.

$$A(d) = \sum_i [\exp(\beta_1 * Cost(o_i, d) * Pop(o_i)^{\beta_2}] \quad (14)$$

donde:

- Cost (oi, d): coste de viaje entre la zona de origen y destino
- Pop(oi): población presente en la zona de origen
- β1: parámetro de calibración; β2: parámetro de calibración.

2.2 Evaluación de la equidad en la prestación del servicio de transporte público

La metodología para evaluar la equidad presenta cuatro fases: análisis de oferta del servicio de transporte público, análisis de la demanda potencial del servicio público, índices de disparidad entre oferta y demanda y análisis global.

2.2.1 Análisis de la oferta del servicio de transporte público

La metodología de evaluación más eficiente formulada por Currie (2010) y Delbosc & Currie (2011), hace posible determinar la oferta por medio del ISTP (Rodríguez et al., 2006) basado en la infraestructura (Geurs & Van Wee, 2004). El análisis de la oferta del sistema de transporte público cuantifica el aprovisionamiento en infraestructura y planificación de rutas que tienen las diferentes zonas del área de estudio. Las zonas que presentan un índice bajo mostrarán poca provisión y, si el índice es alto, el nivel de provisión del servicio será elevado.

$$ISTP_n = \sum_{i=1}^{n}(Buffer_{(i)(n)}/Area_n * NS_i) \tag{15}$$

donde:

- Buffer(i)(n): área de influencia de la parada i en la zona n
- Arean: área total de la zona n
- NSi: nivel de servicio de la parada i (numero de servicios que ofrece cada parada en un día laboral).

2.2.2 Análisis de la demanda potencial del servicio de transporte público

El INSTP clasifica las zonas donde se requiere mayor infraestructura o servicios, dada una mayor demanda potencial y un perfil socioeconómico determinado. Puede ser difícil analizar el papel del transporte en la exclusión social en distintos países, ya que la administración no brinda información suficiente sobre las necesidades de demanda insatisfecha (McCray & Brais, 2007), motivo por el cual se utiliza el método propuesto por Currie (2004; 2010), utilizado en múltiples estudios (Camporeale et al., 2019; Ruiz et al., 2016) y que se basa en un modelo multicriterio ponderado con variables socioeconómicas de la zona, a las que se le asigna un peso en función de su relevancia, según reflejen una necesidad social de transporte público mayor.

$$INSTP_z = \sum_{i=1}^{n}(Buffer_{(i)(n)}/Area_n * NS_i) \tag{16}$$

$$VN = (Valor\ variable - Valor\ minimo\ de\ la\ variable)/$$
$$(Valor\ maximo\ de\ la\ variable - Valor\ minimo\ de\ la\ variable) \tag{17}$$

donde:

- Xi: valor normalizado de la variable socioeconómica de la zona i
- Wi: peso asignado a cada variable X
- VN: valor normalizado

2.2.3 Índice de disparidad entre oferta y demanda

El ISTP cuantifica la oferta de transporte público, en términos del número de paradas y frecuencia de rutas, asignando un valor de aprovisionamiento que tiene cada zona. El INSTP cuantifica la necesidad de transporte público que tiene una zona desde la perspectiva de los residentes. La diferencia entre el ISTP y INSTP se denomina Índice de Disparidad entre Oferta y Demanda (IDOD). Este indicador ayuda a detectar las zonas en las que debería ser mejorado el servicio.

$$IDOD_i = INSTP_i - ISTP_1 \quad (18)$$

2.2.4 Análisis global de equidad

A partir de los índices ISTP y INSTP se procede a calcular la equidad horizontal (EH) y vertical (EV) usando las siguientes expresiones (Ruiz et al., 2016):

$$EH_i = DP_i/ISTP_I \quad (19)$$

$$EV_i = INSTP_I/ISTP_i \quad (20)$$

donde:

- EHi: equidad horizontal de la zona i
- EVi: equidad vertical de la zona i
- DPi: densidad poblacional de la zona i.

Las zonas con EH alto corresponden a un mayor equilibrio entre la población de una zona y el servicio en transporte público que dispone. Un valor de EV bajo representa a zonas con elevada necesidad de transporte público y bajo nivel del servicio. Como complemento, se calcula el Coeficiente de Gini (Delbosc & Currie, 2011), obtenido a partir del análisis de proporción de áreas de la Curva de Lorenz (Rodríguez et al., 2016). Este coeficiente refleja la medida de disparidad con valor que oscila entre 0 y 1; donde 0 corresponde a una distribución totalmente igualitaria (igualdad total en la oferta de servicio público) y 1 refleja una disparidad total (una zona tiene toda la oferta y el resto nada). El coeficiente de Gini se calcula mediante la Ecuación 21.

$$G = 1 - \sum_{i=0}^{n}(\sigma Y_{i-1} - \sigma Y_i) + (\sigma X_{i-1} + \sigma X_i) \quad (21)$$

donde:

- σY: porcentaje acumulado de ISTP
- σX: porcentaje acumulado de EH o EV.

3. CALIBRACIÓN DEL MODELO LUTI PARA EL AMB (AMB-LUTI)

3.1 Área de estudio

El AMB se ubica en Santander-Colombia y está conformada por 4 municipios: Bucaramanga (17 zonas), Floridablanca (8 zonas), Girón (3 zonas) y Piedecuesta (3 zonas), estando el área en conjunto dividida en 31 zonas con una población total de 1.160.244 habitantes (Dane, 2019) (véase la Figura 2). Cada zona tiene una red vial interna e información socioeconómica propia. La población se encuentra distribuida de la siguiente manera: Bucaramanga con 543.574 habitantes, Floridablanca 273.817 habitantes, Girón 181.811 habitantes y

Piedecuesta 161.042 habitantes. El AMB tiene además un total de 58.932 comercios que generan 538.671 empleos (DANE).

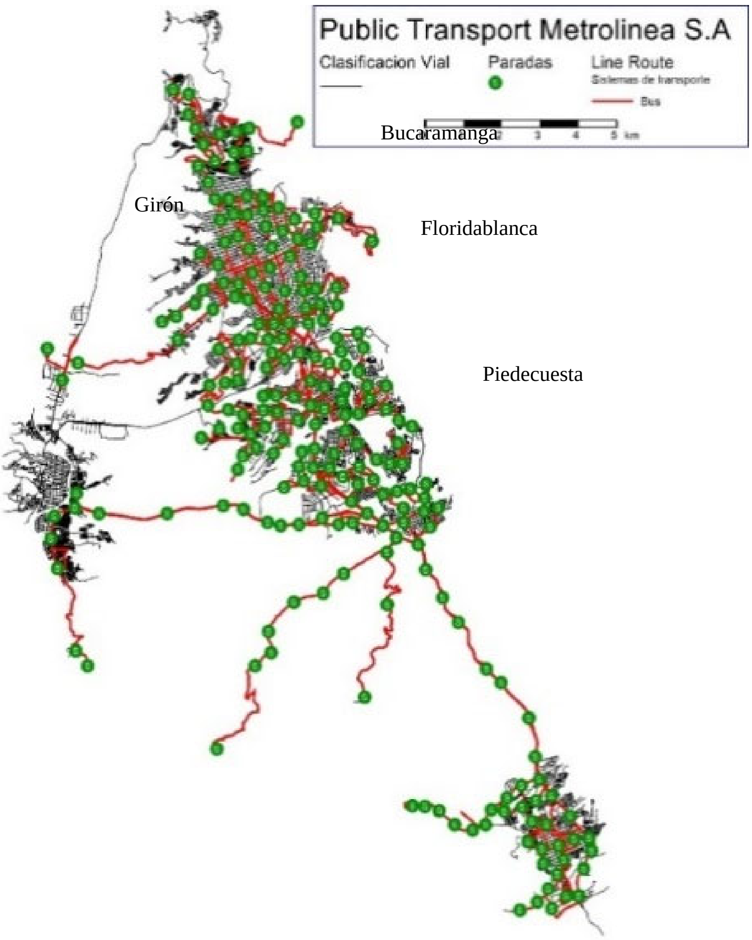

Figura 2: Municipios del AMB y rutas del SITM. **Fuente**: **Metrolínea** (**2019**)

Los datos socioeconómicos, de capacidad vial, tipo de vía y velocidad, son tomados del POT de cada municipio. El SITM es un sistema de autobús tipo BRT que permite viajar por carril segregado en ciertos tramos del viario (Wright & Hook, 2007). Opera de distintas formas, ya que ofrece la posibilidad de construir cada subsistema a la medida aprovechando la infraestructura existente y los vehículos disponibles. Actualmente existen 4 líneas troncales, 10 pre-troncales, 20 alimentadoras y 14 complementarias.

3.2 Calibración del modelo de transporte (MT)

A falta de encuestas de movilidad, los modelos de generación y atracción de viajes se estimaron a partir de una base de datos sobre viajes en día laborable (Manrique, 2016), correlacionada con encuestas domiciliarias de movilidad de la ciudad de Bogotá (Alcaldia de Bogota, 2011) para comprobar su validez. Se formularon los modelos de viajes basados en el hogar (H), que representa el 91,2 % de la movilidad diaria en el área Metropolitana de Bogotá (Guzmán et al., 2015). El modelo de generación se establece con cuatro variables: ingreso *bajo* (1 a 2 salarios mínimos mensual legal vigente smmlv), *bajo-medio* (2 a 4 smmlv), *medio* (4 a 6 smmlv) y *alto* (> 6 smmlv), y la variable *personas por hogar* (P/H). (véase la Tabla 1).

	Modelo de Generación		Modelo de Atracción	
Variable	**Coeficiente**	**p-valor**	**Coeficiente**	**p-valor**
Constante	-0,548	1,39E-06	1,555	0,03123
Ibm/H	0,383	9,23E-20		
Im/H	1,069	8,96E-30		
Ia/H	1,349	1,03E-29		
P/H	1,324	9,81E-30	0,248	0,168143
E/H			1,998	1,03E-38
R^2	0,996		0,998	
R^2 ajustado	0,996		0,998	
F -Test	1869,485		9930,55	

Tabla 1: Estimación de variables y bondad de ajuste en los modelos de generación y atracción de viajes

El modelo de atracción se formula con las variables explicativas *personas por hogar* (P/H) y *empleos por hogar* (E/H). Este último, hace referencia a los empleos en comercios y/o servicios en cada zona. El modelo para distribución de viajes queda establecido en la Ecuación 1 que, a su vez, requiere de la función de coste combinada (Ec. 2), formulada con los parámetros de calibración: a, b y β que se muestran en la tabla 2.

Parámetros de calibración ($\boldsymbol{a}$, b, $\boldsymbol{\beta}$, λ, δ Car, δ Bus)	
a	0,00
b	5,73
β	-0,06
λ	0,007
δ Car	0
δ Bus	208

Tabla 2: Parámetros estimados para la función de coste y para el cálculo del coste compuesto

Estos parámetros representan la distribución de frecuencias de los tiempos de viaje en el AMB. La función de coste del modelo de distribución utiliza el cálculo del coste compuesto (Ec. 3), donde se establece un valor de coste por cada par origen-destino considerando la disponibilidad de transporte privado, de transporte público o de ambos. La Ecuación 3 presenta los paramentos a estimar: λ, δ_{Car} y δ_{Bus}. Los parámetros δ reflejan la penalidad de cada modo, en relación al otro, y son estimados mediante la transformada de Berkson-Theil, con una desutilidad claramente significativa para el transporte público respecto del coche.

En el coste generalizado del transporte privado se utilizó un valor de 426 $ colombianos por kilómetro recorrido con un valor del tiempo de viaje para este modo de 77,80 $ por minuto (Marquez, 2013). Para el coste generalizado del sistema de transporte público se utilizó el coste del viaje de 2.450 $, valor constante en todos los pares origen-destino, dado que, con el valor de un viaje, el usuario puede realizar los trasbordos necesarios mientras se mantenga en el sistema. El valor del tiempo de viaje para este modo se estimó en 55,64 $ por minuto.

3.3 Estimación del MLR y MLAE

El MLR se estimó diferenciando entre residentes con ingreso *bajo* (Ib), *bajo-medio* (Ibm), *medio* (Im) y *alto* (Ia). La utilidad percibida queda especificada con las variables: tiempo de viaje por modo de casa al trabajo considerando congestión y expresado en minutos (JT); accesibilidad activa de la zona (ACA); valor metro cuadrado de viviendas según estrato y características socioeconómicas de la zona (VM2); número de viviendas presentes en la zona (NV); y una variable dummy con valor igual a 1 si la zona tiene un prestigio especial (VP). La estimación de los parámetros de la función de utilidad se realizó mediante máxima verosimilitud (véase Tabla 3); al estar la muestra desagregada a un nivel de elección individual, permite la segmentación de la misma en los cuatro grupos sociales, reduciendo el error de agregación y considerando diferentes variables en la función de utilidad de cada estrato económico. Las personas con ingreso medio fueron el estrato base para el cálculo de los demás parámetros.

	Var.	JT	ACA	VM2	NV	VP	ACP	EMP	RES	CEN	Log (θ)	Log (0)	N
Resid. Ib	β	-0,01181	-	-0,0082	1,75E-05	1,2909					-8717	-10929	3183
	p-val	0	-	0	0,001	0							
Resid. Ibm	β	-0,00946	-	-0,00171	1,75E-05	1,2909							
	p-val	0	-	0	0,001	0							
Resid. Im	B	-	-	-	1,75E-05	1,2909							
	p-val	-	-	-	0	0							
Resid. Ia	β	0,00421	-	0,00241	1,75E-05	1,2912							
	p-val	0,012	-	0.000	0,001	0							
Sector Comer	β			-0,0001			1,22E-06	3,25E-05	4,68E-06	0,64883	-16644	-18833	5504
	p-val			0			0,446	0	0	0			
Sector Serv.	β			5,97E-05			2,38E-05	2,57E-05	9,67E-06	0,80724	-11140	-12797	3742
	p-val			0,007			0	0	0	0			

Tabla 3: Parámetros estimados para los MLR y MLAE

El MLR resultó coherente con las hipótesis teóricas. La log-verosimilitud de -8717 es mayor al modelo nulo, de igual forma las variables explicativas obtuvieron signos consistentes con lo esperado; el parámetro de la variable JT presenta signo negativo en personas con ingreso bajo y bajo-medio, con un nivel de confianza del 95%, lo que señala que prefieren residir en zonas cercanas al lugar de trabajo. Dentro de esta misma variable, las personas con ingreso alto presentaron signo positivo en el parámetro, esto se debe a que este tipo de residentes se localizan en zonas claramente alejadas del centro de la ciudad y de los lugares de trabajo.

El parámetro VM2 presenta signo negativo en personas con ingreso bajo y bajo-medio, ya que este grupo reside en zonas con valor metro cuadrado de vivienda menor, en contraste, el signo positivo en personas con ingreso alto refleja la preferencia de vivir en zonas más costosas. Las variables NV y VP son significativas con signo positivo lo cual es coherente, las personas prefieren residir en zonas donde se tiene mayor presencia de viviendas y prestigio. La variable de accesibilidad activa (ACA) no fue significativa, dado que se cuenta con suficientes variables que soportan el modelo de localización (JT), esta variable no se incluye en el modelo final. Para el MLAE las actividades se dividieron en tres tipos: comercial, de servicio e industrial. La actividad industrial se considera como básica en el presente modelo y su localización es fija. La utilidad sistemática del modelo ha quedado especificada como una combinación lineal de los atributos: accesibilidad pasiva (ACP) de la zona en función del tiempo de viaje y de la localización de la población (Ec. 14); empleos presentes en la zona (EMP); residentes presentes en la zona (RES); y una variable dummy que representa si la zona pertenece al centro urbano (CEN). La estimación se realizó por el método de máxima verosimilitud, obteniendo resultados coherentes con las hipótesis teóricas. Se formularon dos modelos distintos, uno para las actividades comerciales y otro para los servicios. Ambos modelos presentaron una log-verosimilitud mayor a la del modelo nulo. En las actividades de tipo comercial, las variables EMP, RES y CEN presentaron parámetros positivos y significativos, a un nivel de confianza del 95 %, excepto para la variable ACP cuyo parámetro fue significativo a un nivel de confianza del 90 %, aunque, dada su importancia teórica y papel como variable de política, se decidió mantener en el modelo. El precio del metro cuadrado de bienes inmobiliarios en la zona tuvo signo negativo, es decir, la mayoría de los propietarios de comercios prefieren localizar su negocio en zonas de menor coste. En el modelo para las actividades económicas de servicios, todos sus parámetros fueron significativos, incluida la accesibilidad pasiva. La variable VM2 presentó un parámetro positivo lo que significa que, para este tipo de negocio, la localización es influenciada por zonas con residentes de alto ingreso, lo que es coherente con lo observado. La variable CEN presento en ambos casos el parámetro con el mayor peso. Esta calibración, aunque no se aplica directamente en el análisis de equidad de la situación actual, permitiría realizar este análisis en distintos escenarios de planificación.

3.4 Calibración del modelo de accesibilidad (MIA)

La estimación de los parámetros de los modelos de accesibilidad activa y pasiva se realizó linealizando las Ecuaciones 13 y 14, mediante una transformación logarítmica, y posteriormente utilizando mínimos cuadrados. Este proceso exige el uso de una variable dependiente asumida como variable proxy de accesibilidad. Se tomaron los datos del MT del año base 2019 (viajes producidos y atraídos) de cada zona, que tienen relación directa con la accesibilidad activa y pasiva, donde a mayor cantidad viajes el valor de accesibilidad es mayor. La accesibilidad activa y pasiva quedan formuladas bajo las variables coste (tiempo de viaje entre zonas considerando congestión), empleos y población de cada zona. Los resultados se resumen en la Tabla 4.

	Accesibilidad Activa		**Accesibilidad Pasiva**	
Variable	**β**	**P-Valor**	**β**	**P-Valor**
Ln_Job/Ln_Pop	0,98	0,000	0,87	0,000
Cost	-0,015	0,000	-0,017	0,000
R^2	0,97		0,97	

Tabla 4: Parámetros establecidos para los modelos de accesibilidad

La calibración del parámetro coste presentó un signo negativo en ambos casos, con un mayor valor en el caso de la accesibilidad pasiva, hecho que es coherente con la teoría, ya que los viajes relacionados con el trabajo muestran de media una menor impedancia.

4. RESULTADOS SOBRE LA EQUIDAD EN EL TRANSPORTE

El análisis de la oferta de transporte se realizó con la información digitalizada mediante el software Visum y codificación proveniente de Metrolínea considerando: paradas y rutas (977 paradas y 44 rutas de servicio); nivel de servicio en cada parada, número de rutas y frecuencia en día laborable; y evaluación del ISTP por zona con un área de influencia concéntrica de 300 metros desde cada parada. Los valores finales son normalizados en una escala entre 0 y 100 con el objeto de ser comparados con los índices de demanda potencial. El análisis de demanda se realizó por medio del índice INSTP desarrollando un análisis Multi-criterio para la ponderación mediante el método de jerarquías analíticas (AHP) (Saaty, 1995).

Así, se compararon por pares las variables: tasa de trabajadores, tasa de población de recursos bajos, tasa de actividades económicas y valor de accesibilidad al empleo en la zona. La valoración fue realizada por un equipo de seis expertos mediante la plantilla de evaluación AHP propuesta por Goepel (2013) obteniéndose unas ponderaciones para la población de ingreso bajo de 49,8 %, para la accesibilidad al empleo de 21,9 %, para la tasa de trabajadores de 20,2 % y para la tasa de actividades económicas del 8 %. Los valores son normalizados para poder ser comparados con los índices de oferta (véase la Tabla 5).

Zona	INSTP	ISTP	IDOD	Zona	INSTP	ISTP	IDOD
1	80,91	15,94	64,97	**17**	35,66	10,40	25,26
2	68,30	33,84	34,46	**18**	28,72	55,56	-26,84
3	27,97	74,30	-46,33	**19**	0,00	27,49	-27,49
4	31,73	14,21	17,52	**20**	30,70	22,63	8,07
5	39,19	15,64	23,55	**21**	100,00	73,99	26,01
6	24,96	56,40	-31,44	**22**	32,57	36,05	-3,48
7	36,69	23,74	12,95	**23**	33,23	57,80	-24,57
8	54,04	6,59	47,45	**24**	36,91	37,28	-0,37
9	33,60	50,15	-16,55	**25**	62,40	28,04	34,36
10	36,04	92,51	-56,47	**26**	41,87	0,00	41,87
11	37,15	76,86	-39,72	**27**	45,44	5,50	39,94
12	15,19	60,82	-45,63	**28**	43,07	1,53	41,54
13	11,66	75,71	-64,05	**29**	47,13	90,52	-43,38
14	61,72	12,71	49,01	**30**	43,12	100,00	-56,88
15	2,32	50,02	-47,70	**31**	47,39	5,75	41,64
16	30,37	26,25	4,12				
Total	1.220,03	1.238,20	- 18,16				
Media	39,36	39,94	-0,59				
Max.	100,00	100,00	64,97				
Min.	0,00	0,00	- 64,05				
Dev. Std.	20,30	29,22	37,81				

Tabla 5: Índices del nivel de oferta de transporte público (ISTP), necesidad de transporte público (INSTP) y disparidad oferta-demanda (IDOD)

En el caso de la accesibilidad al empleo y tasa de actividades económicas se utilizó un valor inverso, para reflejar que, a mayor valor menor necesidad de transporte público, es decir, las zonas con más comercio y más accesibilidad al empleo tienen una menor necesidad de transporte público para que su población acceda a esas oportunidades.

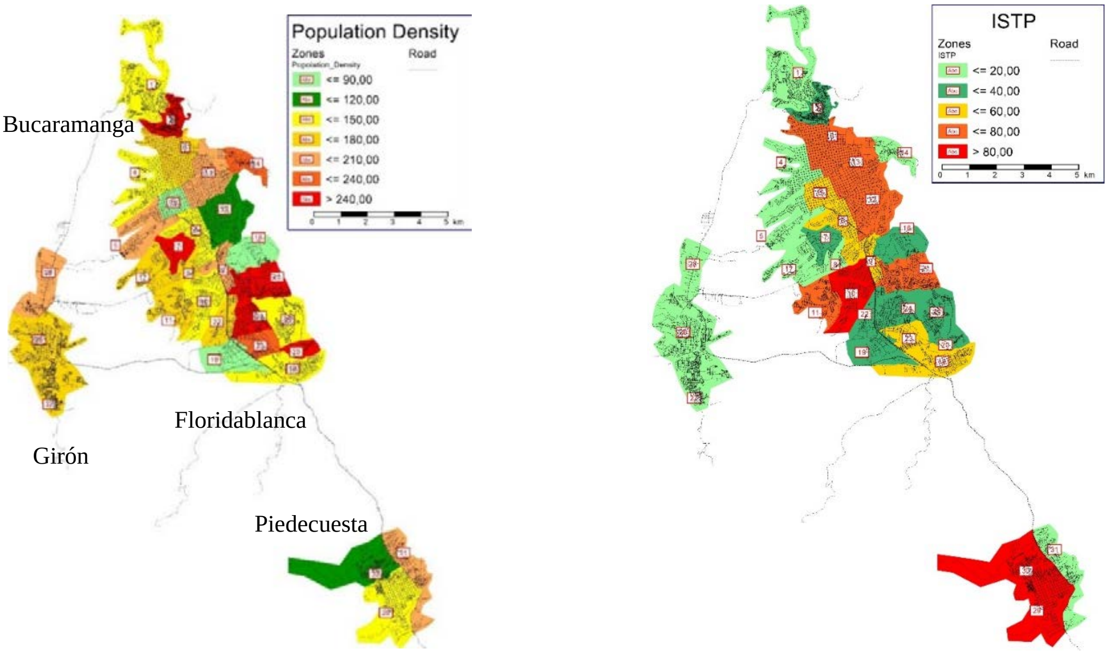

Figura 4: Distribución espacial de la densidad poblacional e indicador ISTP

La figura 4 muestra la distribución de población en el AMB. Destacan las zonas Ciudadela, Nororiental, Morrorico, Caldas Reposo, Valencia, Bucarica y Lagos como las más pobladas, con uso netamente residencial y población de ingreso bajo. Las zonas más comerciales son Centro, Cabecera del Llano, La Concordia, Cañaveral y casco antiguo de Piedecuesta, presentando menos densidad de población, lo que implica que las personas en general residen lejos de su lugar de trabajo. El índice ISTP permite, por su parte, identificar zonas con mayor oferta de servicio: San Francisco, Oriental, Cabecera del Llano y Provenza, en el centro del municipio Bucaramanga. En cambio, las zonas Caldas Reposo en Floridablanca, las zonas centro y norte de Piedecuesta, junto al municipio Girón, lucen totalmente excluidas del servicio, es decir, sin infraestructura óptima que satisfaga la demanda de viajes.

En contraste, se puede observar sobre-provisión de oferta de transporte público en zonas de uso comercial favoreciendo el desplazamiento con fines laborales. Los resultados del modelo muestran que las tres zonas de Girón con indicador bajo de ISTP, aunque pertenece al AMB, están desconectadas del sistema de transporte público. En cuanto a las zonas con mayor necesidad de transporte en el municipio Floridablanca, estas son: Caldas, Reposo y la Cumbre. De igual forma, el municipio de Piedecuesta presenta gran necesidad al presentar un proceso de expansión urbana sin que el servicio se haya adecuado. El indicador de disparidad oferta-demanda, IDOD, muestra que las zonas con valor negativo tienen una oferta de servicio muchísimo mayor a la necesidad estimada.

En cambio, cuanto mayor sea este indicador significa que la provisión de infraestructura y frecuencia de rutas es insuficiente para satisfacer la necesidad estimada (véase la Figura 5).

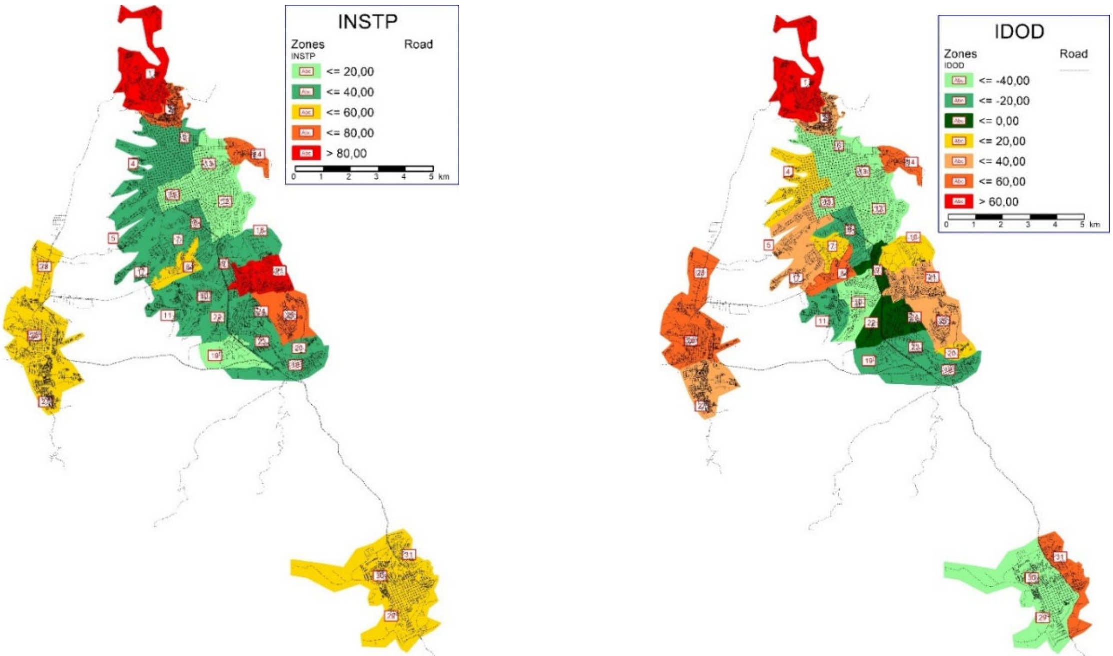

Figura 5: Distribución espacial de los índices INSTP e IDOD

En Bucaramanga, las zonas con indicador negativo son las de uso comercial: San Francisco, Oriental, Cabecera del Llano y Centro. Estas zonas presentan un sobre-aprovisionamiento de infraestructura y servicio justificable, aunque no puede tener más residentes ni población de bajos recursos, ya que presentan en promedio, el 40 % de todos los empleos del AMB. Las áreas residenciales que tienen aprovisionamiento extra en este municipio son: Concordia, Provenza y Sur. Las demás zonas periféricas tienen indicadores positivos lo que señala que podría ser necesario aumentar la infraestructura y la planificación de nuevos servicios en esas zonas. El municipio de Floridablanca es el segundo más grande en términos de área y población, todas sus áreas tienen residentes de bajos recursos y presentan un valor positivo en su indicador IDOD, estas son: Caldas Reposo, La Cumbre y Bucarica, lo que señala que el sistema de transporte público de esta área presenta cierto aislamiento. En el municipio Girón el índice revela la necesidad de una mayor oferta del servicio de transporte público en todas sus zonas pues sus indicadores de IDOD son los más altos en el AMB, es decir, es el municipio peor servido. El municipio de Piedecuesta, a pesar de estar más alejado del centro del AMB, tiene un índice elevado de servicio en relación a la demanda pues sus indicadores en dos zonas de tres son negativos.

En general el sistema de transporte satisface el desplazamiento hacia cuatro zonas: San Francisco, Oriental, Cabecera del Llano y Centro, mientras que el sistema no facilita una movilidad transversal, y en caso de permitirse, implica un desplazamiento que toma mucho tiempo y varios trasbordos, lo que causa desequilibrio en el acceso a los equipamientos y servicios, potenciando el uso de vehículo privado para este tipo de movilidad. El modelo de rutas establecido como Periferia–Centro de Bucaramanga–Periferia, no contempla un municipio como Floridablanca, donde hay zonas con alta densidad de comercio. Este análisis permite ver que el sistema de transporte público contribuye a la consolidación de áreas urbanas periféricas aisladas del conjunto urbano central, debido a que se encuentran conectadas por una sola ruta de servicio troncal. Por su parte, la equidad horizontal, formulada a partir de la densidad de población e ISTP, arrojan resultados de disparidad muy alta dentro del AMB. Las zonas con valor mayor corresponden a áreas con mucha población y servicio ineficiente de transporte público, destacando en Bucaramanga: Norte, Nororiental, Occidental, Morrorico, García Rovira, Mutis y Sur. Todas las zonas ubicadas en la periferia y con residentes de bajo ingreso del municipio Girón tienen valores muy altos en comparación a las demás zonas, señalando una falta de servicios de transporte público. En Piedecuesta solo una de sus tres zonas presenta un servicio ineficiente y el mayor equilibrio de equidad horizontal se da en el centro de los municipios de Bucaramanga y Floridablanca, donde se tiene exceso de servicio e infraestructura frente a su baja densidad demográfica. Es importante resaltar que el SITM tiene en estas áreas varias rutas troncales con carril exclusivo que cruza la ciudad de extremo a extremo, desde Bucaramanga hasta Piedecuesta. Además, el resto de las rutas, ya sean alimentadoras o complementarias, deben como mínimo realizar una parada en las estaciones, lo que ayuda a aumentar el nivel de aprovisionamiento del servicio. En general, ocho zonas se destacan en la equidad horizontal: Morrorico, García Rovira, Mutis, Sur Occidente, Girón Norte, Casco Antiguo Girón, Girón Sur y Piedecuesta Oriente (véase la Figura 6).

La equidad vertical, evaluada por medio del ISTP e INSTP, refleja la relación entre oferta y necesidad de todas las zonas consolidadas, donde zonas con un alto valor corresponden a áreas con alta necesidad de transporte público y bajo nivel de servicio. Es importante resaltar, el desajuste que tiene Girón en todos los indicadores evaluados resultando el área más perjudicada por falta de servicio. Si evaluamos al municipio de Bucaramanga y Floridablanca como una sola entidad (dada su cercanía) podemos deducir que hay ocho zonas que presentan alta densidad de población y muy bajo nivel de servicio de transporte público, en comparación con el resto, siendo estas: Norte, Nororiental, Morrorico, García Rovira, Mutis, Sur Occidente, Caldas Reposo y La Cumbre, siendo nuevamente las zonas con residentes de ingreso bajo las más perjudicadas. El SITM tiene por lo tanto un efecto muy poco positivo en zonas con población de bajo ingreso, como puede verse en todos los indicadores, incluso cuando existe una gran concentración de población. Además, el actual sistema de transporte no contempla las zonas en las periferias de los municipios de Bucaramanga y Floridablanca, ya que cuanto más alejada está la zona de su eje troncal, peor es el servicio de transporte ofrecido. Estas condiciones hacen que estas zonas, en su mayoría con población de bajos ingresos, presenten peores condiciones de acceso al empleo, lo que deteriora aún más sus oportunidades. Además, en zonas de mayores ingresos, la falta de oferta de transporte público incentiva el uso del vehículo privado.

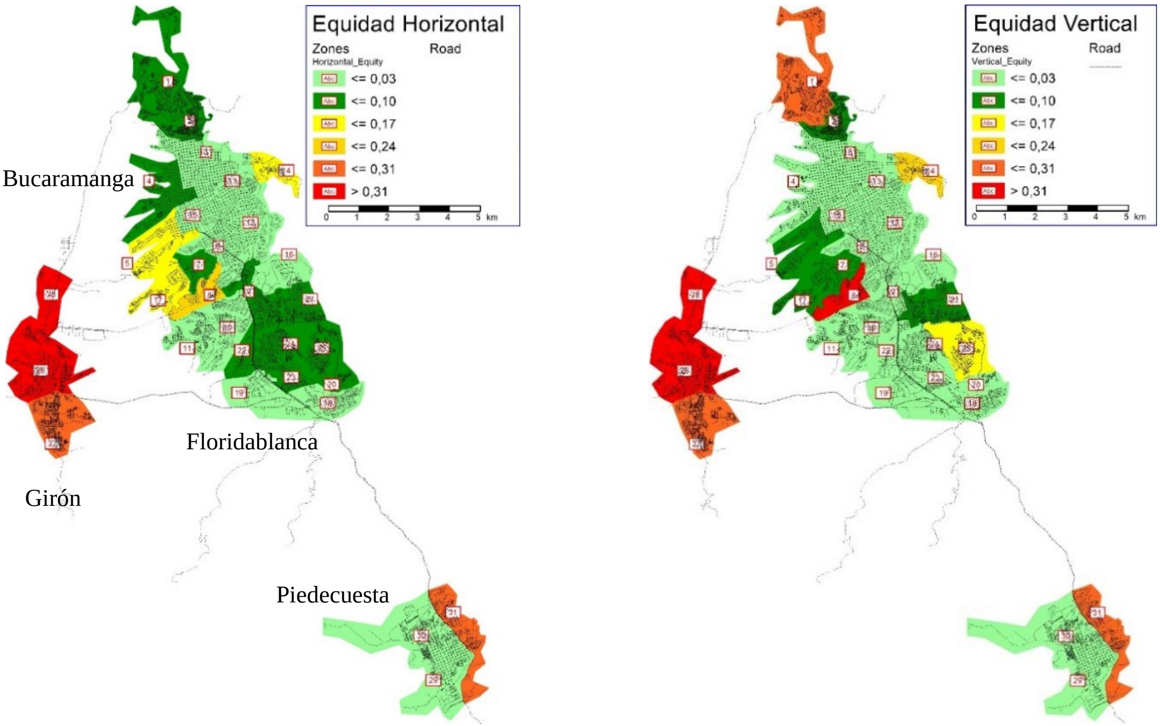

Figura 6: Distribución espacial Equidad Horizontal y Equidad Vertical por zona

Evaluando la equidad horizontal y vertical y la igualdad en la distribución por medio de la curva de Lorenz y coeficiente de Gini, se comprueba que la disparidad entre oferta y necesidad del servicio de transporte público es notable. Las curvas mostradas en la Figura 7 señalan el alejamiento notorio de la situación de igualdad total, tanto según la densidad de población de los residentes en cada zona como en la necesidad social de transporte público estimada.

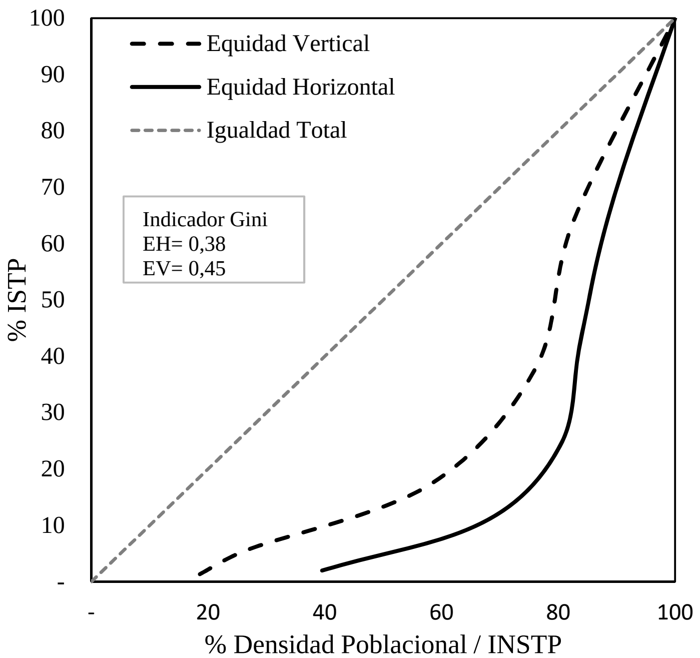

Figura 7: Curvas de Lorenz a partir de índice de equidad horizontal y vertical

El coeficiente de Gini muestra un valor menor de disparidad en equidad horizontal (0,38) evaluado a partir de la densidad poblacional versus el nivel de servicio del transporte público, comparado con la equidad vertical (de 0,45) determinada mediante los índices ISTP e INSTP. Los valores de estos indicadores son diferentes a cero, lo que representa una falta de equilibrio entre la necesidad y oferta del transporte público, tanto en cuantía como en características socioeconómicas.

5. CONCLUSIONES, DISCUSIÓN Y LIMITACIONES

En esta ponencia se ha realizado un análisis de la equidad espacial ofertada por el SITM en el AMB – Colombia. Para ello se ha estimado el desequilibrio existente entre la necesidad social y los servicios ofertados de transporte público mediante los Índices ISTP y INSTP. Además, se ha calculado el coeficiente de Gini a partir de datos proporcionados por el modelo de interacción entre el transporte y usos del suelo AMB-LUTI. Este modelo ha permitido obtener los datos sobre la oferta de transporte público y la demanda potencial en las distintas zonas, basándose en el software de transporte Visum y código propio programado en el lenguaje Python.

El AMB constituye un área urbana en desarrollo donde el sistema de transporte publico presenta debilidades, pudiéndose equiparar a otros territorios metropolitanos similares, afectados por el desarrollo rápido y desorganizado de los usos del suelo y la falta de información para imponer una planificación del transporte más efectiva. Entre estas debilidades se encuentra la de una estructura de la red de transporte público basada en una sola ruta troncal de la que se benefician sólo las zonas centrales de los municipios, constituyendo un sistema rígido que no facilita la movilidad transversal. La falta de interconexión entre los cuatro municipios de Bucaramanga, Floridablanca, Girón y Piedecuesta ocasiona una baja equidad en la oferta del transporte público e indica la necesidad de reestructurar el sistema. Esta reestructuración debería basarse en medidas como: colocar rutas de servicio en función de la densidad poblacional, tener en cuenta las zonas con crecimiento demográfico y urbanístico, relocalizar las paradas en función de las zonas en aras de poder brindar un servicio más equitativo evitando el sobre-aprovisionamiento en algunas áreas, planificar las frecuencias en función de la necesidad de servicio público de las diferentes zonas y adaptar la infraestructura para satisfacer la demanda de movilidad entre municipios, no solo hacia y desde Bucaramanga. En virtud de la dificultad para realizar estos cambios por los costes elevados que pueda representar, es aconsejable disponer de una metodología que permita simular distintos escenarios, incorporando cambios leves que faciliten poco a poco la adecuación de la oferta a la demanda como medida más viable e inmediata a corto plazo.

El AMB presenta por lo tanto desequilibrios notables en la prestación de servicio del SITM, al no facilitar un acceso adecuado al empleo desde todas las áreas. Se puede observar gran dependencia de ciertas rutas del centro urbano comercial, sin contemplar los nuevos centros urbanos que se están desarrollando en la actualidad. Así, en algunos municipios el servicio de transporte público se está quedando obsoleto, no se está adaptando a las modificaciones rápidas de los usos del suelo, y los ciudadanos están migrando paulatinamente de forma progresiva hacia un uso más intenso de transportación individual que implica no solo al vehículo particular sino también al uso de la motocicleta como modo de desplazamiento cotidiano.

La metodología propuesta constituye un avance en este sentido, como integración de técnicas de análisis de datos geográficos y socioeconómicos que permitan evaluar la equidad en el servicio de transporte público en Áreas Metropolitanas. La interrelación de los sub-modelos de transporte, localización residencial, localización de actividades económicas e indicadores de accesibilidad permite tener disponible un modelo útil a la hora de medir los efectos dinámicos de cambios que se ejecuten en el sistema de transporte. Las técnicas de medición de equidad, tanto horizontal como vertical, permiten además una evaluación más completa de estos cambios en términos de impacto social.

El modelo AMB-LUTI presenta ciertas limitaciones que es importante mencionar de cara a trabajos ulteriores. La falta de información desagregada del estrato social por zona afecta el uso del modelo cuando se desee dar información a ese nivel de detalle, dado que se utilizaron valores totales para el AMB. No obstante, los resultados obtenidos fueron buenos, ya que el modelo permite una interpretación global de las condiciones de movilidad existente en día laborable en toda el Área Metropolitana. La metodología implementada, la cual combina el análisis de equidad del servicio de transporte público y el modelo LUTI, puede ser una herramienta útil para evaluar distintos escenarios de planificación en otras áreas de estudio.

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A NOVEL APPROACH TO THE TAIL ASSIGNMENT PROBLEM IN AIRLINE PLANNING

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ABSTRACT

Combinatorial optimization problems abound in the field of airline planning. Aircraft and passengers fly on networks made up of flights and airports. To schedule aircraft, assignments of fleet types to flights and of aircraft to routes must be determined. The former is known as the fleet assignment problem while the latter is known as the aircraft routing problem in the literature. Aircraft routing is typically addressed as a feasibility problem, the solution to which is required for the construction of crew schedules. All these issues are typically resolved 4 to 6 months before the day of operations. As a result, there is little information available about each aircraft's operational status when making such decisions. The tail assignment problem, which has received little attention in the literature, is solved when additional information about operational conditions is revealed, with the goal of determining each aircraft's route for the day of operations while accounting for the originally planned aircraft routes and crew schedules. As a result, it is a problem that must be resolved closer to the day of operations. We propose a mathematical programming approach based on sequencing that captures all operational constraints and maintenance requirements while minimizing operational costs and schedule changes relative to original plans. The computational experiments are based on realistic cases drawn from a Spanish airline with over 1000 flights and over 100 aircraft.

1. INTRODUCTION

Tail assignment is the step in the airline planning process in which specific aircraft (tails) are assigned to flights on a specific schedule. This task is completed a few days before the operation and is subject to several constraints. Firstly, and foremost, all maintenance activities must be ensured. Secondly, information that becomes available following fleet assignment and aircraft routing should be considered. Finally, all operational constraints must be adhered to. The availability of information is the reason for performing tail assignment in the operational horizon. Little to no information about the maintenance needs of each tail is known months or weeks before the day of operations; therefore, generic maintenance opportunities are only considered in the aircraft routing problem. Also, as late adjustments in the schedule occur, the series of flights to be flown by the same tails (line-of-flights) can be modified; certain flights can be cancelled, and others can be added immediately before the service.

The aircraft routing problem has been studied for decades and described in a variety of ways (Barnhart et al., 1998). The following is a generally accepted term. Given the assignment of fleet types to flights, the aircraft routing involves deciding the sequence of flights, i.e., line-of-flights, to be flown by each aircraft and ensuring that each flight is flown exactly once, each aircraft visits maintenance stations at regular intervals, and the solution uses only available aircraft of each type (Desaulniers et al., 1997). It should be noted that it is standard practice to produce flight sequences for aircraft quite early in the planning phase. This early decision is essential to provide input data to the crew planning process and to prepare long-term maintenance, not considering individual constraints but generic maintenance constraints. Then, as the day of operations approaches, the aircraft must be assigned to flight sequences. However, on average, only 80–85 percent of the sequences can be used in actual operations (Liang et al., 2015). This is due to the quality and level of detail of knowledge available about aircraft operational status when solving the aircraft routing, which, on average, is insufficient.

Consequently, the tail assignment problem is addressed very close to the day of operations. Here, all individual operational and maintenance constraints are considered. The problem is solved for a time horizon, which usually spans several days, and provides fully operational assignments of aircraft (tails) to sequences of flights. In practice, the input sequences of flights, which are determined in the aircraft maintenance routing problem, are usually not all suitable for satisfying operational constraints on the day of operations and they must be updated (Liang et al., 2015). Some variants of this problem have been developed in response to different airline business practices and involving planning horizons from months to days (Maher et al., 2018; Grönkvist, 2005; Gabteni and Grönkvist, 2009).

Because of the different approaches to the problem in the literature and real practice, there is not a widely accepted objective function. For example, the aircraft routing problem is not universally recognized as an optimization problem. Many authors have defined it as a feasibility problem, and others have attempted to maximize same-aircraft connections for passengers or to minimize expected delays (Lan et al., 2006). Also, it is common practice for airlines addressing the problem to consider it to be a feasibility problem (Grönkvist, 2005).

A mathematical model, which minimizes constraints violations and conflicts among others, and a solution strategy are proposed to find optimal solutions to real-world large-scale tail assignment problem instances in a short amount of time. The mathematical formulation presented here is based on the one developed for the crew scheduling problem, and it is capable of capturing all of the operational requirements for problem instances as given by our airline partners, including apron-related requirements. Existing methods in the literature fail to capture such a level of detail. Attempts to achieve this while still providing good quality solutions have failed. A rolling horizon approach is used to solve large-scale instances and achieve feasible solutions, in which the model is solved in many smaller sub-models. This approach is useful for finding a viable solution to a problem in a limited amount of time. The obtained solution is then fed into a heuristic-based method, which allows us to empirically demonstrate optimal solutions to the overall model. Computational studies based on data from Vueling Airlines, one of Spain's major airlines, are presented. The model's solutions outperform the airline's solutions, according to empirical proof. Besides, as evidence of the presented approach's effectiveness, a decision support tool was developed and given to the airline. This tool, which is based on the methods described in this report, is now being used in real-world operations.

2. PROBLEM DESCRIPTION

A time-directed graph represents the airline network, with nodes representing tasks such as flights and maintenance duties, and arcs representing relations between tasks. An origin airport, a departure time, a destination airport, and an arrival time define tasks. One tail must be assigned to each task. The remainder of this section introduces rotations, maintenance duties, the guidelines to be followed when assigning tails, and the goals to be pursued.

2.1 Rotations

A rotation is a series of flights performed by the same tail on the same day. A Line of Work (LoW) is a series of rotations to be performed by the same tail over a set period of time, usually several days. It should be noted that rotations and LoWs are results of the aircraft routing problem, which is solved after flight schedules and fleet assignments are determined. Rotations and the fleet allocated to them are the key inputs in tail assignment, and they should be kept as consistent as possible when allocating tails to tasks because crew schedules are dependent on them.

However, if planned rotations become infeasible, for example, due to tail operational conditions, the tail assignment must update them such that the flight schedule remains feasible. When allocating tails to rotations, the maintenance requirements of the tails must be considered, or else assignments will be infeasible. Swaps are used to help or make it easier to meet those requirements. A swap is the recombination of sections of two rotations with different bases, allowing the tails assigned to them to switch bases. Some rules, such as those requiring space-time compatibility, must be followed by swaps. Furthermore, their effect on crews must be minimal, so only a limited collection of all the potential swaps is allowed, as defined when the aircraft routing problem is solved and following the airline's criteria.

2.2 Maintenance duties

Maintenance entails arranging the repair of identified issues, removing objects after a certain amount of flight hours or calendar time, correcting previously found defects (e.g., pilot or crew reports, line inspection, items postponed from previous maintenance), and conducting scheduled maintenance. On an aircraft, various types of maintenance duties must be performed, which may or may not be planned ahead of time. Scheduled duties are identified in advance since they must be completed on a regular basis, while others are the product of operations, typically following equipment failures. They can be classified based on their frequency: flight line inspections are carried out on a regular basis, overnight checks (also known as "daily checks") are small checks conducted every two days during the night, A checks are light checks that are performed every few hundred flying hours, B checks are light checks that are performed every few months, C checks are heavy checks that are performed every 2 years, and D checks are heavy checks that are performed every 6–10 years. The aim of these checks is to perform both routine and non-routine aircraft maintenance. It should be noted that some maintenance checks (hereafter referred to as maintenance tasks) are more flexible than others when conducting tail assignment. Since the tail assignment planning horizon features several calendar days, flight line checks and overnight checks are thoroughly considered. The remaining checks are also fully considered, but are well established prior to operations.

2.3 Allocation rules

Several rules govern the assignment of tails to tasks. They can be classified as hard or soft requirements. Any hard requisite must always be met, while soft ones may be related to market considerations, such as a preference for particular tails due to capacity or efficiency, and may be violated, but, if violated, have a negative effect on the solution efficiency. The number of current rules is usually enormous, and they are complicated, making this problem difficult for planners to solve. They can be general or global rules, but they can also be fleet, aircraft, or airport specific (Grönkvist, 2005).

The following is an example of a hard constraint. Owing to noise restrictions, a specific tail cannot operate at a specific airport at certain times. And an example of a soft constraint follows. Because of its maximum takeoff weight, an aircraft type has limited performance at a specific airport. It will fly from that airport if the tail is not at its maximum weight.

2.4 Objectives

The tail assignment problem can have several objectives. In reality, they can change as the revealed information develops as the day of operations approaches. The primary goal in the early stages is viability, while in the later stages, meeting optimization requirements becomes more important. The following are some of the most important key performance indicators to be minimized: soft restriction violations, fleet changes, swap use, prolonged idle periods, fuel costs, and apron conflicts. Simultaneous departures of neighbouring aircraft on the apron or ramps may cause conflicts and delays. They could need the same airport services at the same time. As a result, they should be kept to a minimum.

3. MATHEMATICAL MODEL

We propose an Integer Linear Programming (ILP) model. Its mathematical formulation is built on a framework in which the tasks to be assigned are nodes and the relations between them are arcs. Mathematically, we consider one type of node (we treat all tasks the same, regardless of their nature) and one type of arc. The model's employed sets, parameters, and variables are described next. The mathematical formulation is then explained.

3.1 Sets

- F is the set of tasks to be covered in the given time-horizon. Tasks are indexed by i and j.
- $FF \subseteq F$ is the subset of tasks which are flights.
- $FSM \subseteq F$ is the subset of tasks which are soft maintenance tasks. They can be postponed if necessary, to improve schedule performance. If they are postponed, they must be rescheduled.
- $FHM \subseteq F$ is the subset of tasks which are hard maintenance tasks. They cannot be postponed.
- $F_i^+ (F_i^-) \subseteq F$ is the set of tasks which may follow (precede) task i in a line of work.
- P is the set of fleet types.
- $P_i \subseteq P$ is the set of fleet types compatible with task i.
- T is the set of tails.
- $T_i^F \subseteq T$ is the set of tails compatible with task i.
- $T_p^P \subseteq T$ is the set of tails belonging to fleet type p.
- $F_t^T \subseteq F$ is the set of tasks which may be assigned to tail t.
- $FA_t \subseteq F$ is the set of tasks which may be the first task in a line of work assigned to tail t.
- C is the set of conflict events. Each conflict event is characterized by a combination of 10-minute time periods and a collection of adjacent parking spots. A possible conflict is identified at each conflict event by combinations of flights scheduled to depart within the predefined time periods and tails located in adjacent parking spots. It should be noted that there is a possible conflict with each flight for which there are other flight departures within a 10-minute time span beginning with the flight's departure.

3.2 Parameters

- c_t^i is a penalty for operating flight i with tail t. This cost accounts for soft operating restrictions.
- b_1^i is the cost of not covering flight i.
- b_2^i is the cost of not covering soft-maintenance task i. Recall that some maintenance tasks, which do not feature urgent, strictly needed, or important repairs or checks may be postponed.
- $\kappa_t^{i,j}$ is a penalty for each combination of tail t and consecutive tasks i and j.
- λ^c is a penalty for each excess conflict at conflict event c.
- μ_i is the change penalty for not operating flight i using the originally planned fleet type.
- $\widehat{w}_i^p$ is 1 flight i was originally scheduled to be operated by fleet type p, and 0 otherwise.
- $\nu_{i,j}$ is the change penalty for not operating tasks i and j consecutively using the originally planned line of work (where task j follows task i in the line of work).
- $\hat{u}_{i,j}$ is 1 flight i was originally scheduled to precede task j, and 0 otherwise.

3.3 Variables

- $x_i^t \in \{0,1\}$ is 1 if tail t is assigned to task i, and is 0 otherwise.
- $y_{i,j}^t \in \{0,1\}$ is 1 if tail t is assigned to consecutive tasks i and j in a line of work, and is 0 otherwise.
- $w_i^p \in \{0,1\}$ is 1 if fleet type p is assigned to task i, and is 0 otherwise.
- $a_i^t \in \{0,1\}$ is 1 if tail t starts a line of work whose first task is i, and is 0 otherwise.
- $s_i \in \{0,1\}$ is 1 if task i is not covered, and is 0 otherwise.
- $u_{i,j} \in \{0,1\}$ is 1 if tasks i and j are consecutive in a line of work, and is 0 otherwise.
- $o_c \in \mathbb{R}^+$ is the number of conflicts in excess of the maximum number of allowed conflicts at conflict event c.

3.4 Objective function

$$z = \sum_{i\in FF}\sum_{t\in T_i^F} c_t^i x_i^t + \sum_{i\in FF} b_1^i s_i + \sum_{i\in FSM} b_2^i s_i + \sum_{i\in F}\sum_{j\in F_i^+}\sum_{t\in T_i^F\cap T_j^F} \kappa_t^{i,j} y_{i,j}^t + \sum_{c\in C}\lambda^c o_c + \sum_{i\in FF}\sum_{p\in P_i}\mu_i\left|w_i^p - \widehat{w}_i^p\right| + \sum_{i\in F}\sum_{j\in F_i^+}\nu_{i,j}\left|u_{i,j} - \hat{u}_{i,j}\right| \quad (1)$$

The objective function in (1) has a total of seven terms in the following order. Penalties for unsuitable task-tail combinations, costs for not covering flights, costs for not covering soft-maintenance duties, penalties for any task link, and penalties for any conflict over the maximum allowed number. The objective function's last two terms penalize deviations from the originally intended schedule. The first penalizes deviations from the initial fleet type assignment. The second penalizes deviations from the initial line of work.

3.5 Task covering constraints

$$\sum_{p \in P_i} w_i^p + s_i = 1 \qquad \forall i \in F \tag{2}$$

$$\sum_{t \in T_p^P \cap T_i^F} x_i^t = w_i^p \qquad \forall i \in F, p \in P \tag{3}$$

Constraints (2) state that each task is assigned to one fleet type or it remains unassigned. According to constraints (3), if a task is assigned a fleet type, it must also be assigned a tail that belongs to that fleet type and is compatible with the tail.

3.6 Line-of-work constraints

$$\sum_{i \in FA_t} a_i^t \leq 1 \qquad \forall t \in T \tag{4}$$

$$u_{i,j} = \sum_{t \in T_i^F \cap T_j^F} y_{i,j}^t \qquad \forall i \in F, j \in F_i^+ \tag{5}$$

Constraints (4) are constraints on line of work initialization. They assign the first task in the line of work to each tail. Constraints (5) define task lines in terms of succession regardless of the allocated tail.

3.7 Task sequencing constraints

$$\sum_{i \in F_j^- \cap F_t^T} y_{i,j}^t + a_j^t = x_j^t \qquad \forall j \in F, t \in T_j^F \tag{6}$$

$$\sum_{j \in F_i^+ \cap F_t^T} y_{i,j}^t \leq x_i^t \qquad \forall i \in F, t \in T_i^F \tag{7}$$

Task sequencing restrictions are constraints (6) and (7). Constraints (6) are backward sequencing constraints; for each task in a line of work to be allocated to a compatible tail, it must be preceded by another task, unless it is the first task in the line of work. Constraints (7) are forward sequencing constraints; there can be up to one successor for each task in a line of work to be allocated to a compatible tail.

3.8 Other constraints

Owing to space constraints, other constraints are not directly shown here. Seating capacity on each cabin type must be equal to or greater than the number of confirmed reservations. Constraints to ensure that operational restrictions are not broken. Constraints preventing night flights from taking place on two consecutive nights. Constraints stating that no tail can fly consecutive nights in order to ensure that every tail rests overnight at least once every two days. Constraints restricting the number of tails that can be used for each day's schedule to the number that are available. Constraints to ensure that hard maintenance and regular maintenance activities are allocated to the appropriate tail. Constraints stating that daily maintenance duties are conducted at every airport where possible for the tails that need it. Constraints on the number of conflicts that may occur, limiting the number of conflicts exceeding the airline's overall allowable.

4. COMPUTATIONAL EXPERIMENTS

We assessed the model's success using case studies based on real-world examples from Vueling Airlines. The information was given by the airline and represents its operations in Europe in 2019. The data set includes operational schedule details, operating expenses, passenger demand values, the BCN airport apron layout, maintenance capacities, and the available fleet from October 6 to October 10, 2019. The air network features 173 airports spread across Europe, as well as those in Asia and Africa. On a typical day, approximately 700 flights operate throughout the network. Three fleet types were available in this case study: a fleet of A-319s with 141 seats per plane, a fleet of A-320s with 171 seats per plane, and a fleet of A-321s with 200 seats per plane. A series of case studies was suggested to evaluate the model and solution methods for real-world instances. All of the case studies were set in the same time period but had different planning horizons ranging from one to five days. This essentially means that the problem size was different with each case study. The tests were performed on an Intel NUC machine equipped with an Intel Core i7-8559U @ 2.70GHz processor and 2x16GB SO-DIMM DDR4 2400 MHz RAM, running Windows 10 Pro. The models were written in Python 3.7.3 and solved with the commercial solver IBM ILOG CPLEX 12.9.0. Many of the instances tested were either solved to perfection or ran for less than 24 hours.

Table 1 displays the mathematical model size for each of the case studies, with each row representing a different case study. Table 1 also indicates how many flights, maintenance duties, and tails are available in each case study. The number of (discrete) variables, constraints, and nonzero elements were given as model sizes.

No. of days	Flights	Maintenance tasks	Tails	Variables	Constraints	Non-zero elements
1	682	59	127	117,217	120,342	352,884
2	1,376	77	127	454,550	242,922	1,150,661
3	1,999	86	127	998,446	352,142	2,347,908
4	2,626	95	127	1,729,013	464,960	3,925,464
5	3,279	100	127	2,731,427	581,291	6,048,599

Table 1: Model size for different case studies.

We began by solving all of the case studies using the branch-and-cut and heuristics approaches given by the commercial solver IBM ILOG CPLEX 12.9.0. Table 2 displays these findings. It contains a case study for each row, which is defined by the number of days in the planning horizon, the number of flights, the number of maintenance duties, and the number of tails. Table 2 also displays the lower bound (L.B.), incumbent solution (I.S.), optimality gap (O.G.), and computational time in seconds for each case study (T.). The lower bound is equal to the solver's highest bound. The incumbent solution is the best solution discovered. The optimality gap is the relative gap between the incumbent solution and the lower bound. The computational time is the amount of time the solver spent running. Except for the case study involving 5 days, all of the case studies were solved to optimality; however, as the problem size grew, the computational time increased exponentially, implying that this solution strategy was unable to produce solutions within a reasonable time if the timeframe to be solved was longer than a few days.

No. of days	Flights	Maintenance tasks	L.B.	I.S.	O.G. (%)	T. (s)
1	682	59	193.050	193.050	0.00	1.05
2	1,376	77	333.025	333.025	0.00	7.88
3	1,999	86	451.525	451.525	0.00	1,200.27
4	2,626	95	599.350	599.350	0.00	47,312.28
5	3,279	100	728.100	18,690.100	2,466.96	86,403.72

Table 2: Solutions of all the case studies using the branch-and-cut and heuristics approach

To efficiently solve the problem, we created and implemented an algorithm based on rolling horizon methods (Sethi and Sorger, 1991) to obtain solutions. The Rolling Horizon Algorithm (RHA) is a technique for solving mixed 0-1 deterministic optimization problems that is based on rolling horizon methods. It involves solving a series of integer programming subproblems in which the variables are partitioned into three subsets. The values of the variables in the first subset are fixed to previous solution values, the 0-1 variables in the second subset are held free, and the values of the variables in the third subset are fixed to 0. However, the RHA cannot prove optimality. A particular approach should be taken to demonstrate it. To that end, the solution can be used as an initial solution for another approach and the whole problem solved. While exact methods should be used to ensure optimality, we have empirically discovered that feeding the CPLEX "solution polishing" heuristic with the initial solution obtained by the RHA provides the optimal solution. Table 3 displays the solutions obtained for the case studies with planning horizons of 4 and 5 days. The obtained incumbent solutions are equal to the respective lower bounds in Table 2, indicating that they are optimal. Furthermore, computational times are significantly reduced.

No. of days	Flights	Maintenance tasks	I.S.	O.G. (%)	T. (s)
4	2,626	95	599.350	0.00	279.50
5	3,279	100	728.100	0.00	407.42

Table 3: RHA solution for the case studies featuring planning horizons of 4 and 5 days

To determine the quality of the model's solutions, they were compared to the actual solutions implemented by the airline. In this comparison, three major performance indices were examined: the number of unassigned tasks (U.), which were either flights or maintenance tasks, the number of hard constraint violations (H.V.), and the number of soft constraint violations (S.V.). Table 4 shows the comparison, which is made the day before the day of operations, when schedules are ready to be implemented. The case study is described in the first column of Table 5. The other two main columns, Model and Airline, display the key performance indices for the mathematical model's and the airline's solutions, respectively. Note that the solutions provided by the model never violate hard restrictions. Moreover, the number of soft restriction violations is significantly reduced.

	Model			Airline		
No. of days	U.	S.V.	H.V.	U.	S.V.	H.V.
1	0	26	0	0	42	3
2	0	56	0	0	90	7
3	0	80	0	0	126	18
4	0	95	0	0	171	27
5	0	119	0	0	224	35

Table 4: Comparison of the model solutions with those used by the airline

Maintenance operations scheduling in airlines is a difficult and complex issue. Maintenance plans are usually prepared in practice based on the expertise of maintenance operators. However, this method is typically time consuming and can result in subpar solutions. Many industries, including the airline industry, are designing better maintenance plans in order to maximize asset availability and performance (Deng et al., 2020). Predictive maintenance techniques predict when maintenance should be done. It saves money over preventive maintenance since tasks are only done when they are required. The aim of predictive maintenance is to make it simple to schedule corrective maintenance in order to avoid unexpected failures. Two additional studies were carried out to demonstrate the possible benefits of using a holistic predictive maintenance method. For the two tests, a 5-day planning horizon was selected. In the first experiment, there is insufficient knowledge on maintenance duties for the entire planning horizon, which means that some of them are revealed as time passes. The aim of this environment is to mimic the airline's current operating model, in which a near-perfect predictive maintenance method is currently unavailable. In the second experiment, maintenance duties feature full or perfect details, implying that a perfect predictive maintenance tool is usable. In the first experiment, the mathematical model was solved every day, which means the model must be solved 5 times. The number of disclosed maintenance duties varied for each run of the model, implying that the schedule is not static. It should be noted that the model's 5 runs were also embedded in a rolling horizon approach. In the second experiment, the knowledge was perfect, so the five days could be solved in a single execution. Table 5 shows the results. The first column lists the main performance indicators (KPIs), the second the solution to the first experiment, i.e., the imperfect information scenario, and the third the solution to the second experiment, i.e., the perfect information scenario. The value of the objective function for the incumbent solution (I.S.) in the second row of the table, the number of unassigned tasks (U.) in the third row, and the number of violations of soft constraints (S.V.) in the last row of the table were used to compare the two scenarios. The findings of the perfect information scenario clearly outperform those of the imperfect information scenario.

KPI	Imperfect information scenario	Perfect information scenario
I.S.	1,655.975	1,072.450
U.	6	0
S.V.	125	119

Table 5: Results for the imperfect and perfect information scenarios

4. CONCLUSIONS

We took a novel approach to the tail assignment issue in airlines. The method we devised gathers a broad range of data and offers a basis for generating optimal proposals rather than just feasible solutions. Among the specifics considered are all applicable aircraft maintenance constraints and flight activity requirements. Furthermore, possible conflicts during aircraft taxi operations in aprons are considered, so that departures are optimally planned to prevent multiple aircraft from departing the same place at the same time. We were able to solve real-world instances in short computational times while proving the optimality of the given solutions using the methodology we devised. The algorithms we created to solve the problem are divided into two stages. Firstly, a feasible solution is found using the rolling horizon process. Secondly, a heuristic-based approach improves the feasible solution obtained. We presented the findings of several computational experiments conducted using data from Vueling Airlines, a major Spanish airline.

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PUBLIC TRANSPORTATION MULTIMODALITY IN THE CITY OF LISBON

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ABSTRACT

Mobility in major European capitals is not yet sustainable. The need to respond to the ongoing changes in public transportation demand, operationalize safety norms of social distancing, and reach carbon neutrality are prompting cities to reassess public transport systems. Cross-mode synergies in multimodal transport systems can be explored (including convenience, reliability, cost, speed and predictability) to foment public and active modes of mobility. In this context, multimodal traffic pattern analysis can unravel cross-mode vulnerabilities, a possibility that is finally rising with the sensorization of cities, integration of ticketing systems, and consolidation of traffic data sources and their situational context.

This work introduces a methodology for the analysis of spatiotemporal indices of multimodality against available situational context, aiding specialists to find vulnerabilities on the public transportation network. Traffic generation poles, large-scale public events, and weather records are the considered sources of situational context. We discuss the role of context-aware multimodality indices to understand demand and its emerging changes, assess cross-modal transfers and preferences, and support cross-mode route and schedule planning. This work further discusses the relevance of multimodal pattern discovery to offer data-centric views ensuring: fully transparent decisions to the citizens; and an objective coordination between carriers, municipalities and authorities. Lisbon is further introduced in this work as a reference case study for context-aware multimodal mobility.

1. INTRODUCTION

Worldwide, city municipalities are establishing efforts to collect urban data in order to gain more comprehensive views of the ongoing changes to city traffic dynamics. The undertaken initiatives are particularly relevant in face of pandemic-driven shifts to traffic demand and private car ownership, city reforms, the need to enforce safety norms, and the rising advocacy towards active modes of transportation. In particular, the Lisbon City Council has established relevant initiatives to this end: city traffic sensorization, consolidation of relevant sources of urban data on its Intelligent Management Platform , the integration of automated fare collection systems and tariffs along the public transport system, and entry requirements for carriers operating in the Lisbon metropolitan area. These initiatives offer unique opportunities for multimodal pattern analysis – encompassing road, railway and inlands waterways modes, as well as active modes such as walking and cycling – and cross-carrier coordination. Still, the inherent nature of multimodal traffic data – heterogeneous, massive in size, rich in spatiotemporal dynamics, subjected to variable aspects, and dependent on context factors – together with the increasing disruptive changes in urban traffic poses challenges to data-centric multimodal decisions.

This work proposes a methodology for a preliminary assessment of multimodal synergies in demanding urban areas of a city using multimodality indices estimated from available traffic data. Context-aware corrections are proposed in the presence of information associated with large-scale public events and available weather conditions. These contextual factors can account for meaningful variations to the level and distribution of traffic demand across transportation modes. A spatiotemporal analysis of multimodality indices is conducted for the city of Lisbon using three major modes of public transportation: bus (CARRIS), subway (METRO) and cycling (GIRA). In addition, we further extend this methodology to relate the gathered knowledge against additional sources of situational context, including traffic attraction-generation poles.

This paper aims at bridging the existing gap on the integrative analysis of multimodal traffic data and its situational urban context. A discussion on the relevance of cross-modal pattern analysis for the articulation between operators, and alignment of the public transport supply with the self-actualizing city dynamics are further provided.

This work is anchored in the pioneer research and innovation ILU project (DSAIPA/DS/0111/2018), a project that joins the Lisbon City Council and national research institutes to bridge ongoing research on urban mobility with recent advances on artificial intelligence.

The manuscript is organized as follows. Section 2 provides essential background. Section 3 introduces a novel methodology for the context-aware assessment of multimodality indices from heterogeneous traffic data. Section 4 gathers results of its application on the Lisbon city. Final remarks and major implications are then synthesized.

2. BACKGROUND

Multimodality is generally defined as the use of more than one transport mode to complete a trip within a certain period. In contrast, monomodality commonly refers to the exclusive use of one mode of transport (Nobis, 2007). Multimodality is a subfield of a broader body of research focused on intrapersonal variability of travel behaviour, comprising temporal, spatial, purpose and modal dimensions (Buehler and Hamre, 2016). Nobis (2007) emphasizes the fact that the general definition of multimodality must entail a time frame, possibly going beyond end-to-end trips to further encompass a week period. The longer the period, the higher the probability for multimodal transport use.

2.1. Opportunities and challenges in Lisbon

The Intelligent Management Platform of Lisbon City (PGIL) was publicly launched in 2017 to meet various policy and planning goals at the operational level. In this context, advancing towards sustainable and multimodal mobility in Lisbon is understood as a policy opportunity while it offers multiple research challenges around the interdisciplinary triaxial lens: data science and statistics – urban mobility planning – artificial intelligence. Using the available big data from various heterogeneous sources of traffic data across public transport operators, the following research challenges have been addressed so far:

- processing and consolidation of raw sources of urban data across public transport operators, and their multimodal descriptive and predictive analysis to support mobility planning decisions at the city level
- discovery of emerging spatiotemporal traffic patterns, while accounting for the stochastic nature of mobility dynamics (Neves et al., 2020, 2021).
- inference of dynamic and multimodal origin-destination (OD) matrices sensitive to missing boarding validations and monthly patterns of circulation (Cerqueira et al., 2020)
- incorporation of contextual data (weather, public events, traffic incidents, etc.) to enhance traffic data analysis and its integrative learning potential for future behaviour inferences (Leite et al., 2020; Cerqueira et al., 2020)
- exploratory policy framework of multimodality indices to measure social equity regarding users’ multimodality options in the city (Lemonde et al., 2020)
- development of the ILU app, namely, to enable visualization of large-scale and heterogeneous data and to enhance specific data-centric views of the relevant information while accounting for each operator/city specificities and both cross-modal or unimodal user-centric perspectives.

The implementation of this set of urban analytics tools within the PGIL platform, managed by the city Council, is expected to support urban mobility planning, giving priority for public transport options and the integration of active travel modes (walking, shared public bicycles) with bus and/or metro/subway. Moreover, the full scalability and online nature of the devised tools can be enriched by targeting other dimensions of the city dynamics in the post-pandemic era.

3. METHODOLOGY

The assessment of multimodal urban transportation is a key issue in modern transport research, and the proposed solutions must handle the massive, heterogeneous, spatiotemporal, context-dependent and incomplete nature of traffic data. In this section, a sequence of procedures (Figure 1) is proposed for context-aware multimodal analytics.

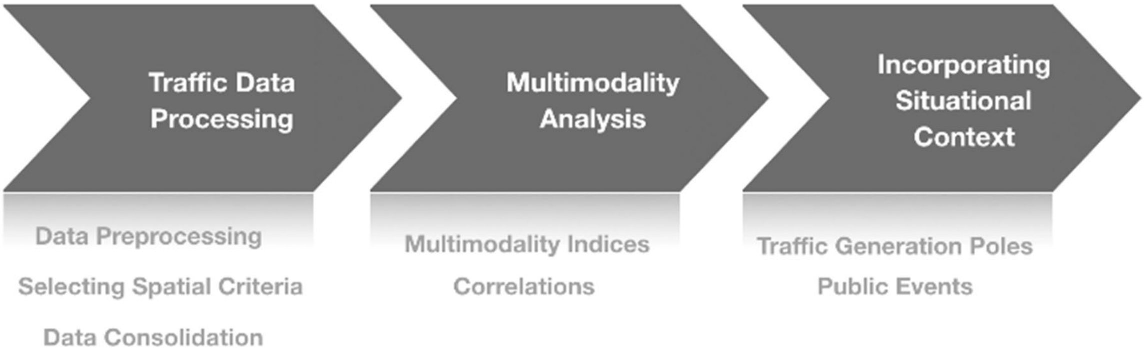

Figure 1: Public transportation multimodality analysis process

3.1. Traffic data processing

Raw traffic data from different sources can come in different formats and structures, being essential to start by preprocessing the collected data, where noise and inconsistencies are removed and high multiplicity of data sources are integrated within a single repository. The consolidation step was accomplished in this work using a multi-dimensional schema to allow for an effective and efficient cross-modal retrieval of trip records from specific users, operators, geographies and time periods. To this end, shared dimensions between sources were identified, including user, carrier, spatial and temporal dimensions.

Given the massive size of urban data, proper indexation of spatial, temporal and modal information was pursued for efficient data retrieval (Mamoulis et al., 2004). Efficient slicing, dicing and drilling query facilities were further made available. Unnecessary memory inefficiencies were further avoided by, for example, decoupling stations, vehicle or card details from the validation records. In addition, data cleaning procedures were applied to ensure the absence of duplicates and gross errors, and estimate missing entries using alight stop inference methods (Cerqueira et al., 2020). Finally, updating routines were applied for the automatic extraction, transformation and storage of continuously arriving trip records.

Given the presence of consolidated trip records, the user can select among pre-established spatial and temporal granularities for the subsequent multimodal traffic data analyzes. In terms of spatial specifications, two main possibilities are made available. One of them is to customly specify the target geographical region of interest (i.e. using a polygon or circular marking). The other is to select predefined regions.

The following zoning maps are considered for the Lisbon Metropolitan Area (Figure 2):

- traffic analysis zones (TAZ): geographical unit used in transportation planning models to assess socio-economic indicators
- administrative zones: coarsest geographical unit for the city, ranging from municipalities to parishes, depending on the geographical organization of the target city; and
- sections: finest geographical unit, comprising small districts and neighbourhoods.

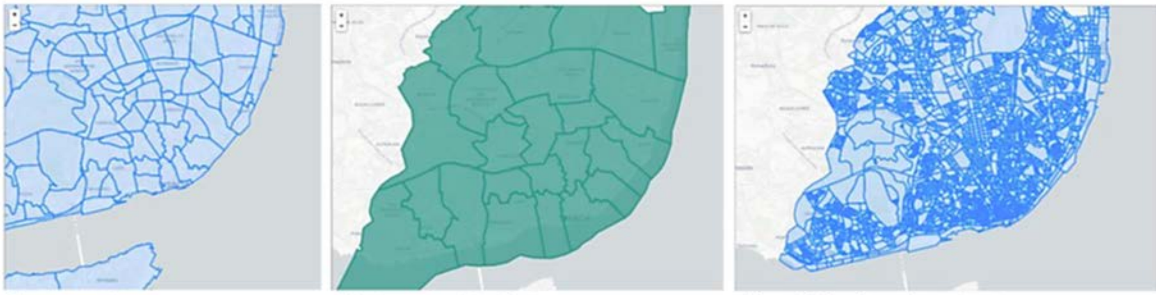
a) TAZ zoning b) City municipalities c) Neighborhood sectioning

Figure 2: Zoning: geographical decomposition of the Lisbon city at different granularities

Two major types of temporal constraints can be placed. First, calendrical constraints – such as day of the week (e.g. Mondays), weekdays, holidays or on/off-academic period calendars – can be specified to segment the available traffic data. Second, time intervals (e.g. on/off-peak hour intervals) or a fixed time granularity (e.g. 15 minute) can be optionally placed to guide traffic data description and prediction.

Once these constraints are fixed, multi-dimensional querying can be automatically derived to produce the consolidated data. Given consolidated traffic data from cross-mode carriers, data mappings are generally further applied to transform the queried data into more conducive data structures (Mamoulis et al., 2004). Illustrating, spatiotemporal data structures can be mapped into georeferenced multivariate time series structures to facilitate subsequent mining tasks.

These time structures can be aggregated at different granularities and barycenter averaging further applied. Correlation between time series from different modes can also support the understanding of multimodal synergies. Linear correlation coefficients (e.g. Pearson's, Spearman's, Kendall's) and detrended cross-correlation analysis for correlating non-stationary time series can be considered to this end (Podobnik and Stanley, 2008).

3.2. Multimodality Data Analysis

Spatial multimodality indices support the analysis of multimodal transport usage in specific urban areas using inequality measures to assess available and enacted options by citizens

(Lemonde et al., 2020). An inequality measure is a function that describes a distribution of ‘income’ in a way that allows direct and objective comparisons across multiple distributions (Cowell, 2011). Although inequality measures are usually used in socio-economics studies, they can by extended to transportation by reformulating their core properties (Diana and Pirra, 2016):

- Weak Principle of Transfers: considering two travel modes with I and Iδ intensities of use. If the intensity of the most used mode decreases and the other increases in same degree $I<2\delta$, then multimodality increases;
- Scale Independence: if the frequency of use of each mode changes by the same proportion, the multimoda-lity index should remain the same;
- Principle of Population: the multimodality index should remain the same for any replication of the modes with their corresponding intensities of use.

The choice of a suitable index for multimodality analysis will depend on the context of the problem. The Gini coefficient is a summary statistic of the Lorenz curve and is usually used as a measure of inequality in a population. Diana and Pirra (2016) translated the usual formulation of the index to the context of multimodal transportation,

$$Gini = 2/\mathrm{n} \cdot (\textstyle\sum_{i=1}^{n} i \cdot f_i)/(\sum_{i=1}^{n} f_i) - (n+1)/(\mathrm{n}) \tag{1}$$

where f_i is the intensity of use of ith transport mode and n the total number of modes. Another possible measure is the Herfindahl–Hirschman index, a typical measure of market concentration to determine market competitiveness,

$$\mathrm{HH}_m = 1/\mathrm{m} \cdot (\mathrm{n} \cdot \textstyle\sum_{i=1}^{n} (f_i - \bar{f})^2)/((\sum_{i=1}^{n} f_i)^2) + 1) \tag{2}$$

where m corresponds to the effective number of used modes (Diana and Pirra, 2016). Both indices range from zero, corresponding to an equal usage of all modes, up to a maximum of one, which refers to monomodality in the presence of an infinite population of modes.

3.3. Incorporating Situational Context

The analysis of multimodality indices can be enriched with the presence of situational context. A major constituent element of such context is ornament information, specially traffic generation poles (Figure 3), including commercial areas, employment centers such as business parks and enterprises, and collective equipment like hospitals, schools and stadiums, that generate or attract a significant volume of vehicle trips, either from contributors, visitors or providers (IMTT, 2011). The combined analysis of these traffic poles locations against the computed multimodality indices, as well as station-route maps, provides a comprehensive and dynamic way of assessing causal factors pertaining to the spatiotemporal distribution of traffic along the city.

Additionally, the surveyed indices can be revised to further measure how the volume of passengers generated and attracted by nearby poles are being currently satisfied by the co-located modes of public transport.

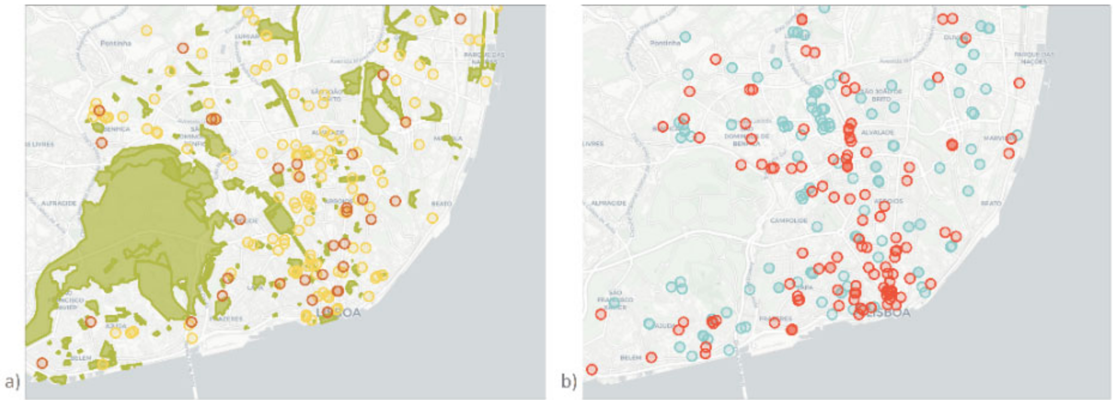

Figure 3: Some traffic generation poles: a) large commercial poles and parks; b) healthcare poles in red and educational poles in blue.

In addition, weather factors and public events can further impact traffic demand and modal choices (e.g. decreased cycling activity under rainy weather conditions). Two major strategies for context-sensitive analysis are suggested to this end. First, data can be segmented according to the available situational context followed by context-specific inference of multimodality patterns (Cerqueira et al., 2020). Second, and in alternative, the context can be directly accommodated in the indices by capturing correlations with the context and using these correlations as correction factors to adjust traffic demand.

4. LISBON'S CASE STUDY

Three public transport modes were considered for this study – bus-and-tram, subway and cycling modes. The bus mode, operated by CARRIS, and the subway mode, operated by METRO, are the two most used public transport modes and their stations offer a good spatial coverage within the Municipality of Lisbon. The stations of GIRA, the biking sharing system, however, can only be found in the center axis of the city and in the neighborhood of Parque das Nações (Figure 4); and the validations during the week are significantly lower than the other modes (Figure 5).

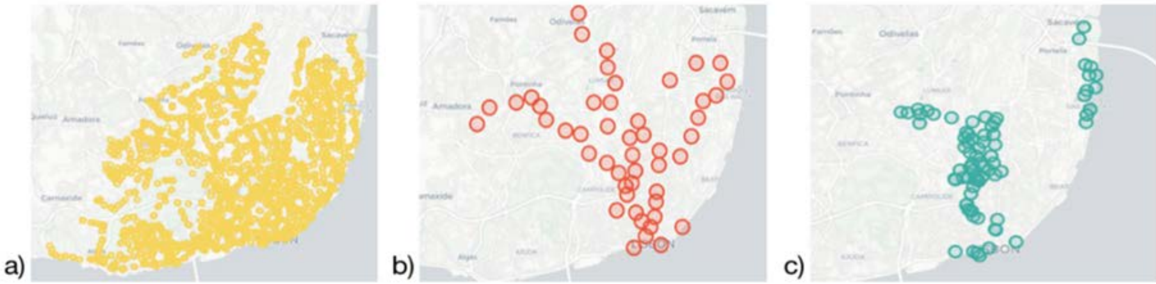

Figure 4: Lisbon's stations location: a) CARRIS, b) METRO, c) GIRA.

Smart card technology was used to gather public transport traffic data. For the bus transportation, as smart card data only monitors entries, estimators are necessary to infer exit validations from vehicle-to-vehicle transfers, daily pendular movements and circulation patterns across days. In this context, multimodal circulation views were considered to capture cross-mode transfers and thus increase the success of the alight stop inference task (Figure 6).

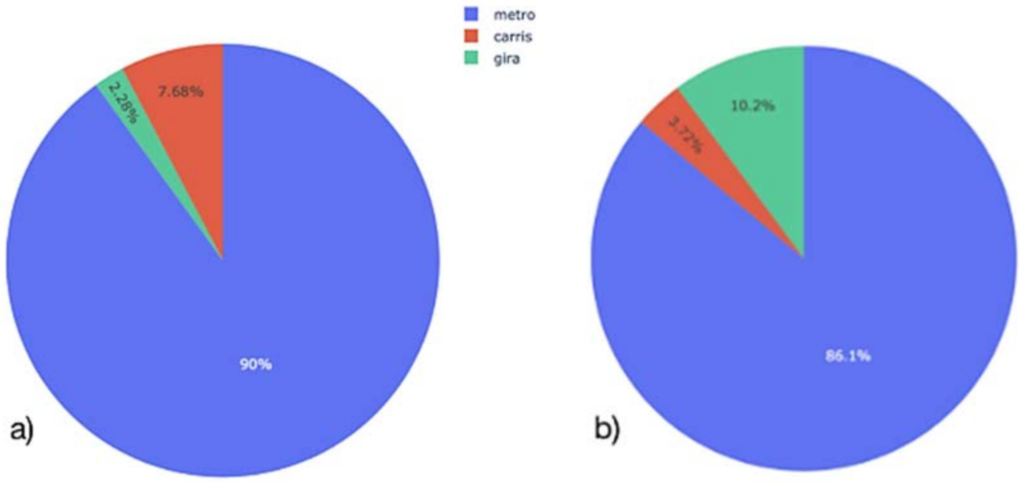

Figure 5: Weekly mode share distribution of TAZ nº 66 (Entrecampos): a) week days, b) weekends.

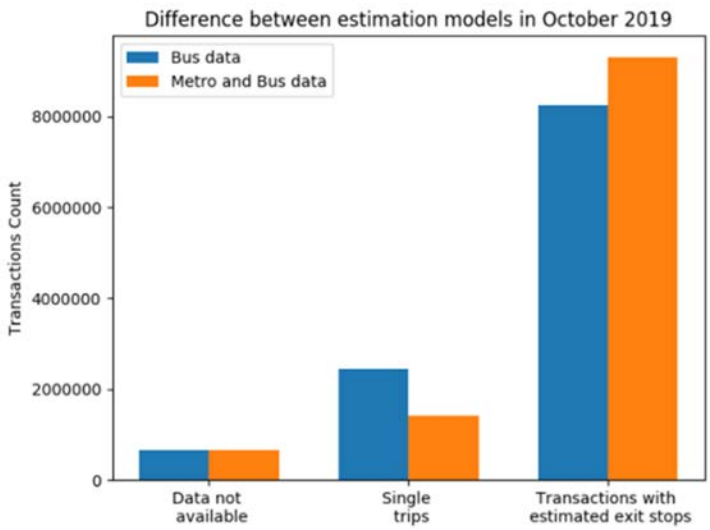

Figure 6: Multimodal alight stop inference success for CARRIS data in October 2019

Traffic Analysis Zones (TAZ) were selected in this study as the spatial granularity criteria (Figure 7). This form of spatial modelling is derived from trip generation densities processed by delineation algorithms that use the peaks of densities as the centre of a zone (Martínez et al., 2009). Subsequently, the public traffic demand is estimated (section 3.1) by retrieving the volume of validations from the stations and stops of the chosen transport modes per zone.

Figure 8 shows the daily volume of validations in TAZ nº66. Figure 9 provides a complementary view of the demand distribution per mode and TAZ.

Figure 7: TAZs of Lisbon Municipality: a) all TAZs, b) TAZs with all modes (subway, bus, bike).

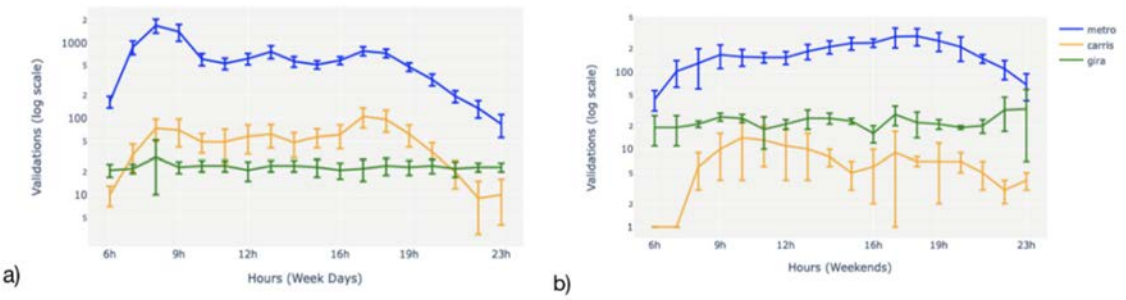

Figure 8: Daily volume and variation of validations in TAZ nº66: a) week days, b) weekends

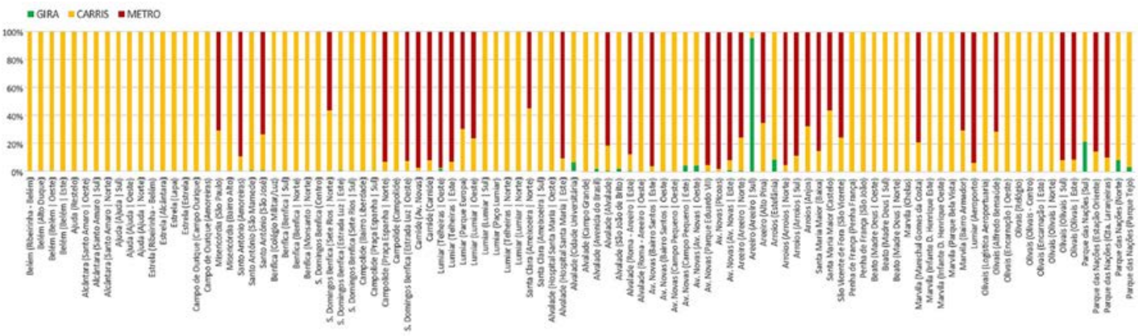

Figure 9: Distribution of demand per transport mode in 2019.

Correction factors corresponding to weather variables (Figure 10) and public events were applied by respectively removing correlation factors on mode-specific demand and replacing demand observed during the spatiotemporal footprint of an event by the average demand on a comparable time period

			station 406	*station 407*	*station 408*	*station 416*	*station 417*	*all*
temperature	check-in	11-13h	0.147	0.178	0.491	0.043	0.05	0.239
		14-16h	0.127	0.255	0.05	0.05	0.088	0.138
	check-out	11-13h	0.112	-0.171	0.273	0.19	-0.057	0.09
		14-16h	0.303	0.082	-0.065	-0.065	0.115	0.167
precipitation	check-in	11-13h	0.124	0.161	0.151	0.251	-0.07	0.161
		14-16h	-0.204	0.017	0.005	-0.163	-0.011	-0.119
	check-out	11-13h	-0.423	-0.146	-0.42	-0.124	-0.237	-0.414
		14-16h	0.146	-0.344	-0.205	-0.267	0.287	-0.068
wind	check-in	11-13h	-0.029	-0.044	-0.033	-0.248	-0.41	-0.288
		14-16h	-0.122	-0.276	-0.116	-0.201	-0.251	-0.268
	check-out	11-13h	-0.417	-0.412	-0.398	-0.147	-0.258	-0.501
		14-16h	-0.14	-0.471	-0.404	-0.332	0.097	-0.337
humidity	check-in	11-13h	0.067	0.278	0.235	-0.112	-0.008	0.111
		14-16h	0.08	0.111	0.027	0.058	0.081	0.1
	check-out	11-13h	-0.107	0.021	0.113	-0.24	-0.09	-0.088
		14-16h	0.244	0.199	-0.159	-0.168	-0.042	0.001

Figure 10: Correction factors produced by the Pearson correlation between weather data and observed check-ins/outs at GIRA's bike stations for 2 hours intervals (7/1/2019 to 28/2/2019).

The public traffic demand from each zone can be correlated with computed spatial multimodality indices, to further detect vulnerabilities in the public transport system of a particular zone. Figure 11 displays four TAZ maps of Lisbon coloured with the values of the Gini index and Herfindahl–Hirschman index respectively at different hours.

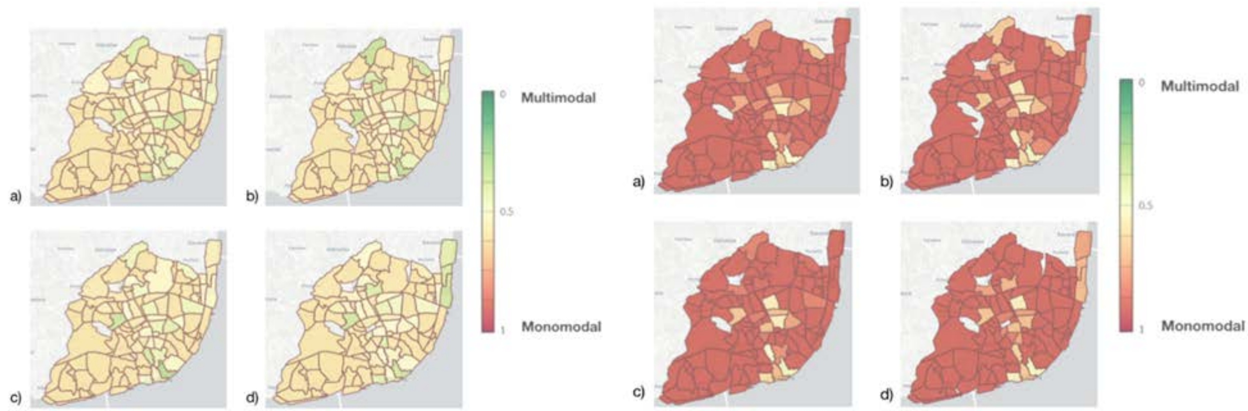

Figure 11: Gini index (left) and HH index (right) on week days: a) 8h, b) 12h, c) 17h, d) 21h.

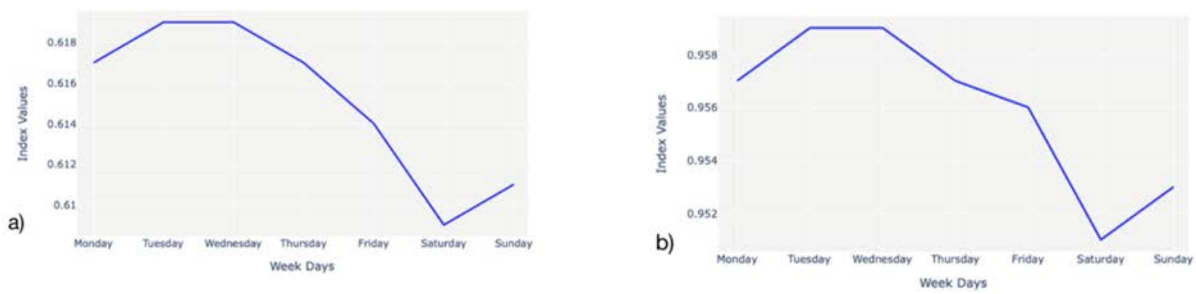

Figure 12: Weekly multimodality index variation: a) Gini, b) HH.

The spatiotemporal analysis of the indices provides an exploratory policy framework to measure social equity regarding the available multimodality options along the zones of an urban region. In the context of the Lisbon case, the TAZs with higher degree of multimodality generally correspond to zones that contain all targeted modes - bus, subway and cycling (Figure 7) - and encompass a large number of traffic generation poles (Figure 3). Considering the Gini index, a few TAZs contain all selected modes yet yield a medium index value (around 0.5). This occurs due to heavy subway usage patterns (scale dependence property). Herfindahl–Hirschman index (HH) results are similar to Gini indices, with the exception that HH is more sensitive to the number of used modes (population property), justifying the red coloring on most TAZs. The variation along a week is coherent for both indices (Figure 12), with a subtle multimodality increase in weekends moved by an increased cycling demand and decreased subway demand.

5. CONCLUDING REMARKS

This work introduced a methodology that offers a solid ground for multimodal traffic data analytics, including a means for the consolidation and efficient retrieval of heterogeneous sources of trip record data; the possibility to estimate missing validations at the entry or exit of stations and vehicles; and the accommodation of correction factors to discount the impact that a given situational context can have on circulation patterns.

We provide preliminary empirical evidence for the relevance of the proposed methodology to aid the calculus of multimodality indices for an initial characterization of mobility restrictions and social equity aspects.

We are currently extending the proposed methodology to accommodate more advanced descriptive and predictive analytics of multimodal traffic, including the discovery of emerging multimodal patterns, inference of origin-destination matrices, and modeling of inter-mode dependencies to assist context-aware predictors of public traffic demand.

These contributions are expected to assist the municipality of Lisbon and comparable cities in moving towards urban mobility plans closely aligned with the real traffic dynamics as objectively given by trip record data, therefore:

- supporting the transparency of urban mobility planning decisions to the citizen
- offering a solid ground for coordination efforts among municipalities and public transport operators
- promoting the continued alignment of the public transport network with the ongoing city transformations, thus ensuring that the public transport system responds to emerging multimodal traffic vulnerabilities, a growing need given the transformations and changing regulations observed in a pandemic context.

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CRITERIA FOR OPTIMIZING A ROAD NETWORK

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ABSTRACT

Cost-benefit analysis (CBA) is the most widely used tool for appraisal of transportation infrastructure projects, but there isn't generalize guidelines about its implementation, there can be found different approaches that suit the perspectives of each evaluating entity. This document, it shows three different guidelines that used in practice for transportation infrastructure projects, in which there are some different costs and benefits considered informing decision makers about the project appraisal. The costs and benefits with market values have been the predominant ones in the CBA, but there is a transition to use without market values, however, there are no generalized methodologies, so more research will be needed.

1. INTRODUCTION

The constant growing world population causes a greater demand for transport infrastructure that are pressured by the increase in users, causing the need for improvements or new infrastructure projects, the problem is limited financial resources (Jones et al., 2014).

Efficient transport infrastructures are essential for the proper financial and social functioning, helping to increase productive capacity and promoting development; their economic impact can be transformative, in particular for those with a low income level (Feick & Roche, 2013; Younis, 2014).

In the last decades, studies have been carried out on the social impact of having access to mobility, with topics such as the role of transport in social exclusion, the importance of accessibility, the interface between social capital and transport, the effect of transport on human well-being and how it influence the actions of decision makers in a region (Lowe et al., 2018).

Transport infrastructures are key in ensuring the accessibility of passengers and goods, helping to shorten distances and time. The other side of the coin is the negative effects such as the investment, becoming physical barriers, the congestion and noise. Active planning minimize negative externalities and enables the shift towards a sustainable transport infrastructure, which is necessary to steer development in a better direction (Banister, 2011; Koglin & Rye, 2014; Meunier et al., 2014).

Countries invest in transport projects as new infrastructure, upgrade, maintenance or repairs to the transport network. The common denominator among these types of projects is that they are the outcome of public sector decision-making at different levels of government and, sometimes, at the international level. Despite the important technical and economic dimension, investments in transport infrastructure may represent partial political statements of objectives, prioritization of financing and target users (Berechman, 2009).

The ability to choose the best projects according to transportation needs, relies on the quality of data used, the tools for its evaluation and choose the correct variables that lead to guidelines for solving public management problems of decision making (Broniewicz & Ogrodnik, 2020).

The term transportation project evaluation is used to describe the formal procedure for determine the net social benefit of different transport project alternatives that may be of different nature, objectives, costs and benefits (Berechman, 2009). To get an idea about whether planning is heading towards a correct development, different tools and models help to analyze transportation projects in order to estimate their benefits in monetary terms (Laird & Venables, 2017), there is an increase interest in knowing the benefits of a more social nature (Johansson et al., 2017).

Within the European context, the most used tool for the evaluation of transport projects is the Cost Benefit Analysis (CBA), in which it is very clear the variables to be used when it comes to direct impacts that are easily translated into monetary terms, but not much with indirect impacts where there are no market values available. The Multicriteria Analysis (MCA) is an alternative that can use variables without market value, is being used to a greater extent as a complement, or as a comparison in the evaluation of projects with the CBA (Bristow & Nellthorp, 2000).

This document intends to show the costs and benefits taken into consideration in three different contexts, making known the actuality of centralized guidelines of the CBA for transport infrastructure projects, as it is the most used tool to evaluate projects and thus know possible areas of opportunity for improvement or updating.

2. EUROPEAN CONTEXT

The transport infrastructure for the European Union (EU) is essential since it is a single market, so it must have a solid transport network that links its members, without it the internal market would be affected. For this reason, all levels of government have addressed the resolution of the dilemma that exists between policies that promote economic growth and consequently the generation of more transportation infrastructure projects and environmental policies that require reducing environmental impact (Villa et al., 2020).

The global economic recession has affected investment in transport infrastructure since 2008, the percentage of the Gross Domestic Product (GDP) allocated to infrastructure projects is at the bottom, that remember the limited resources despite current transportation needs (OECD, 2019).

Investments have focused on improving the quality of transport, accessibility, mobility and safety, while covering the demand (European Commission, 2014). Despite limited resources and the need to allocate them in the best way, it has been shown that project evaluation tools have had little relevance during the decision-making process and are often seem as tedious obstacles to get the investment required for the project (European Parliament, 2019). Another problem is the enthusiasm in the CBA, the evaluator may be too optimistic about key parameters of the project, causing the projected benefits to be less or impossible to meet (ECA, 2018).

Country	CBA	MCA	QM	QA	NA
Austria	x	x	x	-	-
Belgium	x	-	x	-	-
Cyprus	x	x	-	x	-
Czech Republic	x	x	-	-	-
Denmark	x	-	-	-	-
Estonia	x	-	-	-	-
Finland	x	-	x	-	-
France	x	-	-	-	-
Germany	x	-	-	x	-
Greece	x	-	-	x	-
Hungary	x	x	-	-	-
Ireland	x	-	x	x	-
Italy	x	-	-	-	-
Latvia	x	-	-	-	-
Lithuania	x	-	-	-	-
Malta	x	-	-	-	-
Netherlands	x	-	x	-	-
Poland	x	x	-	-	-
Portugal	x	-	-	-	-
Slovak Republic	x	x	-	-	-
Slovenia	x	-	-	-	-
Spain	x	x	-	-	-
Sweden	x	-	-	-	-
Switzerland	x	x	-	-	-
UK	x	x	x	x	-
Total	25	9	6	5	0

Table 1: Type of analysis by country in road project appraisal. Ref: Adapted from (Odgaard et al., 2005)

The role of the tools for project evaluation is inform to decision makers about relevant data, in this way it will be possible to prioritize projects from the same program, choose the best solution alternative for a problem, know the social benefits of the project and above all choose if it is the right time to make the investment.

The most common tool of evaluation in the EU member states are the CBA and MCA, in some cases the CBA is complemented with the MCA to get a quantitative or qualitative evaluation to include other impacts that are not monetized for technical reasons or policies (Bristow & Nellthorp, 2000).

In 25 European countries, table 1, the most used types of analysis for the evaluation of road transport projects are: CBA, MCA, Quantitative Measures (QM), Qualitative Evaluations (QA) and Not Available (NA) (Odgaard et al., 2005):

Transportation contributes to economic growth that enables a global market, but it also gives rise to externalities, some of which can be expressed in monetary terms. External costs (externalities) are the effects imposed on society, in contrast to benefits, not assumed by the users of the infrastructure and, therefore, not considered in the decision-making process. Internalizing these costs means making such effects part of the decision-making process, using market-based instruments is considered an effective way of limiting the negative side effects of transportation (European Commission, 2019).

(Odgaard et al., 2005) mentions certain effects that are used within the European scope being;

- Infrastructure costs: construction costs, system operation and maintenance costs.
- Benefits for the user: time savings in passenger transport, vehicle-operating costs, benefits for freight traffic.
- Externalities: security, noise, air pollution (local - regional), climate change.
- Also; user charges, revenue and construction disruptions.

According to (Odgaard et al., 2005) in 25 European countries the CBA is used to a greater extent according to the type of element to be evaluated, which is complemented with another type of analysis. Table 2, shows the distribution of analysis used in the countries of the study, it can be seen that the countries mostly use the CBA for purely convertible effects to monetary terms:

Effects	CBA	MCA	QM	QA	NA
Construction Cost	25	4	1	1	0
Disruption from construction	10	1	0	6	11
System operating cost and maintenance	24	4	2	2	0
Passenger transport saving	24	4	3	2	0
User charges and revenues	17	1	1	3	6
Vehicle operating costs	23	4	1	0	2
Benefits to goods traffic	17	2	1	1	8
Safety	24	4	3	1	0
Noise	13	3	7	8	3
Air Pollution - Local/Regional	14	2	5	7	3
Climate change	8	1	3	7	10

Table 1: Type of analysis by effect. Ref: Adapted from (Odgaard et al., 2005)

In 2016, total external costs in EU countries amounted to €726 billion and congestion costs to €271 billion with a total of €987 billion, representing 6.6% of GDP. Road transport is the mode with the highest impact on external costs, accounting for 83%, when including aviation and maritime modes; 97.5%, when excluding them. Considering accidents, congestion, climate change, air pollution, environmental damage and noise (European Commission, 2019).

3. COST-BENEFIT ANALYSIS

CBA is a technique developed in the field of economics, mathematics, statistics, and operations research, which seeks to provide guidance to decision-makers on the formulation of public policies (Nilsson et al., 2008).

The CBA was the first formal economic evaluation method to be applied to potential projects with the impetus of selecting more rational investments that represent better value for money. The CBA through indicators shows a comparative description of the potential costs and benefits of the project, indicating its economic contribution to society, as well as to the project's investors. Currently, during the analysis not only the cash flow is considered but also the economic, environmental and social impacts, both positive (benefit) and negative (costs), quantified in monetary terms adjusted for the present value of money (Dimitriou et al., 2016).

The CBA is the dominant method in the economic evaluation of projects since the 1970s (Macharis & Bernardini, 2015). Despite its wide use, there is still no universal standard CBA model, each organization or country defines its own specific requirements for evaluation, although with similar criteria (Vickerman, 2017).

The methodological advantages of using the CBA are; it carries the improvement of the evaluation since out under the same scenarios and impacts. Decision makers have more complete information to appraise the projects according to its effects, however, it should be taken into consideration that the information might be incomplete or of poor quality, which may cause the decision taken not to be the best one. The CBA can be a good discussion platform for those involved in economic research, design and planning of infrastructure, improving the quality of information for decision-making, helping to support final decisions. Among the negative points, the CBA lacks transparency for the final reports to society, as well as its difficulty to worth environmental impacts without market value. Although it may seem to have few negative points, the area of work is controversial and of great economic impact (Annema et al., 2007).

4. REVIEW OF CBA GUIDELINES

This section provides the costs and benefits that are included in the CBA guidelines by government agencies for the evaluation of transport projects, as a tool to support decision making in road projects, which are: CBA Guide for EC, United States (US) and New Zealand (NZ) investment projects.

4.1 The CBA Guide for transport investment projects of the EC

The CBA Guide of Investment Projects (CBA Guide) for transport projects for the EU aims to provide guidance on the common rules for the European-wide use of the BCA for large projects, referring to works, with a total cost of more than 50 million Euros. Having the intention to ensure; the improvement in the movement of people and goods in order to obtain better accessibility, mobility and safety, improving the quality and safety of infrastructures; better linkage between EU member states, promoting the single market and meeting transport demand, developing transport infrastructures and improving transport services; promote national or regional economic development by investing in newly created, extended or linked infrastructures (European Commission, 2014).

4.2 The U.S Department of Transportation's CBA Guide for Investment Projects.

The application of the CBA in highway projects is to ensure that funding is directed to projects that contribute to the economic growth of the users and the nation as a whole. Through an efficient transportation system, requiring repairs, expansions and modernizing aging facilities but also new projects to ensure that they continue to meet the needs of the population and the marketplace. (USDOT, 2018).

4.3 The N.Z. Transportation Agency's CBA Guide.

The purpose of applying CBA to highway projects is to establish a quality transportation system that promotes the well-being and livability of society through new, upgrade or extension of road projects. The CBA should identify economic effects (including social and environmental) in decision-making, whether or not it can be quantified, establishing consistency, transparency and compatibility between activities to help assess their economic efficiency (NZ Transport Agency, 2020a).

	EC	US	NZ
Transport mode	General	Road	Road
Discount rate (%)	3 - 5	7	4
Economic performance indicators	VAN, B/C, ERR	VAN, B/C	VAN, B/C
Decision indicator	VAN	VAN, B/C	B/C
Time horizon (years)	Up to 30	Upgrade: 20 New project: 30	Up to 40
Risk assessment	Sensitivity (Monte Carlo)	Sensitivity (Monte Carlo)	Sensitivity (Monte Carlo)

Table 2: Guideline’s summary. Ref: Own elaboration with data from (European Commission, 2014; NZ Treasury, 2015; USDOT, 2018)

4.4 Review of stages in the application of the CBA

The reviewed guidelines have a similar structure, although they differ in the number of steps in which their application is applied, it can be divided into 3 stages:

- Determination of the project: Describes the context of the project, establish the objectives, introduce the alternatives and define the base case for measure the incremental cost and benefits.
- Identification of costs and benefits: Costs and benefits are identified with/without market prices, usually divided into financial and economic analysis, discounted over the analysis time horizon to obtain the project's performance indicators.
- Analysis of results and report: The results are analyzed and the alternatives ranked. A report is prepared showing the results of the CBA in which the project's performance indicators are shown, as well as the data used to obtain them.

4.5 Financial analysis

4.5.1 Investment Costs

- EC: It is recommended to present both total project cost and unit value, infrastructures should be shown separately to allow comparative assessment and include all works necessary for their operation, land cost (property) and environmental protection costs (European Commission, 2014).
- US: The capital cost of a project is the sum of the monetary resources required to carry out the project, including, direct construction costs, capital costs, planning costs, project design, environmental reviews, land acquisition, utility relocation, or transactions to secure financing (USDOT, 2018).
- NZ: These are the costs required for the planning, analysis and delivery of the transportation infrastructure. Costs include any contingencies in the estimation of infrastructure costs, which may cause a cost overrun (NZ Transport Agency, 2015).

4.5.2 Operation and Maintenance costs

- EC: Operation and maintenance (O&M) cost can be grouped into the following categories; infrastructure operation, service operation, service management, routine maintenance and periodic maintenance. In the financial analysis, they are estimated in on-project and off-project scenarios (European Commission, 2014).
- US and NZ: Transportation facilities require continuous O&M to provide adequate service, maintain assets in operating condition and its costs should be included throughout the analysis period and should be directly related to the proposed project service plan (NZ Transport Agency, 2015; USDOT, 2018).

4.5.3 Revenue projections

- EC: Revenue projection are the product of the charges applied to users for access to the infrastructure, which are estimated based on: traffic volume forecast, projection of changes in the tariff system, pricing policy, traffic forecast for each projection of the tariff system and subsidy projection. In case the operating cost is not fully covered, the gap must be filled with other sources to avoid service closure (European Commission, 2014).
- US: Revenues from user charges (tolls, taxes, etc.) for the right to access transportation infrastructure, are an important source for public agencies to finance the operation of the infrastructure. These revenues cannot be considered "benefits" of the infrastructure, taking them would mean a double counting of the benefits, since the user chooses to pay for greater security, less travel time or operating costs (Lawrence et al., 2014).
- NZ: A comparison of the costs incurred in the transport infrastructure with the revenue is made to determine the financial viability of the project. The existing gap, if any, is determined by testing the funding gap values until the sum of the present value of the net annual cash flows is zero (Wallis et al., 2013).

4.6 Economic analysis

4.6.1 Travel time

- EC: Travel time savings can be derived from the construction of new or improvement of existing transport infrastructure, tell apart between work and non-work travel time estimation (European Commission, 2014).
- US: Estimated travel time savings will depend on engineering calculations and their effects on the operations of the improved infrastructure and the local area transportation network. These improvements can reduce travel time for drivers and passengers, including both in-vehicle time and waiting time (USDOT, 2018).
- NZ: Productivity and utilization of the network are related to the efficient use of the land transport network, seeking to optimize it instead of maximizing its use. The monetization of network productivity is measured through changes in travel time and financial costs of transport use (NZ Transport Agency, 2020a).

4.6.2 Vehicle operating costs

- EC: Vehicle operating costs are defined as costs borne by vehicle owners to operate vehicles, including fuel consumption, lubricant consumption, tire deterioration, repair and maintenance costs (European Commission, 2014).
- US: Operating cost savings commonly result from improved transportation infrastructure projects, resulting in lower fuel consumption and other operating costs (USDOT, 2018).

4.6.3 Accidents

- EC: Transport activities involve a risk to users of suffering an accident, because of mechanical failure or, more commonly, due to the influence of human error (European Commission, 2014).
- US: Transportation infrastructure improvements help to reduce the likelihood of death, injury, and property damage by reducing the number of crashes and / or their severity (USDOT, 2018).
- NZ: There are three variables, the first is the "social cost of death and serious injury" which includes the cost to the user, the cost to the health system and the costs of delay in the network. It considers loss of life, production, incapacitation, legal costs and property damage. In accidents, not only the user is impacted, but also the family and friends who may be affected by the accident. The second is "System safety", which focuses on investment aimed at improving system safety. The third is "Perception of safety and security", physical attributes such as lighting, safety cameras and speed controls that enhance the feeling of safety (NZ Transport Agency, 2020a).

4.6.4 Noise

- EC: Noise pollution can be defined as "unwanted external sound that has negative effects on human health". Noise emissions have a local impact, relating the magnitude of the effect to the location of the infrastructure, vibrations affect the quality of life and the productions of certain goods (European Commission, 2014).
- US: Noise pollution is caused by high levels of ambient sound that cause annoyance, distraction, or harm to people and animals. The US Department of Transportation doesn’t have a reliable means of estimating the public value of noise reductions (USDOT, 2018).
- NZ: Noise and vibration have significant effects on human health, mainly with sleep disruption and stress. Humans are sensitive to vibration and noise, which can come from the construction, operation, maintenance and use of land transport infrastructure (NZ Transport Agency, 2020a).

4.6.5 Air pollution

- EC: Transport investments can significantly affect air quality, reducing or increasing the level of pollutant emissions, having harmful effects on health, causing damage to infrastructure and impacts on nature (European Commission, 2014).
- US: The economic damages caused by exposure to air pollution are borne by society rather than by travelers and transportation operators that generate those emissions. Transportation projects can reduce overall fuel consumption and thus can produce climate and other environmental benefits (USDOT, 2018).
- NZ: The effects of air emissions from road transport that impact human health are monetized by assigning a cost to each tonne of pollutant as a proxy for the harm caused to people exposed to air pollutants (NZ Transport Agency, 2020a).

4.6.6 Climate change

- EC: Economic cost of positive or negative variations in Greenhouse Gas (GHG) emissions, the main emissions are carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4). These emissions contribute to global warming, therefore, it has a global impact and the related cost does not depend on the location of the investment (European Commission, 2014).
- US: GHG emissions have long-lasting even intergenerational impacts, unlike all other benefit categories (USDOT, 2018).
- NZ: Road transport is the largest contributor to emissions, the number of vehicles emitting GHGs emissions should be identified, get their fuel consumption and thus emissions can be monetized (NZ Transport Agency, 2020a).

4.6.7 Benefits to existing and additional users

- US: The main benefits of a project will arise in the "market" that the project would improve, with its users experiencing them directly. Users attracted by the improvement are willing to pay less for use it than the original users (USDOT, 2018).
- NZ: User experience can include comfort, simplicity, convenience, crowding, travel time and network condition (NZ Transport Agency, 2020a).

4.6.8 Loss of emergency services.

- US: Transportation projects can help to reduce the frequency of emergency service delays, generating benefits by reducing damages caused by delay (USDOT, 2018).

4.6.9 Modal diversion

- US: Improvements in transportation infrastructure or services may attract additional users of alternative routes or modes of transportation, it is challenging to capture the impacts of such modal shift within CBA and should be carefully examined to ensure that such benefits are correctly calculated within the analysis (USDOT, 2018).

- NZ: It is critical to know the variables that may encourage or discourage a user from selecting a transport mode. The user assigns a value to options, i.e., the value to individuals or groups of knowing about or having transport mode options available, even if they are not used (NZ Transport Agency, 2020a).

4.6.10 Work zone impacts

- US: A common example of "downsides" associated with transportation projects is impacts during construction or maintenance activities, such as delay due to traffic, increased insecurity, and vehicle operating costs (USDOT, 2018).

4.6.11 Agglomeration economies

- US: Transportation infrastructure improves connections between communities, people and businesses by reshaping the economic space of a region. The economic theory of agglomeration suggests that firms and households enjoy positive benefits from the spatial concentration of economic activity. These benefits can stem from a more efficient exchange of information and ideas, access to larger and more specialized workforce (USDOT, 2018).
- NZ: Changes in productivity result from of agglomeration, where scale and spatial concentration enables an increase of productivity by enabling a better learning, bonding and economic exchange (NZ Transport Agency, 2020a).

4.6.12 State of good repair

- US: These are the project benefits while replacing, repairing, or improving existing transportation assets to bring them to a state of good repair. These are generally captured by cost and benefit factors, such as maintenance, asset repair costs, improved safety, improved reliability, and service or facility quality (USDOT, 2018).

4.6.13 Resilience

- US: Incorporating resilience benefits requires an understanding of the expected frequency of each stressful event and its economic impacts on infrastructure (USDOT, 2018).
- NZ: These are system vulnerabilities and redundancies, are about reducing the risk of exclusion of communities from social and economic opportunities due to system disruptions. These may also relate to the preparation of solutions to ensure that the economic and social needs of communities are met (NZ Transport Agency, 2020a).

4.6.14 Quality of Life

- US: Transportation projects can provide benefits that improve quality of life but are difficult to monetize; these can be as varied as improved pedestrian connectivity, increased accessibility to remote communities, and other localized amenities. Quantifiable data on impacts should be provided, focusing on the changes expected to be generated by the transportation improvement project itself (USDOT, 2018).

- NZ: The impact of transport mode on physical and mental health is related to users' transport mode choice which is associated with the adoption of active modes (NZ Transport Agency, 2020a).

4.6.15 Increased in property values.

- US: Transportation projects improvements can increase the accessibility or improve the attractiveness of land parcels near infrastructure, resulting in increased land values (USDOT, 2018).
- NZ: The role of the transportation system is enabling and maintaining the normal functions of a community, with others or areas of the same community that due to a lack of transportation infrastructure may suffer a disconnection with the rest of the community (NZ Transport Agency, 2020a).

4.6.16 System reliability

- NZ: Comprises the user being able to have on a similar travel experience on the transport system each time with the same travel conditions (NZ Transport Agency, 2020a).

4.6.17 Employment

- NZ: An important impact of transport infrastructure is job creation, not referring to the direct or indirect employment produced by its construction. New or improved infrastructure can make it easier for people to get to work faster and can reduce the discouragement effects on workers by reducing travel times, which increases worker performance (NZ Transport Agency, 2020a).

4.6.18 Imperfect competition

- NZ: As transportation infrastructure improves, output increases in sectors where there may be differences between the price of the product and its marginal cost. Conventional CBA assumes economic sectors operate in perfect competition, where the prices are equal to its marginal costs. However, since there is a margin between price and cost, there is a gap between gross hourly labor costs and the market value of what is produced in that hour (NZ Transport Agency, 2020a).

4.6.19 Regional economic development

- NZ: There is an increase in gross domestic product or gross national income and a change in demand for goods and services (NZ Transport Agency, 2020a).

4.6.20 Water pollution

- EC: Pollution of water bodies occurs by discharging pollutants directly or indirectly without adequate treatment, affecting seriously the water quality, biodiversity and society (European Commission, 2014).

- NZ: Transport infrastructures during their life cycle can have a major impact on water flow and its quality, having short or long term effects, impacting the natural or artificial environment (NZ Transport Agency, 2020a).

4.6.21 Impact on soil and biodiversity

- EC: The presence of chemicals or soil disturbance due to industrial activity or improper waste disposal has long-term social and economic effects on society (European Commission, 2014).
- NZ: Biodiversity is fundamental to the existence of life, as people, animals and other organisms depend on it. Natural resources underpin the economic and social area of our society, during the different stages of the life cycle of transport infrastructures impact biodiversity (NZ Transport Agency, 2020a).

4.6.22 Resource Efficiency

- NZ: Sustainable use of resources, materials and reduction of environmental damage can be achieved by minimizing waste by using green energy and monitoring the carbon footprint generated (NZ Transport Agency, 2020a).

4.6.23 Access to opportunities

- NZ: Transport can function as an enabler and integrator of land use, focusing on the importance of destinations, services and activities that can be equitably accessed to enable economic and community participation (NZ Transport Agency, 2020a).

4.6.24 Heritage and cultural values

- NZ: Cultural values can be closely related to heritage values, the former are physical and can be expressed in monetary terms, the latter are based on perceptions and are not so easily expressed in monetary terms. Cultural values are considered both tangible and intangible benefits. The historic environment is important for health and well-being, playing an important role in urban development and in generating economic activity (NZ Transport Agency, 2020a).

4.6.25 Impact on landscape

- EC: This is the loss of recreational or aesthetic value and not only for rural environments, also there may be urban areas that may be affected (European Commission, 2014).
- NZ: The relationship between people and landscape can be explained as a reflection on their relationship (NZ Transport Agency, 2020b).

4.6.26 Urban landscape

- NZ: It is the constant changes in the urban environment, its form and character that generate an identity (NZ Transport Agency, 2020b).

Variable	EU	Methodology	US	Methodology	NZ	Methodology
Investment costs	✓	✓	✓	✓	✓	✓
Operation & Maintenance costs	✓	✓	✓	✓	✓	✓
Revenue projections	✓	✓	✓	X	✓	✓
Travel time	✓	✓	✓	✓	✓	✓
Vehicle operating costs	✓	✓	✓	✓		
Accidents	✓	✓	✓	✓	✓	✓
Noise	✓	✓	✓	X	✓	✓
Air pollution	✓	✓	✓	✓	✓	✓
Climate change	✓	✓	✓	✓	✓	✓
Benefits to existing and additional users			✓	✓	✓	✓
Loss of emergency services			✓	✓		
Modal diversion			✓	✓	✓	✓
Work zone impacts			✓	X		
Agglomeration economies			✓	X	✓	✓
State of good repair			✓	X		
Resilience			✓	X	✓	X
Quality of life			✓	X	✓	X
Increase in property value			✓	X	✓	✓
System reliability					✓	✓
Employment					✓	✓
Imperfect competition					✓	✓
Regional economic development					✓	X
Water pollution	✓	X			✓	X
Impact on Soil and biodiversity	✓	X			✓	X
Resource efficiency					✓	X
Access to opportunities					✓	X
Heritage and cultural values					✓	✓
Impact on the landscape	✓	X			✓	✓
Urban landscape					✓	✓

Table 3: Cost and Benefits in CBA Guidelines. Ref: Own elaboration with data from (European Commission, 2014; NZ Transport Agency, 2020a; USDOT, 2018)

5. CONCLUSIONS

During the evaluation of projects in the part of the economic analysis may be have difficulties in valuing variables (without market values) that can be easily identified. Despite the difficulties there has been significant progress in integrating them into the economic analysis process of the CBA, there are no methodologies for its analysis but given the importance of these variables to be considered in transportation infrastructure projects, future research still needs to be done in the area. Improvements in the CBA and its evaluation guidelines contribute to better informed decisions and investment, hence the importance to interpret these terms into more useful terms for decision makers.

Table 4 shows the costs and benefits of the guidelines reviewed. The EC, US and NZ columns represent the guidelines by country and the Methodology column represents the existence of guidelines to analyze the cost or benefit by country. In the European case, the costs and benefits have market values, or are easily converted, to avoid the calculation having multiple methodologies that may hinder the evaluation in the possible case of needing EC resources to finance the project. In the U.S. case, some costs and benefits without market value are mentioned, encouraging the evaluator to use their own method with caution and relying on projects carried out previously. The New Zealand case has a greater consideration of non-market value costs and benefits, which they intend to integrate in their CBA, encouraging the evaluator to develop their own method for the time being, but mentioning that a centralized methodology will be provided in future editions of the manuals.

The guidelines reviewed have a similar structure in the application of the CBA, so it can be said that are guidelines with a classic CBA core, differing in the types of costs and benefits taken into account. An important consideration is the update of the guides, NZ (2020) and US (2018), while the last update of the CBA Guide is from 2014 with the experience gained in the previous policies goals, it is expected that there will be a next update that studying at great length the impacts of difficult monetization, given the beginning of the new stage of the EC cohesion policies.

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DISEÑO DE UN ENFOQUE COLABORATIVO PARA LA EVALUACIÓN DE POLÍTICAS DE TRANSPORTE DESTINADAS A MEJORAR LA CALIDAD DEL AIRE EN EL CENTRO DE LAS CIUDADES

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RESUMEN

Las políticas de transporte para mejorar la calidad del aire se aplican cada vez más en los centros urbanos de todo el mundo. A pesar de que la eficacia de estas políticas se encuentra notablemente afectada por una fuerte controversia social, no se ha aprovechado en su totalidad el rol que pueden desempeñar los stakeholders a la hora de identificar posibles impactos así como potenciales estrategias de implementación. Esta investigación ha permitido la evaluación por parte de stakeholders de un conjunto de medidas de transporte para mejorar la calidad del aire. La ciudad de Madrid (España), donde existe una clara intención de reducir el tráfico en su zona centro, ha servido como caso de estudio. Stakeholders locales participaron en una serie de entrevistas semiestructuradas y en un workshop final de manera presencial para evaluar impactos potenciales, aceptabilidad y viabilidad de ocho medidas de transporte. Los resultados muestran dos grupos diferenciados: por un lado, participantes de instituciones públicos y movilidad sostenible; y por otro lado, participantes con relación con el comercio, logística y servicios de movilidad compartida. La mayor dificultad a la hora de encontrar un consenso se estableció en tres medidas de transporte:

- restricciones por número de matrícula
- cobros por tipo de motor
- desarrollo de infraestructura peatonal y ciclista.

Este artículo describe el proceso metodológico, indicando la utilidad de la participación de los stakeholders en el proceso de creación de políticas y concluye con una discusión sobre la aceptabilidad de las medidas de transporte en el contexto local de Madrid.

1. INTRODUCCIÓN

La fuerte relación entre el transporte y la vida diaria de las ciudades requiere de un enfoque más amplio en el planeamiento del transporte. De esta manera, se deben conectar lugares y actividades espacialmente dispersas y, a su vez, encontrar formas de reducir los impactos ambientales del transporte (Bertolini, 2017). En el largo plazo, está aumentando el consenso sobre la necesidad de integrar políticas para conseguir el transporte futuro deseado a nivel ciudad (compactación urbana, tecnologías verdes, etc.) (Hickman, Saxena, Banister, & Ashiru, 2012; Soria-Lara & Banister, 2008). A corto plazo, la implementación de medidas de transporte específicas para mejorar la calidad del aire (Transporte Policies for improving Air Quality, TPAQ) en el centro de las ciudades está ganando importancia en las últimas décadas. Estas TPAQ están fundamentalmente enfocadas a reducir el tráfico motorizado, si bien su tipología y características varían en función de las peculiaridades de la ciudad, sus normas culturas y sus objetivos específicos (Kelly et al., 2011; Polichetti, 2017; Ramos, Cantillo, Arellana, & Sarmiento, 2017; Wen & Bai, 2017). Ejemplos de TPAQs los encontramos en las restricciones por número de matrícula, las cargas por tipo de motor, la promoción de la movilidad compartida, las restricciones temporales de tráfico, etc.

La controversia social ocasionada por estas TPAQs es normalmente alta, afectando a su aceptabilidad y a su viabilidad. Sin embargo, las investigaciones previas han prestado limitada atención a estudiar la influencia de los stakeholders en los procesos ex ante de evaluación de impactos y aceptabilidad de dichas medidas. La mayoría de estudios han sido dirigidos a analizar ex ante y ex post los efectos de una única medida o un reducido número de ellas frente a objetivos ambientales, económicos y sociales (Mohan, Tiwari, Goel, & Lahkar, 2017; Moncada, Bocarejo, & Escobar, 2018; Pucher & Buehler, 2008; Szarata, Nosal, Duda-Wiertel, & Franek, 2017; Zhang, Chen, Wang, Huang, & Wang, 2017). El reto que debe afrontar la planificación del transporte se basa en la aparición de enfoques colaborativos basados fundamentalmente en la participación e interacción de los stakeholders (Le Pira, Marcucci, et al., 2017). Esto significa una reorientación que busque el consenso a través de la discusión entre stakeholders y ámbitos profesionales (Willson, 2001). Cascetta, Carteni, Pagliara, and Montanino (2015) señalan tres acciones clave para activar este cambio en el campo del planeamiento del transporte:

- identificación y modelización de impactos relevantes para stakeholders y responsables políticos
- procesamiento y presentación de los resultados obtenidos para los no expertos
- y uso de métodos mixtos (cualitativos y cuantitativos) para involucrar al máximo rango de stakeholders. Esta situación es de especial interés cuando se implementan políticas controvertidas, por lo que los TPAQs en el centro de las ciudades son un buen ejemplo de ello.

Sobre la base de estas cuestiones, se ha identificado una brecha de conocimiento en los estudios académicas sobre la evaluación de los efectos de las medidas de transporte para mejorar la calidad del aire en los centros de las ciudades y la participación de stakeholders. La resolución de esta brecha de colaboración puede ayudar a implementar de una manera más viable y efectiva diversas políticas de actuación.

Así, las TPAQ pueden ver aumentada su credibilidad como parte de un objetivo colectivo donde diferentes actores de la sociedad pueden deliberar y exponer sus puntos de vista sobre la viabilidad, aceptabilidad y efectividad, promoviendo un proceso de decisión más inclusivo e igualitario.

Este artículo presenta un marco de evaluación colaborativa para evaluar ex ante un total de ocho TPAQs (restricciones por tipo de motor; restricciones por número de matrícula; restricciones por límite de velocidad; cargas a vehículos por tipo de motor; desarrollo de infraestructura peatonal y ciclista; ayudas económicas para la renovación de la flota de vehículos; promoción de la movilidad compartida; y desarrollo de infraestructura de transporte público). La evaluación ex ante abarca los impactos potenciales derivadas de la implementación de los TPAQs (tanto de manera general como de manera específica para sectores concretos), su aceptabilidad, y posibles estrategias de implementación para incrementar su efectividad y viabilidad.

La ciudad de Madrid (España), donde existe una clara intención gubernamental de restringir el tráfico motorizado en la zona centro, ha sido utilizada como caso de estudio. El marco de enfoque colaborativo ha sido designado de acuerdo a tres aspectos innovadores:

- un proceso bottom-up, en el cual los stakeholders determinar tanto los impactos relevantes que pueden originarse por la aplicación de las medidas en el centro de la ciudad de Madrid como estrategias potenciales de implementación para incrementar su aceptabilidad, viabilidad y efectividad
- un proceso colaborativo en dos etapas, que comienza con entrevistas semiestructuradas y finaliza con un espacio de diálogo abierto llevado a cabo en un workshop final
- un proceso de aprendizaje, donde los participantes se conocen de manera presencial, promoviendo la transparencia y el conocimiento de las visiones colectivas sobre las TPAQs.

El equipo investigador ha actuado como director y observador en este proceso colaborativo, tomando distancia cuando ha sido necesario para facilitar el intercambio de opiniones e identificar los resultados de la investigación. El proceso ha contado con la participación de un total de 28 stakeholders locales de diferentes sectores afectados por la implementación de las TPAQs en la ciudad.

El capítulo 2 revisa la literatura previa relacionada con esta investigación. El capítulo 3 describe la ciudad de Madrid como caso de estudio. El capítulo 4 detalla el diseño de la investigación mientras que el capítulo 5 muestra los principales resultados obtenidos. Finalmente, el capítulo 6 cierra el artículo con las principales discusiones y observaciones finales.

2. REVISIÓN DE LITERATURA: EVALUACIÓN DE TPAQs

La adopción de un proceso de participación bottom-up para diseñar y evaluar políticas de transporte ha experimentado un rápido crecimiento durante las últimas décadas, encontrando ejemplos relacionados con el uso de la planificación de escenarios en el ámbito del transporte (Soria-Lara & Banister, 2017), el proceso de financiación de infraestructuras urbanas de transporte (Roukouni, Macharis, Basbas, Stephanis, & Mintsis, 2018) y la selección de las medidas políticas más adecuadas para la sostenibilidad (Hickman et al., 2012). Sin embargo, se ha dedicado escasa atención a evaluar TPAQs bajo escenarios colaborativos.

Para analizar esta brecha teórico-práctica de conocimiento, se ha realizado una revisión de literatura utilizando la base de datos de Scopus. Las palabras clave utilizadas durante la búsqueda han sido: políticas de calidad de aire, políticas de restricciones de tráfico y zonas de bajas emisiones. Esta revisión ha resultado en un creciente número de estudios en los últimos años centrados en llevar a cabo evaluaciones ex ante y ex post sobre efectos de TPAQs en la calidad del aire, el cambio de flota y el espacio público entre otros (Fatima & Moridpour, 2016; Invernizzi et al., 2011; Lu, 2016; Wang, Shao, Wang, & Sun, 2010; Xu & Ma, 2012). No obstante, la evaluación de impactos potenciales de dichas TPAQs a partir de la participación de stakeholders ha sido un tema fuera de los ámbitos de estudio frecuentes.

Un grupo relevante de los estudios consultados desarrolla evaluaciones ex post sobre efectos de las TPAQs ocurridos varios años después de su implementación. Estos estudios detallan principalmente impactos específicos de las medidas frente a los objetivos ambientales, económicos y sociales. Por ejemplo, Chowdhury et al. (2017) evalúa los impactos de las restricciones por número de matrícula sobre las concentraciones de $PM_{2.5}$ en la ciudad de Delhi (India). Jia, Zhang, He, and Li (2017) proponen un modelo teórico, basado en una encuesta, para estudiar la aceptación de los commuters y sus comportamientos frente a las restricciones por matrícula en Tianjin (China). La afección de las restricciones de tráfico sobre la concentración de PM_{10} en ciertas franjas horarias en Nápoles ha sido analizado por Polichetti (2017). Liu, Yan, and Dong (2016) han conducido una investigación diseñada para comparar y analizar los efectos sombre el cambio en los patrones de viaje generados por las políticas de restricción de coches en Beijing (China). Un último ejemplo lo podemos encontrar en el estudio de Kelly et al. (2011), quien evalúa la efectividad de la zona de bajas emisiones de Londres sobre la disminución de la concentración de contaminantes en la ciudad.

Un segundo grupo de estudios se centran en implementar evaluaciones ex ante para anticipar posibles efectos de la implementación de TPAQs. Los estudios consultados se basan en modelar y simular dichos efectos futuros de acuerdo a características socioeconómicas y variables de comportamiento de viaje. Tal y como se ha comentado, la participación de stakeholders en este grupo de estudios es muy limitada. Por ejemplo, Ramos et al. (2017) modela los efectos de sustituir las restricciones actuales por número de matrícula en Medellín (Colombia) por políticas de cobro ambiental. Zhang et al. (2017) trata de anticipar como las restricciones en Beijing (China) pueden impulsar un cambio modal desde los vehículos privados al sistema de metro. Wen and Bai (2017) usan un modelo dinámico para simular variaciones en el consumo de energía urbana y en los kilómetros recorridos por la población a través de la comparación entre diferentes TPAQs: restricciones por número de matrícula, restricciones por un sistema aleatorio y desarrollo de la infraestructura de transporte público. Otro ejemplo se puede encontrar en el estudio de Hanna, Kreindler, and Olken (2017), quienes simulan hasta qué punto las políticas de vehículos de alta ocupación podrían impulsar una reducción de la congestión del tráfico urbano en Yakarta (Indonesia).

En resumen, y a diferencia del conjunto de estudios mostrados anteriormente, este artículo proporciona una evaluación ex ante sobre los impactos potenciales, aceptabilidad y estrategias de implementación de varias TPAQs en el contexto de la ciudad de Madrid, usando una metodología colaborativa bottom-up que involucra a múltiples stakeholders de la ciudad.

3. CASO DE ESTUDIO: LA CIUDAD DE MADRID (ESPAÑA)

La ciudad de Madrid se encuentra en el centro geográfico de España. Su área metropolitana cuenta con aproximadamente cinco millones de habitantes en un área de 2.000 km^2. Dicho área metropolitana está formado por 27 municipios, siendo la ciudad de Madrid su centro. Desde los años 90, la población alrededor de la ciudad de Madrid ha iniciado un proceso de expansión geográfica, generando efectos relevantes en el transporte. Por ejemplo, el ratio de posesión de coches en Madrid (690 coches por cada 1.000 habitantes) es superior que la media española (500 coches por cada 1.000 habitantes). La mencionada suburbanización de residencia y empleo, así como el incremento de vehículos, ha originado nuevas tendencias de transporte. De hecho, de acuerdo con la encuesta de movilidad de Madrid, el número de viajes motorizados ha incrementado un 46% desde 1996 a 2014, con un incremento del 50% en la posesión de vehículos propios por vivienda, mientras que la población ha incrementado únicamente un 29% en el mismo periodo.

La red de carreteras de acceso a la ciudad de Madrid es muy amplia, con 10 autopistas (4 de ellas de peaje) conectando la ciudad de Madrid con los municipios del área metropolitana. Además, hay que destacar los cuatro cinturones que rodean la ciudad de Madrid (M-30, M-40, M-45 y M-50) siendo los dos primeros, por su carácter de anillo (interior M-30 y exterior M-40), los más importantes. El anillo interior, de 32 km de longitud, es utilizado mayoritariamente por vehículos de pasajeros mientras que el anillo exterior, de 64 km de longitud, tiene un gran porcentaje de tráfico pesado. Ambos presentan problemas de congestión durante las horas punta.

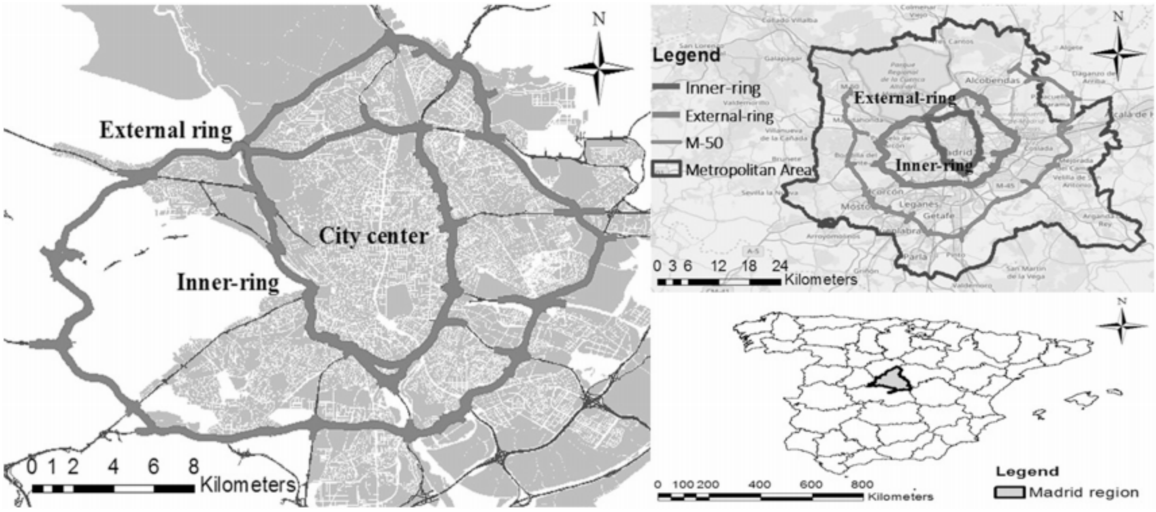


Figura 1: Localización del caso de estudio

La expansión de la población y el empleo ha provocado un aumento del uso del coche por parte de los viajeros que se dirigen desde municipios exteriores hacia el centro de la ciudad de Madrid. Hay aproximadamente 2 millones de viajeros diarios en el anillo interior. Esto ha generado efectos negativos en el medioambiente, especialmente en las emisiones de gases de efecto invernadero y en la emisión de contaminantes como NOx y PM. En algunos episodios, normalmente durante el otoño y el invierno, el anillo interior de Madrid ha superado los umbrales de salud establecidos por la Unión Europea.

Para solucionar este problema de salud pública, el gobierno local de Madrid ha implementado recientemente el Plan de Calidad del Aire “Plan A”, destinado a la mejora de la calidad del aire en el centro de la ciudad. Este Plan incluye un conjunto de TPAQs para reducir la congestión de tráfico en el anillo interior de Madrid.

A pesar de que el Plan A ha sido aprobado, la mayoría de sus políticas continúa bajo discusión debido a una alta controversia social. De hecho, se espera que la mayoría de sus políticas se modifiquen en los próximos años.

Bajo este contexto, es oportuno y conveniente llevar a cabo una evaluación ex ante involucrando a stakeholders en la evaluación de impactos potenciales de las TPAQs implementadas en el centro de la ciudad de Madrid (incluyendo impactos generales e impactos específicos para sectores particulares), en la aceptabilidad de las medidas y en las estrategias de implementación. De esta manera, la ciudad de Madrid es un excelente lugar para realizar esta investigación.

4. DISEÑO DE LA INVESTIGACIÓN: MARCO DE EVALUACIÓN COLABORATIVA

Para conseguir el principal objetivo del artículo, la evaluación ex ante de ocho TPAQs en la ciudad de Madrid a partir de la participación de stakeholders, se ha diseñado e implementado un enfoque de evaluación colaborativa en tres fases secuenciales:

- Identificación de TPAQs
- Entrevistas semi-estructuradas
- Espacio de diálogo abierto.

4.1 Fase 1: Identificación de TPAQs

El equipo investigador llevó a cabo una revisión de TPAQs basado en dos aspectos clave:

- TPAQs previamente implementados en otras ciudades del mundo (Méjico, Londres, Beijing, etc.) con diferentes niveles de efectividad, viabilidad y aceptación social
- TPAQs en línea con los objetivos locales de Madrid para mejorar la calidad del aire.

La revisión incluyó tanto estudios académicos como trabajos profesionales disponibles para su análisis. El proceso concluyó con un total de 43 referencias. Dichas referencias fueron analizadas en profundidad por medio de un análisis de contenido (Bryman, 2012), destilando tanto TPAQs previamente implementados en otros contextos como potencialmente aplicables en la ciudad de Madrid. Una descripción detallada del trabajo realizado analizando múltiples TPAQs en todo el mundo se presenta en Vassallo, Bueno, Ortega, Soria, & Tarriño (2018).

Se resalta que el objetivo de este estudio no es evaluar las TPAQs específicas implementadas por el mencionado PLAN A en Madrid, sino evaluar un mayor número de TPAQs potenciales alineadas y diseñadas de acuerdo a los objetivos de Madrid en cuanto a la calidad del aire. Así, las TPAQs seleccionadas pueden coincidir con algunas de las medidas incorporadas en el Plan A. Las 8 TPAQs seleccionadas para el estudio fueron (Tabla 1):

- restricciones por tipo de motor
- restricciones por número de matrícula
- restricciones del límite de velocidad
- cobros a vehículos de motor
- desarrollo de infraestructura peatonal y ciclista
- ayudas para el cambio en la flota de vehículos
- promoción de la movilidad compartida
- desarrollo de infraestructura pública de transporte.

Los stakeholders también fueron estimulados para añadir TPAQs durante el proceso participativo si lo consideraban necesario. Sin embargo, no fue propuesto ningún TPAQ adicional.

TPAQ	Descripción
Restricciones por tipo de motor	Restricción total a vehículos diésel y vehículos antiguos en el anillo interior de Madrid en 2020 afectando a vehículos de pasajeros y mercancías.
Restricciones por número de matrícula	Restricciones totales a vehículos según su número de matrícula (par o impar) en el anillo interior de Madrid afectando a vehículos de pasajeros y mercancías.
Restricciones del límite de velocidad	Reducción del límite de velocidad de 50 a 30 km/h en el anillo interior de Madrid y de 90 a 70 km/h en el anillo exterior afectando a vehículos de pasajeros y mercancías.
Cobros a vehículos de motor	Cobro variable a los vehículos en función de afección al medioambiente por su tipo de motor y en función de la congestión en la red del anillo interior de Madrid, afectando a vehículos de pasajeros y mercancías.
Desarrollo de infraestructura peatonal y ciclista	Desarrollo de infraestructura peatonal y ciclista adicional en el anillo interior de Madrid a costa de espacio actual dedicado al tráfico motorizado.
Ayudas para el cambio en la flota de vehículos	Subsidios locales y regionales para sustituir vehículos privados diésel y antiguos por vehículos con nuevas tecnologías tanto en vehículos de pasajeros como de mercancías. Estas ayudas provienen de impuestos a la ciudadanía.
Promoción de la movilidad compartida	Los vehículos de alta ocupación tienen preferencia para acceder al anillo interior de Madrid. En el caso del transporte de mercancías, se promueve un sistema colaborativo entre compañías para facilitar el reparto.
Desarrollo de infraestructura pública de transporte	Desarrollar infraestructura de transporte público en el anillo interior de Madrid a costa de espacio actual dedicado al tráfico motorizado.

Tabla 1: Descripción de las TPAQs seleccionadas

4.2 Fase 2: Entrevistas semiestructuradas

Un total de 28 stakeholders fueron seleccionados para participar, consiguiendo una matriz de expertos que asegura la retroalimentación de todos los actores clave potencialmente afectados por las TPAQs en la ciudad de Madrid. Entre estos sectores se encuentran los siguientes: instituciones públicas, sector de mercancías, comerciantes, ambientalistas, asociaciones de transporte público, autoridades de transporte, operadores de transporte público, asociaciones de taxi, etc. La lista completa de perfiles se presenta en el Apéndice 1.

Los participantes fueron entrevistados individualmente por el equipo investigador a través de entrevistas semiestructuradas, donde el entrevistador dispone de una serie de cuestiones generales que se formulaban con libertad para obtener aspectos más detallados ante respuestas significativas (Bryman, 2012). El trabajo empírico fue completado durante otoño de 2017.

Después de clarificar el rol de los entrevistados en el sector transporte (posición, intereses generales, etc.) cada entrevista semiestructurada constaba de cuatro bloques diferentes relativos a las ocho TPAQs previamente mencionadas. Para cada medida, los participantes fueron preguntados sobre sus opiniones en:

- impactos generales producidos por la TPAQ (ambientales, económicos o sociales)
- impactos específicos producidos por la TPAQ en su sector profesional
- aceptabilidad de cada TPAQ dentro del sector del entrevistado
- estrategias de implementación para conseguir una mayor aceptabilidad de dicha TPAQ (temporalidad, etc.).

Los stakeholders fueron animados a expresar libremente sus ideas y opiniones así como a añadir cualquier aspecto no incluido en la entrevista semiestructurada. Cada entrevista tuvo una duración aproximada de 40’-60’. La mayoría de encuestas fue realizada de manera presencial y, excepcionalmente, por teléfono. Todas las encuestas fueron guardadas para su posterior análisis.

Las entrevistas fueron analizadas mediante un proceso sistemático de transcripción individual, incluyendo codificación y varias rondas de interpretación de los códigos asociados con las ocho TPAQs de estudio. Se consiguieron un total de 1287 visiones independientes durante dicho proceso. Estas ideas fueron agrupadas en 540 códigos de acuerdo a los diferentes bloques de la entrevista semiestructurada:

- impactos generales
- impactos específicos por sectores
- aceptabilidad
- estrategias de implementación.

Por ejemplo, varias opiniones con un mensaje similar (reducción de contaminantes, aire más limpio) fueron agrupadas bajo el mismo código (mejora de la calidad del aire). El objetivo de esta fase metodológica fue obtener opiniones adicionales sobre los impactos de las TPAQs. Por lo tanto, los resultados obtenidos en esta etapa muestran percepcionesque son, por definición, subjetivas. Se creó una base de datos final para comparar las opiniones de las partes interesadas, incluyendo estadísticas descriptivas sobre consenso o desacuerdo con los distintos temas en función de la frecuencia y el contenido de las respuestas de las partes interesadas.

4.3 Fase 3: Espacio de diálogo abierto

El espacio de diálogo abierto se llevó a cabo mediante un workshop donde los participantes se conocieron en persona. Se centró especialmente en aquellas TPAQs donde existían discrepancias entre las opiniones recogidas por los participantes. De esta manera, se focalizó en la discusión de posibles estrategias de implementación que pudieran incrementar la aceptabilidad y viabilidad de los TPAQs analizados.

Los 28 stakeholders fueron invitados al workshop si bien finalmente 15 de ellos asistieron al mismo (Apéndice 2). El objetivo era la creación de un espacio donde los participantes tuvieran la oportunidad de conocer al resto, relacionarse y aprender de la visión de los demás. La posibilidad de escuchar diferentes valoraciones podría modular discursos y permitir incrementar las oportunidades de buscar soluciones en beneficio de todos. El workshop fue estructurado en dos partes:

- Parte 1: El equipo investigador presentó un resumen de los resultados obtenidos durante las entrevistas individuales. Esto facilitó la generación de nuevas visiones y reacciones por parte de los stakeholders. La duración de la primera parte fue de 25'. Se dedicó especial atención a aquellas TPAQs donde predominaba falta de consenso entre los participantes, explicando que dichas medidas constituirían el cuerpo del debate en la segunda y principal parte del workshop.
- Parte 2: Se centró exclusivamente en aquellas TPAQs con bajo consenso entre los stakeholders según los datos obtenidos de las entrevistas. Para cada TPAQ, el equipo investigador mostró tres posibles estrategias de implementación y los stakeholders debían elegir una de ellas mediante un voto anónimo. No se permitía la abstención. Seguidamente, los stakeholders debían responder si estaban o no de acuerdo con cada una de las tres estrategias de implementación mostradas por el equipo investigador, activando tres nuevas rondas de votación anónimas por cada TPAQ. Una vez realizado el recuento, se mostraron los resultados agregados y los stakeholders fueron animados a tener una discusión abierta sobre los resultados de la votación para alcanzar un consenso sobre la estrategia de implementación más poderosa para aumentar la aceptabilidad y la viabilidad de cada TPAQ. Tras ello, los participantes fueron estimulados a proponer nuevas estrategias de implementación si lo consideraban necesario. La duración de esta parte fue de aproximadamente 40' para cada TPAQ a discutir.

El equipo investigador, integrado por un total de 5 miembros, no tomó parte activa en el workshop, actuando 2 de ellos como moderadores y 3 de ellos como observadores. Los observadores tomaron notas durante el workshop, e cual también fue grabado para futuras consultas.

5. RESULTADOS

Este capítulo presenta los resultados obtenidos durante el marco de evaluación colaborativa, destacando el éxito conseguido mediante consenso entre los participantes sobre los posibles impactos de las TPAQs (tanto genéricos como específicos para sectores concretos), la aceptabilidad y las posibles estrategias de aplicación.

5.1 Resultados de las entrevistas semiestructuradas

Durante las entrevistas semiestructuradas, fueron registradas en la base de datos un total de 1287 visiones de los participantes referentes a los diferentes aspectos de la misma. Estos puntos de vista cubrían las ocho TPAQs incluidas en la investigación y fueron clasificados en los cuatro principales bloques de la encuesta:

- impactos generales
- impactos específicos
- nivel de aceptabilidad
- estrategias de implementación.

Posteriormente, se clasificaron en 540 códigos tras varias fases de codificación, agrupando puntos de vista similares bajo el mismo código. Las TPAQs que originaron un mayor número de opiniones fueron las restricciones por tipo de motor y el desarrollo de infraestructura peatonal y ciclista, mientras que las TPAQs con el menor número de códigos fueron las restricciones al límite de velocidad y las cargas a los vehículos de motor. Las disidencias se observaron fundamentalmente en las restricciones por número de matrícula, las cargas a los vehículos de motor y el desarrollo de la infraestructura peatonal y ciclista. Por esta razón, las tres TPAQs mencionadas fueron posteriormente incluidas en el espacio de diálogo abierto.

5.1.1 Identificación de impactos generales

El primer bloque de las entrevistas semiestructuras se centraba en la percepción de los stakeholders sobre la capacidad de las TPAQs de conseguir una mejora de la calidad del aire. De manera general, se observó un alto nivel de acuerdo entre los participantes en cuanto a la alta capacidad de la mayoría de las TPAQs para mejor la calidad del aire en el anillo interior de Madrid, con la excepción de las restricciones por límite de velocidad. De hecho, se considera que esta medida puede generar el efecto contrario y las emisiones podrían ser mayores tras su implementación.

El impacto de las ocho TPAQs en la congestión urbana de tráfico fue un tema frecuente de discusión entre los participantes. No existe un consenso sobre cuáles de las TPAQs resultarían efectivas para conseguir este objetivo. Si bien hubo consenso en la reducción de la congestión del tráfico si se aplicaban restricciones por tipo de motor y tasas a los vehículos de motor, se encontraron divergencias cuando se trataba de restricciones por número de matrícula, desarrollo de infraestructuras peatonales y ciclistas, y subvenciones para cambiar el parque de vehículos. En estos casos, los participantes del sector público afirmaron que los tres TPAQs mencionados contribuirían a reducir la congestión del tráfico en el centro de Madrid, pero los participantes del sector privado, específicamente los comerciantes, los taxistas y el sector de las mercancías, señalaron que estas medidas podrían incluso empeorar los niveles de congestión. Estos stakeholders también creían que las restricciones por número de matrícula aumentarían el ratio de posesión de vehículos privados, mientras que el desarrollo de infraestructura para peatones y ciclistas implicaría un número similar de vehículos circulando por calles de baja capacidad, lo que aumentaría la congestión urbana.

Finalmente, el impacto de las TPAQs en las desigualdades sociales fue otro tema recurrente entre los encuestados. En particular, se encontró un alto nivel de desacuerdo en las respuestas otorgadas sobre las restricciones por número de matrícula, los cobros a vehículos motorizados y el desarrollo de infraestructura peatonal y ciclista. Los participantes de instituciones públicas y los operadores de transporte indicaron que las restricciones por número de matrícula y el cobro de tasas podrían afectar enormemente a familias con bajos ingresos. Sin embargo, para los comerciantes, taxistas y sector de mercancías, el desarrollo peatonal y ciclista provocaría mayores desigualdades sociales ya que muchas personas se verían impedidas de participar en actividades diarias como consecuencia de las restricciones al coche.

5.1.2 Identificación de impactos específicos para cada sector

El segundo bloque de las entrevistas semiestructuras se focalizó en los impactos específicos generados por las TPAQs en cada uno de los sectores de trabajo. Los stakeholders estuvieron de acuerdo en el impacto neutro o positivo de dos TPAQs: restricciones al límite de velocidad y ayudas para renovar la flota de vehículos. Sin embargo, se encontró un alto nivel de desacuerdo en el resto de medidas de estudio.

Por un lado, los operadores públicos de transporte y los responsables políticos coincidían en que dichas TPAQs propiciaban una reducción del uso del coche en el centro de la ciudad de Madrid, originando impactos positivos en sus respectivos sectores. Por otro lado, comerciantes, taxistas y trabajadores del sector de mercancías observaban impactos negativos para sus respectivos sectores. Consideraban que disminuiría su competitividad y que aumentaría las desigualdades entre grandes y pequeñas compañías. La controversia fue particularmente notable en las restricciones por número de matrícula, apoyadas fuertemente por los responsables políticos y rechazadas por el sector del transporte; los cobros a vehículos de motor, secundado por los operadores de transporte público y con el resto de participantes en contra; y el desarrollo de infraestructura peatonal y ciclista, apoyado enormemente por responsables políticos, operadores de transporte público y ambientalistas, mientras que el resto de sectores rechazaban dicha medida.

5.1.3 Nivel de aceptabilidad de TPAQs

El tercer bloque de las entrevistas semiestructuradas analizó los niveles de aceptabilidad de las TPAQs de estudio para cada sector (Figuras 5 y 6). En el caso de las restricciones por tipo de motor, el 60% de los stakeholders declararon una alta y muy alta aceptabilidad para sus sectores, mientras que un 17% indicó una aceptabilidad neutra. Sin embargo, las restricciones por número de matrícula encontraron un alto nivel de disidencia. El sector transporte de mercancías se posicionaba totalmente en contra de esta medida, mientras que los operadores de transporte público, responsables políticas y ambientalistas apoyaban la implementación de la misma. Un caso similar ocurrió con las tasas a los vehículos de motor, donde el nivel de discrepancia fue muy alto. Un 50% de los stakeholders señalaron una aceptabilidad alta o muy alta ara esta medida, principalmente desde instituciones públicas y operadores de transporte. No obstante, un 33% indicó una aceptabilidad baja o muy baja, principalmente desde el sector del transporte de mercancías y los ambientalistas.

En cuanto a las restricciones al límite de velocidad, el 42% de los entrevistados señaló una alta o muy alta aceptabilidad (principalmente responsables políticos y ambientalistas) y un 46% declaró una aceptabilidad neutra. El desarrollo de infraestructura peatonal y ciclista mostró un alto nivel de discrepancia en cuanto a su aceptabilidad. Un 50% (incluyendo instituciones públicas, sector tecnológico, operadores de transporte y sector de la movilidad compartida) indicó una aceptabilidad alta o muy alta; frente a un 33% que señaló una aceptabilidad baja o muy baja en sus respectivos sectores, principalmente desde el sector de mercancías, comerciantes y taxistas. Para el resto de medidas, los niveles de aceptabilidad fueron similares. La mayoría de stakeholders indicaron una aceptabilidad neutra o alta para sus respectivos sectores.

5.1.4 Identificación de estrategias potenciales de implementación

El cuarto bloque de la entrevista consistió en la discusión de estrategias potenciales de implementación que podrían incrementar la aceptabilidad, viabilidad y efectividad de cada TPAQ. Se consiguió un alto nivel de consenso en cinco TPAQs:

- restricciones por tipo de motor, basadas en una progresiva implementación en el tiempo que diese suficiente tiempo a viajeros y empresas para renovar su flota de vehículos
- restricciones al límite de velocidad, a través de un programa de desarrollo educativo y conciencia social para conductores
- ayudas para la renovación de la flota de vehículos, resaltando la necesidad de comenzar con los sectores de población de menores ingresos
- promoción de la movilidad compartida, considerando la necesidad de un marco legal que garantizase la libre competencia en el sector
- y desarrollo de infraestructura de transporte público, estableciendo un balance adecuado en el diseño de calles entre el espacio otorgado al transporte público y el espacio dedicado al resto de modos.

Sin embargo, no se encontró consenso en la aplicación de las restricciones por tipo de matrícula, los cargos a los vehículos de motor y el desarrollo de infraestructura peatonal y ciclista. Este es otra de las razones para que fueran las tres TPAQs incluidas en el espacio de diálogo abierto.

5.2 Resultados del espacio de diálogo abierto

Como consecuencia de la falta de consenso entre los participantes durante la fase de entrevistas, se incluyeron tres TPAQs en el workshop: restricciones por número de matrícula, tasas a los vehículos motorizados y desarrollo de infraestructura peatonal y ciclista. En este apartado se resumen los principales resultados obtenidos en esta fase, incluyendo una descripción detallada de los debates en torno a las tres TPAQs mencionadas.

Las restricciones por número de matrícula fueron la primera medida analizada durante el workshop. Una vez que los participantes fueron informados sobre los resultados agregados obtenidos en las entrevistas, el equipo investigador planteó tres estrategias de implementación:

- Opción A: Implementación temporal afectando tanto a vehículos de pasajeros como de mercancías (a excepción del transporte público), exclusivamente en periodos donde la concentración de contaminantes fuera superior a los umbrales de salud establecidos por la normativa.
- Opción B: Implementación permanente de la media con excepciones para transporte de mercancías, alta ocupación y transporte público.
- Opción C: Implementación permanente de esta medida únicamente en horas punta, tanto para vehículos de transporte de pasajeros como de mercancías (a excepción del transporte público).

Tras la primera ronda de votación, la opción B fue apoyada por el 53% de los participantes, seguida de la opción A (40%) y la opción C (7%). La opción B fue principalmente seleccionada por participantes del sector transporte de mercancías, movilidad compartida, comerciantes y operadores de transporte. La opción A fue la elegida por ambientalistas y empresas de movilidad sostenible. Finalmente, la opción C fue apoyada por stakeholders del gobierno local.

La segunda ronda de votación tenía el objetivo de captar el acuerdo o desacuerdo de cada agente con cada una de las tres estrategias de implementación. Los resultados mostraron que la mayoría de los votantes se mostraban contrarios a la opción A (73%), la cual tenía sus votos favorables en agentes ambientalistas. Un hecho similar ocurría con la opción C, apoyada únicamente por un participante proveniente del gobierno local de Madrid. Sin embargo, un 60% de los stakeholders (representando al sector transporte de mercancías, movilidad compartida, comerciantes y operadores de transporte) se mostraban de acuerdo con la opción B.

Los resultados agregados fueron mostrados a todos los participantes antes de iniciarse una ronda de debate. En esta parte del workshop, se incluyeron 11 nuevos códigos en la base de datos asociada a esta TPAQ. Durante la discusión, los agentes del sector de mercancías y los operadores de transporte mostraron la necesidad de establecer excepciones para sus respectivos sectores si esta TPAQ se implementaba. Por su parte, los ambientalistas alertaron de que estas excepciones podían generar desigualdades que hicieran menos efectiva la medida en el largo plazo. Tras escuchar diversas opiniones, el agente del gobierno local que había elegido la opción C acabó cambiando su punto de vista y admitiendo esta medida únicamente como política temporal en periodos de superación de los límites de salud establecidos por la normativa. Stakeholders del sector transportes, comerciantes y operadores de transporte declararon admisible una implementación temporal de la medida, teniendo en cuenta la baja posibilidad de que se llevase finalmente a cabo.

En resumen, se consiguió un acuerdo final en la mayoría de participantes sobre la conveniencia de la opción A como estrategia de implementación para mejorar la aceptabilidad y viabilidad de esta TPAQ en Madrid.

Las tasas a los vehículos de motor fueron la segunda TPAQ analizada durante el workshop. Una vez que los participantes fueron informados sobre los resultados agregados obtenidos durante las entrevistas, se presentaron las tres estrategias de implementación a debatir:

- Opción A: Implementación permanente de tasas dentro del anillo interior de Madrid, afectando de igual manera a todos los vehículos motorizados a excepción de los sistemas de transporte público.
- Opción B: Implementación permanente de tasas dentro del anillo exterior de Madrid, con excepciones para transporte de mercancías, taxistas, vehículos de movilidad compartida y transporte público.
- Opción C: Implementación permanente de cargas en horas punta dentro del anillo externo de Madrid, afectando a todos los modos de transporte con la excepción del transporte público.

La primera ronda de votación mostró una preferencia mayoritaria por la opción B (80%), seguida muy de lejos por la opción C (13%) y la opción A (7%). La opción B fue seleccionada por agentes del sector mercancías, comerciantes, taxistas y empresas de movilidad compartida porque sus vehículos estaban exentos. Sin embargo, la opción C fue elegida por stakeholders del gobierno local de Madrid y pequeñas compañías centradas en la movilidad sostenible.

La ronda de votaciones siguiente mostró un amplio rechazo a la opción A (73%) y un resultado similar para la opción C. En cambio, un 60% de los participantes se mostraron de acuerdo con la opción B, representando en su mayoría al sector de mercancías, movilidad compartida, comerciantes y operadores de transporte.

Una vez que los resultados agregados fueron expuestos a todos los participantes, se abrió el turno de debate, en el que se introdujeron 10 nuevos códigos referidos a esta TPAQ. Esta medida tuvo menor controversia en comparación con las restricciones por número de matrícula. Se observó unanimidad entre los participantes en el rechazo de las cargas a vehículos de motor, con un porcentaje bajo de aceptación en las tres estrategias de implementación planteadas. El principal argumento fue que provocaría un incremento en la desigualdad social si fuese implementada. No obstante, sectores como el transporte de mercancías y los comerciantes mostraron conformidad con esta medida si se tenían en cuenta las particularidades del sector transporte durante su implementación. De esta manera, no quedó establecida cuál podría ser la mejor estrategia de implementación para aumentar la aceptabilidad y viabilidad de esta medida.

La última TPAQ estudiada durante el workshop fue el desarrollo de infraestructura peatonal y ciclista. Las tres estrategias planteadas, tras informar a los participantes de los resultados agregados durante las entrevistas, fueron las siguientes:

- opción A: Reducir el número de carriles en las calles de varios carriles para ampliar la infraestructura para peatones y ciclistas de forma homogénea en barrios del anillo interior de Madrid.
- Opción B: Establecer una restricción total del tráfico en algunas calles seleccionadas con alta actividad comercial para construir una infraestructura para caminar y andar en bicicleta que cubra todo el espacio de tráfico. El resto de las calles permanecerían como estaban.
- Opción C: Establecer una restricción total del tráfico en las calles secundarias, implementar una infraestructura para caminar y andar en bicicleta que cubra todo el tráfico espacio de tráfico en esas calles, con excepción de los residentes, que podrían acceder a sus garajes utilizando vehículos motorizados.

La primera ronda de votación mostró igualdad de preferencias entre las opciones A y C, con un 40% de votos para cada una de ellas, mientras que la opción B fue seleccionada por el 20% de los agentes. La opción A fue elegida principalmente por los operadores de transporte de mercancías, comerciantes y el sector de la movilidad compartida, quienes creen que una restricción total al tráfico podría dañar seriamente a sus sectores. La opción C fue indicada en su mayoría por instituciones públicas y operadores de infraestructuras. La opción B fue apoyada exclusivamente por ambientalistas.

La segunda ronda de votación mostró un 60% de apoyo favorable a la opción A, incluyendo representantes de instituciones públicas, servicios de movilidad sostenible y ambientalistas). La opción C fue apoyada por el 53% de los encuestados, incluyendo de nuevo agentes de instituciones públicas y ambientalistas. Sin embargo, la opción B fue rechazada por el 53% de los stakeholders, entre los que se encontraban comerciantes, movilidad compartida y sector de transporte de mercancías. Se debe mencionar que los agentes representantes del

Ayuntamiento de Madrid apoyaron las tres estrategias de implementación mostradas por el equipo investigador. En su opinión, "recuperar las plazas de tráfico para hacer las ciudades más caminar era esencial para alcanzar resultados sostenibles a nivel de la ciudad".

La fase de debate abierto sobre la medida, en la que fueron incluidos 25 nuevos códigos en la base de datos, mostró dos grupos diferenciados. Por un lado, los participantes que consideraban un gran problema para su sector la sustitución de plazas de tráfico por áreas para movilidad no motorizada: transporte de mercancías, comerciantes, servicios de movilidad compartida y operadores de infraestructura. Por otro lado, los stakeholders de instituciones públicas, movilidad sostenible y ambientalistas se mostraban de acuerdo con la idea de reducir las áreas de tráfico por movilidad no motorizada. No obstante, algunos de los agentes de instituciones públicas indicaron que las tres estrategias de implementación planteadas eran muy radicales para tener un mínimo nivel de aceptabilidad en la sociedad. De esta manera, tras escuchar las opiniones del resto de grupos, los representantes del Ayuntamiento local de Madrid (que previamente habían apoyado las tres estrategias propuestas) cambiaron su opinión e indicaron su rechazo sobre todas ellas. Estas estrategias se consideraron finalmente con un bajo nivel de viabilidad y fiabilidad para la ciudad de Madrid. Finalmente, no se pudo llegar a un consenso tras el debate sobre qué estrategias de aplicación aumentarían la aceptabilidad de este TPAQ.

6. CONCLUSIONES

Este trabajo ha desarrollado y testado un novedoso enfoque de colaboración para evaluar ex ante la implementación de TPAQs en el centro de las ciudades a través de la participación de stakeholders. Un total de ocho TPAQs fueron estudiadas y comparadas en el contexto de la ciudad de Madrid:

- restricciones por tipo de motor
- restricciones por número de matrícula
- restricciones del límite de velocidad
- cobros a vehículos de motor
- desarrollo de infraestructura peatonal y ciclista
- ayudas para el cambio en la flota de vehículos
- promoción de la movilidad compartida
- desarrollo de infraestructura pública de transporte.

Los resultados de la investigación arrojan luz sobre la mejor manera de implementar TPAQs para alcanzar los mayores niveles de aceptabilidad desde los diferentes actores de la sociedad. El análisis muestra que todos los stakeholders están concienciados en la adopción de medidas políticas para mejorar la calidad del aire en las ciudades, pero tienden a oponerse a aquellas políticas que afectan directamente al tráfico motorizado de vehículos. El método colaborativo demuestra que un diálogo abierto y activo entre stakeholders clave puede sur una manera útil de encontrar inteligentes estrategias de implementación que son efectivas ambientalmente y aceptables para la mayoría de los grupos afectados.

Las principales conclusiones del artículo son las siguientes:

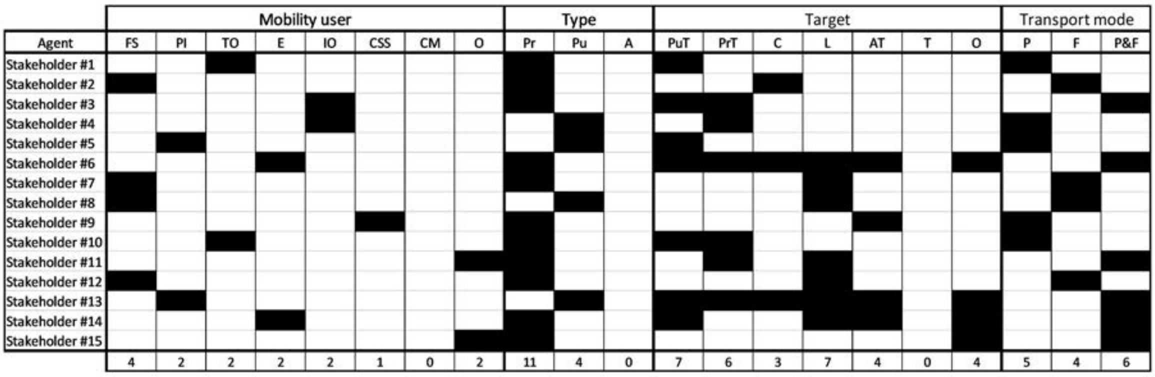
- TPAQs en el caso de estudio: la ciudad de Madrid constituye una ciudad adecuada en tiempo para llevar a cabo esta investigación Las autoridades locales están involucradas activamente en la formulación de políticas para mejorar la calidad del aire en el centro de la ciudad. Un ejemplo de esto es la implementación del Plan A, que recopila un número relevante de medidas destinadas a reducir el tráfico de vehículos y las emisiones de transporte. Mientras los niveles de controversia en la población respecto al mencionado plan siguen aumentando, se ha prestado limitada atención a implementar escenarios colaborativos que promuevan la participación de stakeholders en el diseño de políticas. En este sentido, el estudio proporciona una base para diseñar estrategias de implementación basada en consensos entre stakeholders que podría incrementar el nivel de aceptabilidad de algunas medidas incluidas en el planeamiento local de Madrid. Este es el caso de las restricciones por número de matrícula, que se aceptan únicamente en episodios temporales de alta contaminación y el desarrollo de infraestructuras peatonales y ciclistas, que se considera preferible realizarlo en calles secundarias frente a las calles principales. Otra contribución ha sido la identificación de TPAQs con un alto consenso, como la promoción de la movilidad compartida; y el acuerdo general sobre el rechazo a las cargas por tipo de motor.
- Existen dos grupos de opinión diferenciados en el contexto de Madrid: como se indicó previamente, el consenso general ha sido conseguido satisfactoriamente en 5 TPAQs, mientras que los puntos divergentes fueron fácilmente identificados en las restricciones por número de matrícula, las cargas por tipo de motor y el desarrollo de infraestructura peatonal y ciclista. Los impactos potenciales más discutidos fueron la mejora de la calidad del aire, la reducción de la congestión urbana y la generación de desigualdades sociales. A pesar de que todos los grupos mostraron su apoyo a la necesidad de implementar políticas de transporte para mejorar la calidad del aire en los centros de las ciudades, se ocasionaron altos niveles de desacuerdo entre dos grupos. Por un lado, responsables políticos, operadores de transporte público y ambientalistas. Por otro lado, conductores de taxi, comerciantes y operadores de transporte de mercancías. Se debe tener en consideración tanto el transporte de pasajeros como el transporte de mercancías.
- Participación de stakeholders y activación del proceso de aprendizaje: la inclusión de stakeholders en la evaluación ex ante de TPAQs ha probado ser una forma eficiente de integrar múltiples puntos de vista en el proceso de formulación de políticas, generando un consenso base para asegurar una mayor efectividad y aceptabilidad de las TPAQs. Esta idea es considerada un punto crucial cuando para la implementación de políticas con una alta controversia social (Mohan et al., 2017;

Moncada et al., 2018; Pucher & Buehler, 2008), obteniendo un proceso más democrático. Otro punto relevante ha sido el proceso de aprendizaje estructurado en fases secuenciales donde los participantes han podido conocer los resultados globales obtenidos en las entrevistas, aprender de ellos y aprender de otros agentes mediante su interacción cara a cara. Esto ha facilitado la modificación y modulación de sus opiniones. En concreto, el encuentro llevado a cabo en el workshop ha contribuido a alcanzar cierto nivel de consenso en cuanto a potenciales estrategias de implementación para las restricciones por número de matrícula y las cargas a vehículos por tipo de motor. Esto ha sido posible gracias a que stakeholders relacionados con instituciones públicas han cambiado su punto de vista al escuchar el razonamiento de otros grupos de actores.

- Necesidad de combinar enfoques cualitativos y cuantitativos. Frente a la evaluación basada en la modelización y los enfoques plenamente cuantitativos, se apuesta por la necesidad de utilizar también un enfoque cualitativo. De esta manera, se espera capturar en mejor medida cómo la efectividad de las TPAQs puede verse afectada por un bajo nivel de aceptabilidad social, normas culturales y hábitos individuales.
- El marco de evaluación colaborativa y otras técnicas de apoyo a la decisión. Combinr el enfoque bottom-up desarrollado en esta investigación con otras técnicas conocidas (EIA, Análisis Coste-Beneficio, Análisis multicriterio, etc.) constituye un futuro desafío. En este sentido, los resultados obtenidos pueden ser una aportación para dichas técnicas de evaluación tradicionales (Cascetta et al. 2015), anticipando potenciales conflictos entre actores así como su posible interés de considerar estrategias para reducir los impactos esperados de las TPAQs. La experiencia en Madrid indica que la evaluación bottom-up debe ser diseñada para cada caso particular. Los factores que influyen en el proceso participativo de diseño incluyen el tiempo, coste, tradiciones culturales, la predisposición a la participación y otros factores.

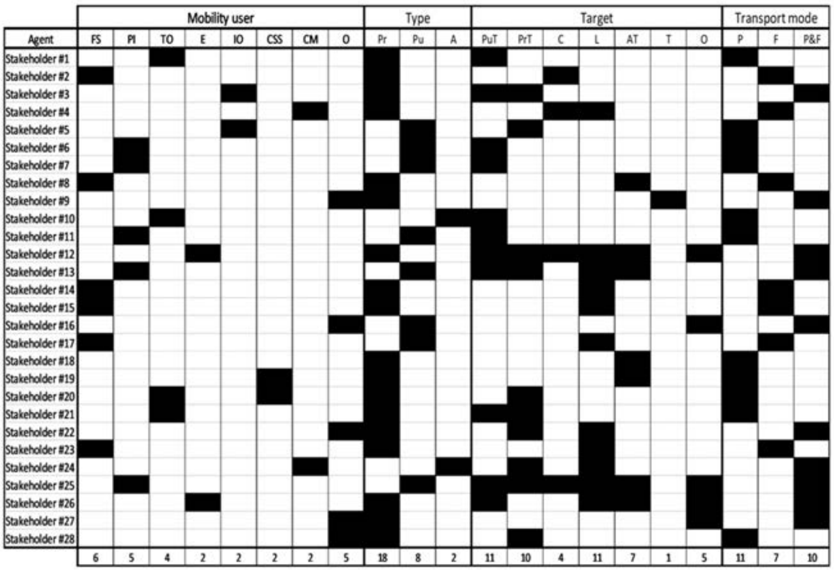
Por último, cabe mencionar que en esta investigación se ha desarrollado un conjunto de nuevos fundamentos de evaluación, más democráticos, colaborativos y basados en la participación ascendente. Un reto importante es también cómo integrar finalmente estos enfoques de evaluación en los procesos de planificación institucional, que tradicionalmente son más tecnocráticos y se limitan a pequeños grupos de deliberación.

APÉNDICE 1



Mobility User	Type	Target	Transport mode
FS: Freight Sector	Pr: Private	PuT: Public transport	P: Passengers
PI: Public Institutions	Pu: Public	PrT: Private transport	F: Freight
TO: Transport operators	A: Association	C: Customers	P&F: Passengers & Freight
E: Environmentalists		L: Logistics	
IO: Infrastructure operators		AT: Alternative transport	
CSS: Car-sharing sector		T: Technology	
CM: Car manufacturers		O: Others	
O: Others			

APÉNDICE 2



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IDENTIFYING MOBILITY PATTERNS AND BARRIERS FROM AGEING POPULATION TO ACCESS TO RETAIL ACTIVITY

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ABSTRACT

While the role of ageing population is considered crucial for Sustainable Development Goal at city level, limited attention has been paid to study the walking accessibility level of this population group to retail activity. Moreover, one missing element is the analysis of the ageing population willingness to reach retail activity on foot, which is here seen as a key point to generate friendly, liveable, and decarbonised urban environments. The city of Granada (Spain) is taken as spatial laboratory for the research. For this city, the planning of ageing population mobility in the mid-term seems to be challenging. First, a questionnaire regarding the willingness of ageing population to walk to daily, weekly, and incidental retail locations was conducted, including the identification of the main barriers to cover those distances on foot. Data were collected between January 2018 and January 2019. Second, a detailed description of the main existing problems to access to different types of retail activities be explored and compared, distilling findings for urban diagnosis. This research provides a strong basis for policy-making formulation, which can be orientated towards making cities more inclusive, liveable, and sustainable. Its findings can facilitate the identification and mapping of locations where ageing population groups can be under risk of walking accessibility disadvantage.

1. INTRODUCTION

It is widely believed that accessibility planning can be a powerful tool to effectively link transport and land use planning, two disciplines traditionally rooted in separated realms (Bertolini, 2017; van Wee & Handy, 2016). In this sense, the accessibility planning approach has gained prominence between academics, professionals, and institutions to become a key aspect in achieving sustainable planning outcomes at city and regional levels (Arranz-López et al., 2017; Geurs & van Wee, 2004; van Wee, 2016). Moreover, accessibility to major opportunities has been even recognised as a human right (United Nations, 2014), as it is one of the crucial factors that enable the participation of individuals in social life (Kenyon et al., 2003; Lucas et al., 2016).

Accessibility is usually seen as the relationship between the availability of opportunities in a given location and the transportation supply to reach them (Bocarejo S. & Oviedo H., 2012), being traditionally applied as an absolute concept affecting equally to the full spectrum of population. However, accessibility is conditioned by contingencies such as cultural norms, physical environment, and personal characteristics (Morency et al., 2011). In other words, different individuals display varying levels of willingness to travel to reach opportunities (Morency et al., 2011; Moniruzzaman, Paez, Nurul Habib, & Morency, 2013). Limited attention has been paid to how accessibility levels vary between population groups (Chang & Liao, 2011; Chia et al., 2016; Páez, et al., 2010), and the study of walking accessibility variations between seniors is a significant case in point (Böcker, van Amen, & Helbich, 2017; Negron-Poblete, Séguin, & Apparicio, 2016; Cao, Mokhtarian, & Handy, 2010; Hess, 2012).

A more in-depth understanding on how the senior population can reach major locations on foot is crucial for policy-making at local level (Givoni and Banister, 2013; Vale et al., 2015). That has triggered a growing number of studies focused on the accessibility levels of seniors (Páez et al., 2010; Páez et al., 2013). It has been reported how within the senior population exists significant differences regarding its travel behaviour and its capacity to access to certain locations (Hildebrand, 2003; Rahaf and Hensher, 2003).

Nevertheless, the senior population is frequently analysed as a homogenous group to be compared with other socio-economic groups. It is also known that the willingness of the senior population to reach retail locations on foot significantly diverges from the rest of population groups (Arranz-López et al., 2018; Negron-Poblete et al., 2016). It is evidenced that at least 1/3 of daily travels between the senior population is on foot (Paez et al., 2013). However, studies on walking accessibility focused on the senior population are limited.

To bridge the abovementioned gaps, this paper aims at exploring if and to what extent walking accessibility to retail activities is similar for different socio-economic groups among the senior population. The empirical focus will be the city of Granada in Spain, as it is a city with a high ageing population rate and where retail locations are widely dispersed across the city reducing distances between population and destinations. A questionnaire regarding the willingness to reach daily, weekly, and incidental retail locations on foot was elaborated and disseminated in the case study among population older than 55 years old. Then, a K-modes clustering method was implemented distinguishing four socio-economic groups among seniors (the “non-motorized seniors”; the “motorized seniors”; the “older seniors”; the “younger seniors”), followed by a statistical comparison of time-willingness decay functions to reach retail locations on foot for each identified cluster. Finally, walking accessibility to retail activity was estimated and mapped by using a gravity-based model.

The remainder of the paper is organized as follows: Section 2 reviews previous studies on accessibility to major destinations among the senior population. Section 3 presents the case study, while Section 4 shows the research design. Section 5 summarizes the main obtained findings. Finally, Section 6 closes the paper with some concluding remarks, including reflections on future research lines.

2. ACCESSIBILITY STUDIES ON THE SENIOR POPULATION

The strong ageing population trends in developed countries have facilitated a growing concern regarding travel patterns associated to seniors and its accessibility levels to major locations. Most of the consulted studies in the field are based on comparing motorised accessibility standards between seniors and other socio-economic groups. For example, Ricciardi et al., (2015) explored the accessibility levels to public transport systems in the context of Perth (Australia) between seniors, low-income people, people without car availability, and the rest of population. The authors showed how the biggest accessibility differences were focused on the group of seniors, who had the lowest accessibility levels to public transport systems. Similarity, Delbosc & Currie (2011) also analysed the access to bus system stops in Melbourne (Australia), finding that the low-income people had the lowest accessibility levels followed by the senior population. Páez et al., (2013) demonstrated that the likelihood to access to major destinations by car was higher for the senior population in comparison with other population groups in the city of Montreal (Canada). Also in Montreal, Páez et al., (2010) evidenced how the accessibility of seniors to health care facilities was significantly lower in suburban areas than in the city centre compared with other population groups in the same location.

Less attention has been traditionally paid to compare non-motorised accessibility levels between seniors and other groups. In that way, Arranz-López et al. (2018) demonstrated significant differences between seniors and the rest of population regarding their time-willingness to reach retail by walking and cycling in the city of Zaragoza (Spain). Generally, seniors were more willing to cover distance on foot to most of retail types, while the rest of population preferred taking motorised modes. On the contrary, Chia et al. (2016) showed that seniors walked shorter distances than younger people to reach public transport systems in Brisbane (Australia), affecting to its accessibility levels. Lord et al. (2011) also found that seniors from Brisbane had more difficulties to participate in the social life of its community when the access to car was limited, signalling the need for increasing non-motorised levels among seniors in comparison with other population groups. While most of accessibility studies identified seniors as a genuine group, it is almost unexplored how those accessibility standards can vary within this group and its consequences for policy-making.

3. THE CITY OF GRANADA IN SPAIN

Granada is a medium-size city (232.770 inhabitants) located in the southern Spain (Figure 1). The city shows a strong increase of the senior population during the last decades. Specifically, the demographic cohorts of people over 55 years old have experienced an increase of 20.000 individuals in 20 years, supposing a total of 34.5% of the population in 2020 (INE, 2020). The spatial distribution of seniors across the case study is not homogenous. The neighbourhoods with the highest rate of seniors (greater than 35%) are historical places, located in the city centre. Conversely, peripheral neighbourhoods have experienced a positive population growth in recent years, predominating young and active-age population.

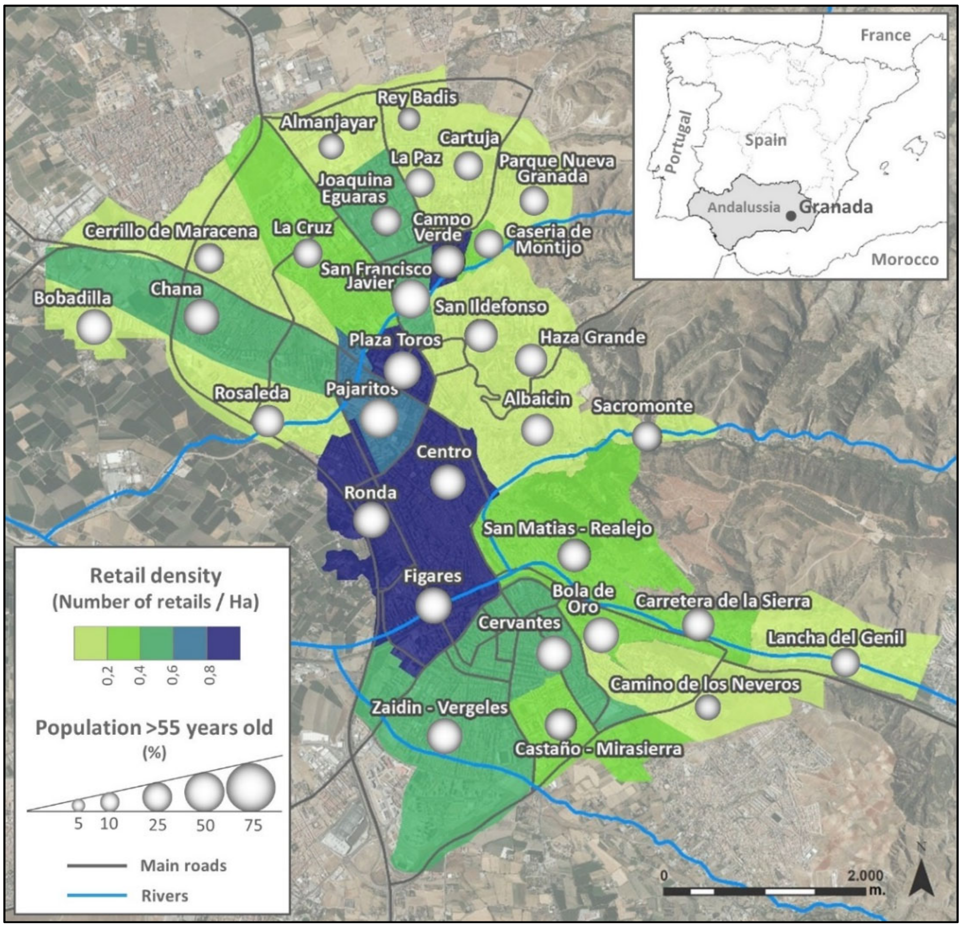

Figure 1: The city of Granada

Regarding transportation issues, short distances between population and destinations predominate across the city, providing with a good local environment to foster non-motorised transport modes. Non-motorized trips represent a total of 54% of local movements (PMUS, 2013). However, the rate of motorised trips has been drastically increased to approx. 80%, especially when trips take place between Granada and surrounding municipalities (The Metropolitan Area of Granada), where the main shopping centres are located. Shopping trips are almost a total of 38% of all local trips (PMUS, 2013). The density of retail activity decreases from the city centre to the periphery, where the new residential neighbourhoods located. Consequently, an important number of motorised shopping trips are originated from those neighbourhoods in the periphery to the city centre or to the surrounding shopping centres.

4. RESEARCH DESIGN

This research followed a three-stage approach (Figure 2):

- data gathering
- clustering analysis of seniors and comparison of its time-willingness decay functions
- calculating and mapping relative walking accessibility.

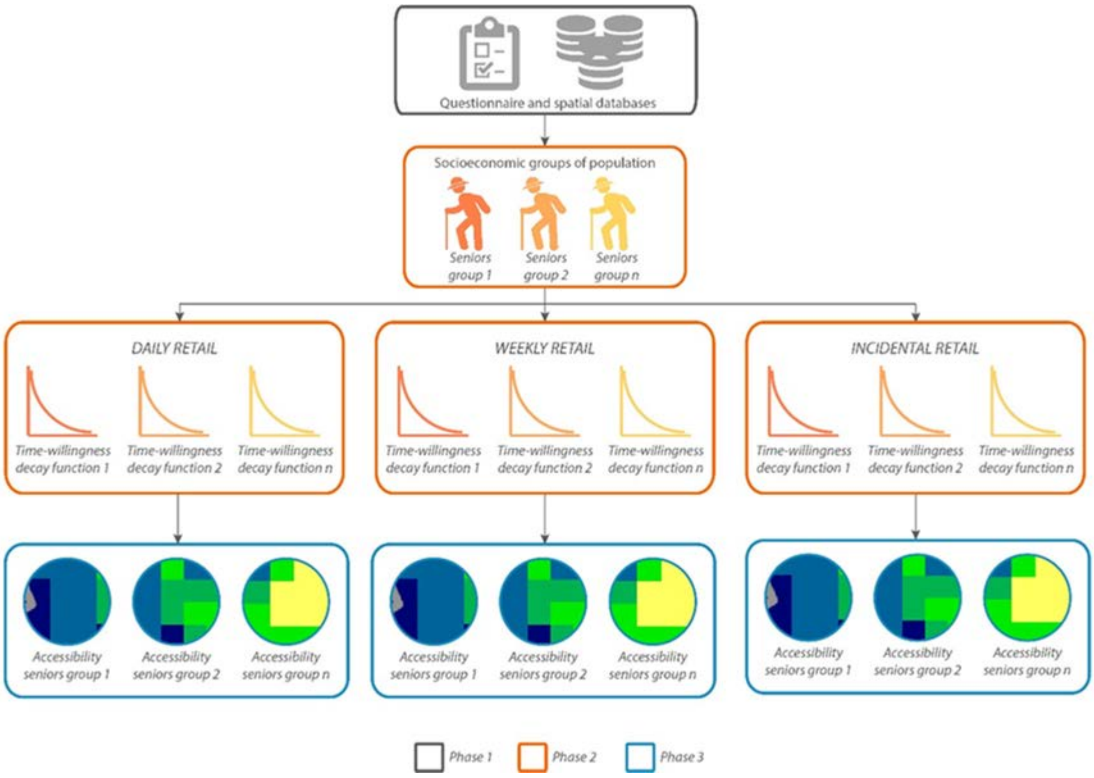

Figure 2: Methodological scheme

4.1. Data gathering

The main data source for this study was a questionnaire addressed to population over 55 years old. A total of 171 questionnaires were via face-to-face conducted visiting to the public active participation centres for seniors. Such centres were distributed equally across the city of Granada with a total of 6 centres, and all of them were visited during the fieldwork. The questionnaire was also disseminated online, obtaining a total of 31 responses. Totally, 202 valid questionnaires were collected, representing a 95% confidence interval with a bias of 5% in the context of the case study. Face-to-face interviews were especially relevant since the target population of study was seniors, who had limited access to online resources and a high rate of digital divide.

The questionnaire was structured in two blocks. The first block consisted of questions focused on demographic and socio-economic characteristics of the target group, such as gender, age, neighbourhood, household size, living alone, monthly household income, household car availability, educational level, and employment status. The second block of the questionnaire asked to seniors for their time-willingness to reach daily, weekly, and incidental retail locations on foot. Daily retail included food store, butcher, charcuterie, greengrocers, bakery, fishmonger, supermarket, and kiosk. Weekly retail included bazar, drugstore, perfumery, pharmacy, DIY store, copy shop, tobacconist, herbalist, houseware store, stationer's shop, hairdresser's, barbershop, clothing store and shoe store. Finally, incidental retail included travel agency, car/motorcycle/bicycle rental, pet shop, comic store, car dealership, sports shop, electronic/informatics shop, florist, garden store, jewellery, toy store, bookshop, furniture store, music store, optics, orthopaedics, gift shop, souvenirs, and videogame store. An example of question was: "*Independently of the neighbourhood where you are currently living, how much time are you willing to spend to reach daily/weekly/incidental retail stores on foot?"*.

Additionally, spatial databases required to calculate accessibility indicators were both collected and manually digitised. A grid from the European Environment Agency was used as a spatial basis to represent accessibility values. Furthermore, a street network from the Spanish National Centre of Geographic Information was used to calculate the distance between origins and destinations. On the other hand, retail locations were manually digitised from a databased developed by the Andalusia Regional Government, and cross-checked with Google Maps and Open Street Maps, yielding a total of 2,929 retail locations.

4.2 Clustering analysis of seniors and comparison of distance-decay functions

Clustering techniques were employed to group seniors into homogeneous socio-economic groups of population. Those groups were the basis for both analysing time-willingness decay functions and conducting accessibility analysis. A k-modes algorithm was used due to the categorical nature of the data involved. During the process, special attention was paid to the choice of the variables that would characterise those population groups as well as the optimal number of clusters.

Regarding the choice of the variables for the clustering process, it was calculated Pearson correlation coefficients at $p<0.05$ level between socio-demographic variables to assess the relationships between them, being the most correlated variables discarded. It was noticed that age, monthly household income, household car availability, and living alone were the less correlated variables, and therefore, the most suitable for the clustering process.

On the other hand, the choice of the optimal number of clusters was based on the gap-statistic method, which compares for different numbers of clusters the total intra-cluster variance observed and it finds the value with which the cluster structure obtained is as far as possible from a random uniform distribution. An error bar analysis with a confident interval of 95% was carried out to check the suitability of the clusters to the sample. This has allowed a correct definition of the socioeconomic groups based on the representative variables.

Time-willingness decay functions to reach daily, weekly, and incidental retail were empirically obtained for each socio-economic cluster from the questionnaire, being a total of 12 walking time-willingness decay functions. The mentioned functions were statistically compared to identify time-willingness thresholds between the socio-economic clusters by using the following process:

- The first step consisted of the simultaneous comparison of the absolute values of time-willingness between clusters. To address this step, the non-parametric Kruskal-Wallis test was used. Significant differences at $p<0.05$ level indicated that at least one socio-economic cluster had its time-willingness decay function significantly different to other clusters for any time-willingness slot.
- If no significant differences were found during the first step, the second step consisted of the simultaneous comparison of the percentile values of time-willingness between clusters. This allowed the identification of statistical differences between clusters within a specific time-willingness slot.
- Finally, the non-parametric Mann-Whitney U test was used to analyse pairs of time-willingness decay functions for those cases where differences at $p<0.05$ level were obtained for the Kruskal-Wallis test during steps one or two.

4.3 Calculating and mapping relative accessibility

Relative accessibility to retail locations for each socio-economic group was calculated by using a gravity-based model (Equation 1), meaning that access indicators are based on the distance between origins and destinations, weighted by both the availability of retail stores at the destination and the time-willingness decay functions of each cluster. Accessibility was calculated for daily, weekly, and incidental retail.

$$GA_i = \Sigma_{j \neq i} E_j e^{-\beta X_{ij}} \quad (1)$$

where A_i is the accessibility for zone i; E_j is the number of stores at destination j; X_{ij} is the distance, along a street network, between origins and destinations, and β is the parameter of the time-willingness decay function.

5. RESULTS

5.1 Clustering and distance-decay analysis

The population sample included a higher number of women (56%) than men, and the average age of the respondents was 69 years old. A total of 79% of individuals reported to be retired, while 83% of participants indicated that they had some type of motorized vehicle. The most common monthly family income was between 1000-2000 €, while at least a total of 20% of the respondents declared to live alone (mostly women). Regarding transport modes choices, 88% of seniors stated to go to daily retail stores on foot. However, that ratio was lower for reaching both weekly (66%) and incidental retail destinations (44%).

From the described sample, a total of four socio-economic groups were identified by using the K-modes algorithm and according to the following variables: age, motorized vehicle availability at home, monthly household income, and whether seniors lived alone or did not (Figure 3). Cluster#1 was labelled as “the non-motorised seniors”, including people between 65-75 years old, most of them had not vehicle availability at home, their average monthly household income was around €1000-2000, and mostly they did not live alone. Cluster#2 was called “the motorised seniors”. That is population who were 65-75 years old, with motorised vehicle availability (usually car), with a high monthly household income between €3000-5000, and who usually did not live alone. Cluster#3 were nominated as “older seniors”. Their ages were over 75 years old, without motorised vehicle availability at home, with a low monthly household income (<€1000), and most of them were living alone. Cluster#4 were labelled as “younger seniors”. Their age range was 55-65 years old, with availability of a motorised vehicle at home, medium-high monthly household income (€2000-3000), and rarely lived alone.

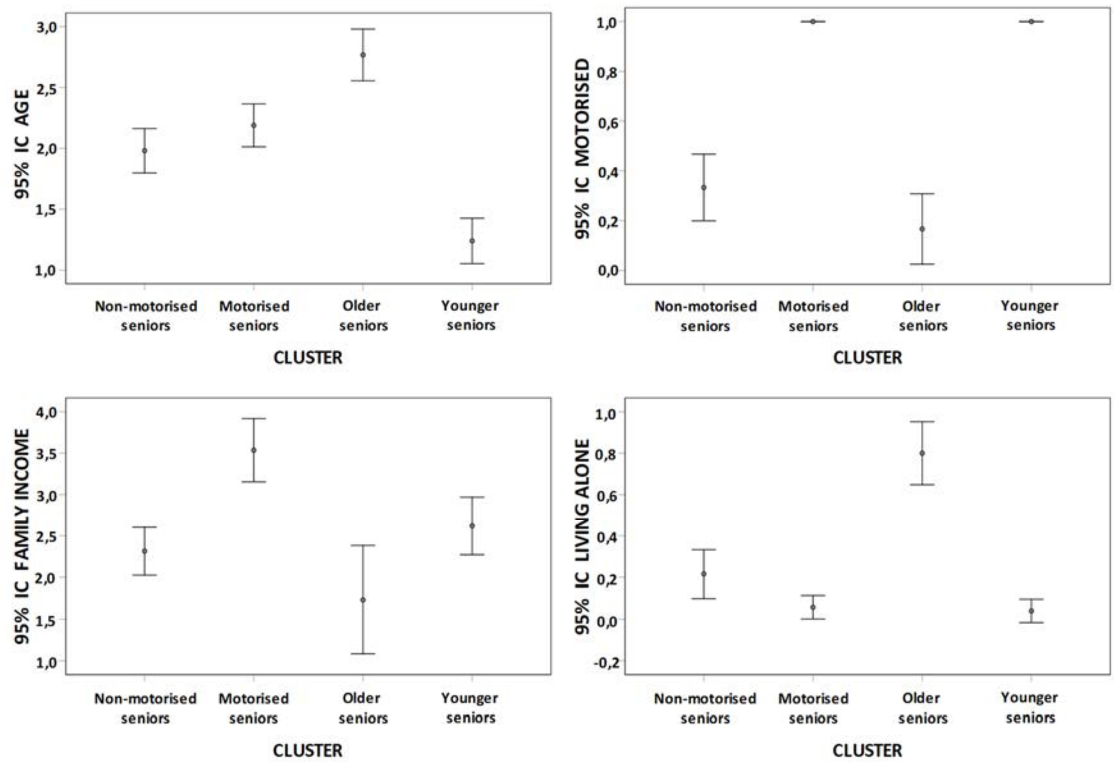

Figure 3: 95% IC error bars by cluster and socio-economic variable

For each socio-economic group, the time-willingness decay functions for walking to daily, weekly and incidental retail were empirically obtained by using the questionnaire described in the methodological section. When analysed the absolute values of the time-willingness decay functions with the Kruskal-Wallis test, significant differences at p-level 0.05 were not found to any type of retail (daily, weekly, and incidental). That meant that there were no differences when the full range of time-willingness decay function was studied. Accordingly, percentiles of time-willingness for walking were then analysed by using again the Kruskal-Wallis test. That would facilitate the identification of significant time-willingness differences for specific time-slots. For both daily and incidental retail significant differences were not found for any particular time-slot (Figure 4a and Figure 4c).

In the case of daily retail, it was seen that the time-willingness decay functions were very similar between the four population clusters. In all cases, participants were not willing to walk more than 15 minutes to reach daily retail locations, as it was generally assumed that daily retail should be located very close to residential areas in the case study. The need for daily retail proximity was especially relevant for the group of “non-motorised seniors” (C#1), since 94% of them are only willing to walk 10 minutes. Most of respondents from the four socio-economic clusters declared that they usually reached daily retail on foot. All clusters preferred local small stores followed by medium-sized stores (e.g., supermarkets) for daily retail. It was also signalled how seniors felt more confident buying in retail stores located in their own neighbourhood and knowing the shopkeeper. No differences between socio-economic clusters were seen in that respect.

For the incidental retail, differences were not found for any particular time-slot. Most of people from the different socio-economic groups stated to be willing to walk until 30 minutes to reach incidental retail destinations. Those average time-willingness were higher than the rest of the retail types because of the infrequent use those stores. Some differences were seen according to the modal choice to reach retail between the clusters. On the one hand, the "non-motorised seniors" (C#1) and the "older seniors" (C#3) opted for reaching incidental retail on foot and by using the public transport, as individuals from those groups tended to go to small and medium stores highly dispersed around the city. On the other hand, the "motorised-seniors" (C#2) and the "younger seniors" (C#4) preferred using the private vehicle to reach bigger shopping centres where incidental retail was mainly concentrated in one single place. Nevertheless, the average to walk to incidental retail were similar between groups of seniors, independently of the mentioned differences regarding modal choice preferences.

The analysis of time-willingness by percentiles showed significant differences for weekly retail. Results showed statistical differences in the time-willingness slots between 20 to 30 minutes, as well as for the 60 minutes (Figure 4b). It indicates that at least one socio-economic cluster had a walking time-willingness decay function significantly different from the other clusters within those time-willingness slots. The results for the Mann-Whitney test, used to identify significant differences between pairs of time-willingness decay functions for weekly retail, shown that the time-willingness decay function for "the younger seniors" (C#4) was significantly different from the other clusters for the 20 to 30 min slot (Figure 4b). This is especially relevant if we consider that 40% of the sample revealed that its willingness to walk to weekly retail was within that 20 to 30 min slot. On the other hand, for the 60 min slot, the distance-decay function for "the motorised seniors" (C#2) is significantly different from the rest of the clusters (Figure 4b). The "younger seniors" (C#4) had one of the lowest willingness to walk to the weekly retail. In particular, the percentage of people included in C#4, who were willing to walk more than 20 minutes to reach the weekly retail is very small compared to the rest of the groups. This suggests that, if weekly retail is located at a distance that takes more than 20 minutes to walk, there would be high probability that the "younger seniors" opted for motorised transport modes. The previous can be explained by the characteristics of the "younger seniors", who are mostly workers with family responsibilities, so they could have major temporary restrictions in comparison with the rest of senior groups. In addition, the "younger seniors" declared to go more often to weekly retail than the rest of the groups, which increases the need for establishing policies that facilitate the non-motorised access of the "young-seniors" to the weekly retail.

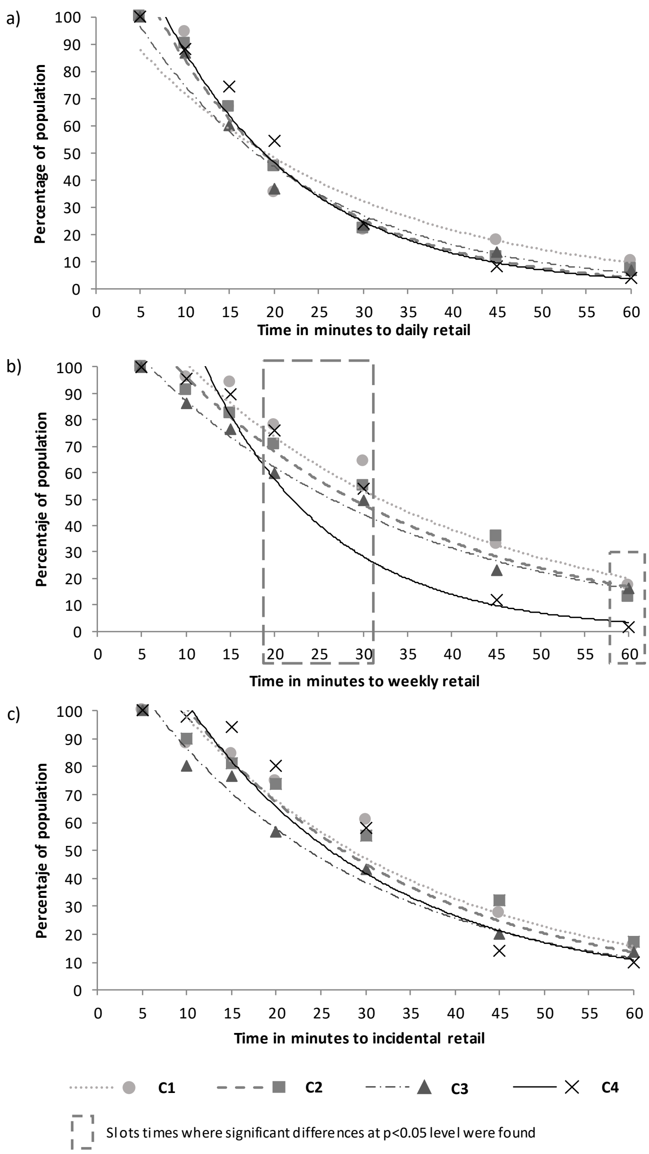

Figure 4: Time-willingness decay functions for daily (a), weekly (b), and incidental (c) retail.

5.2 Mapping relative accessibility

A gravity-based model was used to spatially show the accessibility to weekly retail, as statistical differences were found for this type of retail (Figure 5).

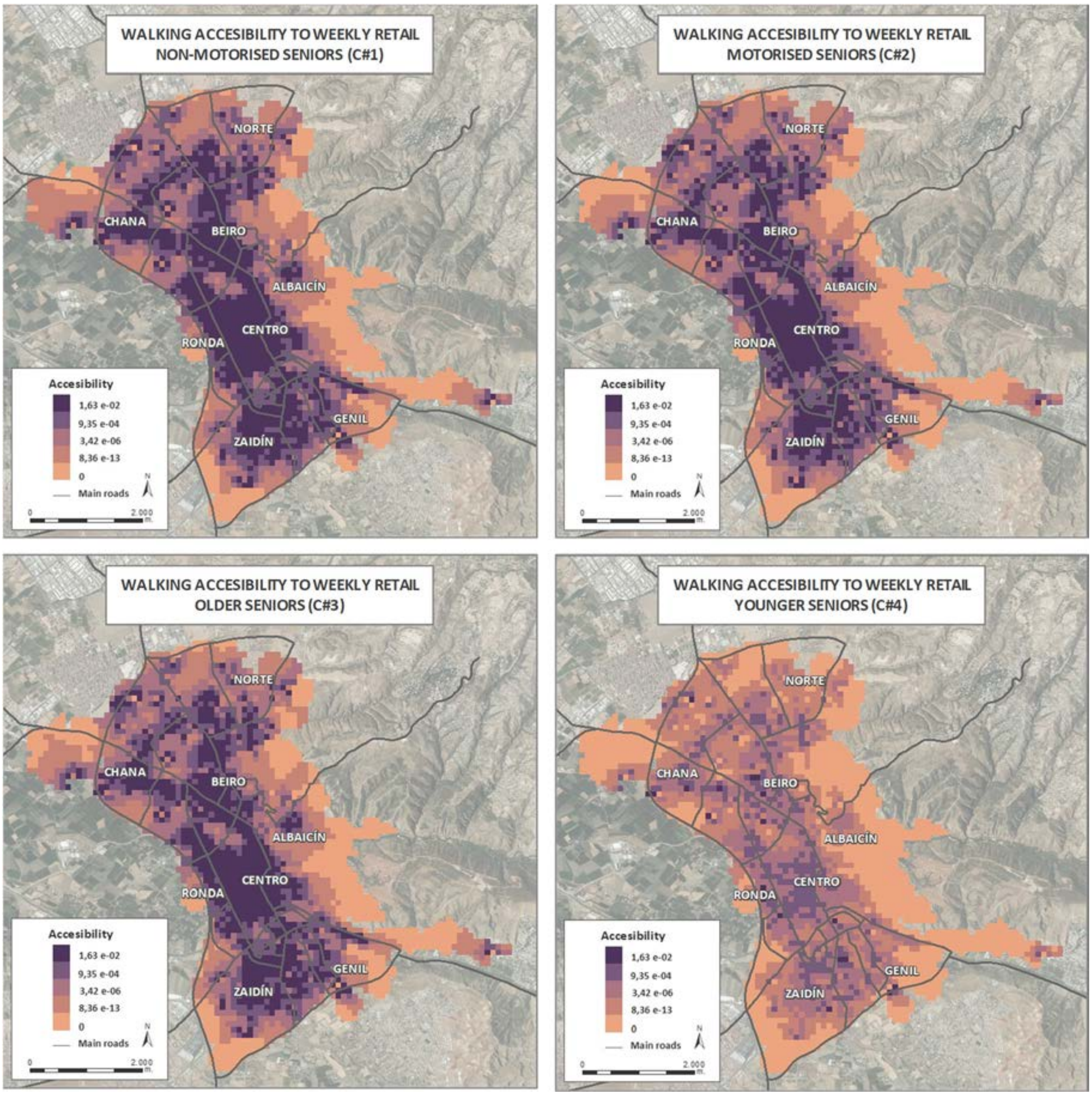

Figure 5: walking accessibility to weekly retail for the four clusters

Results show potential neighbourhoods with risk of presenting higher motorised rates to reach weekly retail, being geographical areas needed for the implementation of policies that foster a transition towards increasing walking accessibility levels to weekly retail. It was noticed that the less willingness to walk to the weekly retail of “younger-seniors” resulted in a loss of accessibility to weekly retail throughout the city. That is particularly relevant in the city centre, where “younger seniors” are less concentrated that the rest of ageing groups. However, weekly retail is highly present in that city centre, resulting in a strong increase of motorised trips from the “younger-seniors” to reach weekly retail.

Spatial analysis also identified places with low levels of walking accessibility to weekly retail for the four socio-economic clusters simultaneously. That is the case of the central-eastern zone. Those neighbourhoods have an important touristic activity and weekly retail does not predominate. However, such accessibility levels to weekly retail are also low in other residential neighbourhoods such as Genil, Chana, and Realejo. In those cases, the situation supposes a challenge for policy makers because of the ratio of senior population is high, leading a higher likelihood of weekly retail trips to the city centre. Policies that enhance the location of weekly retail in the mentioned neighbourhoods, as well as the promotion of pedestrian itineraries to the city centre would facilitate a reduction of traffic congestion in the city centre.

6. CONCLUSIONS AND DISCUSSION

The present research explored the following research questions: *to what extent is walking accessibility to retail activities similar for different socio-economic groups among the senior population?* Obtained results conclude that walking accessibility is significantly different for the case of weekly retail between the four studied clusters of seniors, while it is quite similar for both daily and incidental retail. In particular, it has been evidenced the existence of time-willingness thresholds in the slot between 20-30 minutes to access to weekly retail for the “younger seniors” in comparison with the rest of seniors, who have a significantly less willingness to go to this type of retail on foot for that time slot.

This research has revealed a strong preference between seniors for reaching different types of retail on foot in Granada, especially for “the motorized seniors”, “the non-motorized seniors”, and “the older seniors”. A total of 88% of participants declared to walk to daily retail, 66% to weekly retail, and 44% to incidental retail. Those results diverge from other studies that highlight the high dependence of motorized accessibility to major locations among seniors (Ricciardi et al., 2015). On the contrary, it represents a strong basis for obtaining sustainable planning outcomes in the mid-term in the case study, assuming that around 30% of population in the south of Spain will be over 65 years old (Soria-Lara and Banister, 2017). For that reason, future urban designs should facilitate walking itineraries for seniors (fundamentally for people over 65 years old), avoiding obstacles, stairs, and any other physical barrier that can impede the walking transit. Mapping those physical barriers and designing policies to overcome them are key issues to foster an effective transition towards lower carbon mobility in the city of Granada.

As seen in previous studies, seniors located in peripheries of cities are under situations of disadvantage accessibility in comparison with seniors living in the city centre (Páez et al., 2010). That also happen for walking accessibility to retail in the case study analyzed. On the one hand, the group of “younger seniors” predominate in those locations and they are group with the lowest willingness to reach retail on foot. On the other hand, peripheries use to have a poor dotation of retail (especially weekly retail), which foster motorized trips between the external neighbourhoods of the city and its centre. Representative examples of that situation in Granada are the neighbourhood of Chana and Zaidin. The implementation of policies that encourage the location of new retail in peripheries could help to solve this situation (e.g., reduced taxes), as well as carrying out policies that restrict the access of motorized vehicles to the city centre triggering a higher number of local and short-distance trips.

It was seen how preferences to reach retail on foot was highly related to the presence of small and traditional stores across the city. All socio-economic clusters with the exception of the "younger seniors" declared its preferences for buying in traditional stores, while "younger seniors" preferred using private vehicles to travel to mall shopping centre for weekly retail in the peripheries of the city.

In this respect, legal regulations that protect the small and traditional stores should prevail because of they are one of the most important source of non-motorized trips in Granada. In this respect, e-commerce is also an on-going threat, but it is still unexplored its impact on the time-willingness of seniors to reach retail on foot.

The obtained findings also open new research horizons. For example, by comparing how relevant is the size of the city in the time-willingness of seniors to reach retail on foot, and by analysing how e-commerce can affect to the walking accessibility. Furthermore, the use of living labs by implementing track systems can be another important source of knowledge to understand more in-depth how the walking accessibility of seniors is different for other groups and what to do to foster it.

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SPATIAL ANALYSIS OF PUBLIC TRANSPORTATION INFRASTRUCTURE IN SANTIAGO, CHILE

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ABSTRACT

Santiago, the capital city of Chile, has seven million inhabitants in an area of 850 km2. This city has a metro network with seven lines extending 140 kilometers and transports approximately 2.6 million people daily. The bus system has undergone significant transformations over the last three decades. The most relevant change having been Transantiago, the public transportation system implemented in 2007 for Santiago, Child, which combines the use of Metro and buses (BRT). Metropolitan Mobility Network (called Red) is the latest version of the public transportation plan.

This paper aims to analyze the current subway infrastructure using the continuous approximation method for Santiago, Chile. We previously proposed a macroscopic methodology to identify the needs for an adequate level of service in urban mobility and transportation, and we applied it to Santiago's Metro network. Our work focuses on functionality and demand distribution. Santiago's demand varies spatially in volume and extension throughout the city. Using the latest origin-destination survey from 2012, we deduct the critical components in this current network structure. It is worth mentioning that the metro design bases its network on a ring-radial structure.

With our macroscopic model applied to Santiago, Chile, we have detected infrastructure needs in the current transit network. The supply of infrastructure should increase for two reasons: first, to achieve balanced cost levels between users and the agency and second, to reduce subway occupations. The optimal model outcomes for Santiago define the optimal network in which the system requires five rings and ten end-to-end longitudinal lines (20 radial routes), including lower levels of occupation. The obtained results are a good preliminary solution, considering the subway infrastructure supply could be sub-estimated in the public transportation plan.

1. INTRODUCTION

Santiago de Chile is an extensive city of 850 km^2, with a population of 7 million inhabitants. The city's road network tends to have a concentric structure with the city's original principal roads crossing the city from East to West. However, only one of the rings proposed with the urban planning tools is in operation. Regarding public transportation, Transantiago is the urban public transportation system that operates in Santiago's metropolitan area, the Chilean capital city.

Transantiago is the result of a sequence of efforts by several governments to improve the public transport system since the early 1990s. Precisely, in 2007, the government launched the system that includes a network of trunk and feeder services whose structural mode is Santiago's subway called Metro, with an integrated and electronic payment system using the Bip card. Unfortunately, the operation exposed errors in design and implementation, which have attracted criticism so far. In 2019, Transantiago changed its name to Metropolitan Mobility Network (Red in Spanish) to improve the existing service.

Santiago's Metro is the articulated mode of transportation for Transantiago. The Metro transports more than 2.6 million people daily on its seven lines extending 138 kilometers and 136 stations. The Metro will continue to expand in the next decade, and is expected to reach 220 kilometers of extension with three new projected lines, lines 7, 8, and 9, in addition to the extension of existing lines 2, 3, and 4.

Several scientific works analytically study the operation of a transit system, e.g., classic articles such as Vuchic and Newell (1968), Wirasinghe and Ghoneim (1981), Chua (1984), and others. Some of these works analyze concentric cities using a structure of polar coordinates for radial networks, such as Haight (1964) and Smeed (1965, 1968).

In this paper, we analyze the current transit infrastructure in Santiago, Chile. The objective is to analyze the Metro network using a proposed macroscopic methodology to identify infrastructure needs to reach an adequate service level in urban mobility and transportation. The continuous approximation method uses analytical formulations and transit information from the latest origin-destination survey in 2012 to deduct the critical components in this current network structure. Our work focuses on functionality and demand. We assume that demand varies spatially in volume and extension over the city. A balance between user and agency costs provides the most efficient network configurations. The city of Santiago has a heterogeneous distribution considering its demand and network distribution.

The next section presents the city of Santiago and its structure, delving into the public transportation network. After that, we explain the methodology, which we apply to the Santiago case. Finally, we present the outcomes and conclusions.

2. GENERAL FEATURES OF SANTIAGO, CHILE

2.1 Santiago's Metropolitan Region and its urban structure

Santiago, founded in the 16th century around the Mapocho River. Currently, Santiago also known as *Gran Santiago* is the capital of Chile. The city belongs to the Metropolitan Region of Santiago, which has six provinces. The province of Santiago is the central province, which has 32 city councils called *Communes*. Fig shows *Gran Santiago* includes these 32 zones plus two more zones: San Bernardo and Puente Alto. The last two zones belong to other provinces; however, these zones are considered as part of the city.

Regarding private transportation, Santiago concentrates 37% of the Chilean automobile market. The city has over eight hundred cars in which the car rate is one car per 7 inhabitants. The primary road is Bernardo O'Higgins Avenue, well-known as Alameda. This road lies from the southwest to the northeast direction of the city, connecting Los Pajaritos Avenue to the west and avenues Providencia and Apoquindo to the east (Fig).

Several longitudinal roads cross the main avenue from the north to the south of the city, e.g., General Velásquez, Panamericana, Independencia, Gran Avenida, Recoleta, Santa Rosa, Vicuña Mackenna, Macul, and Tobalaba. Finally, the ring road called Américo Vespucio surrounds the intermediate zone of the city (Fig).

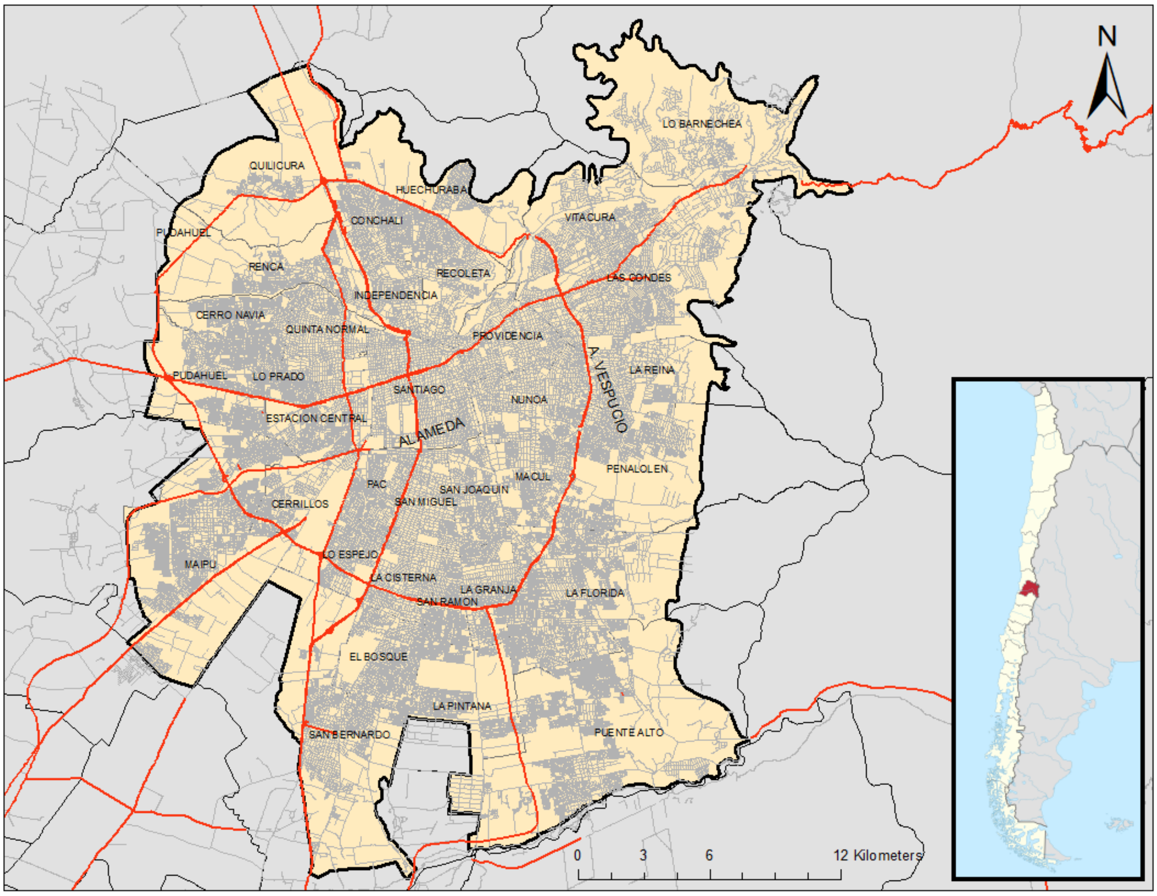


Figure 1: Map of Santiago's urban structure and primary road network.

Most of these roads are very old, even some of them are pre-Hispanic. The roadway had an intercity role from the founding city to other towns. In recent decades, the horizontal growth caused a conurbation of Santiago and the surrounding towns. The foundational Santiago is currently the central commune, a small area representing around 3% of Santiago's total area. Intercity roads become the primary urban roads of the city. Thus, Santiago's town tends to have a radial road structure, although urban planning in Santiago also has mixed development. The planning instruments in Santiago have defined several rings, but only one currently exists.

In 2000, Santiago began the construction of tendered urban freeways. First, Central Freeway runs inside the city from north to south using the old Panamericana road, incorporating General Velásquez Avenue. Second, Américo Vespucio Avenue changed into a freeway, and this road will soon be the first ring freeway in Chile. Third, the Norte Costanera freeway runs parallel to Mapocho River's riverbed and even runs under the river on a road segment. Subsequently, Santiago incorporates the San Cristóbal tunnel and the Access Northorient Highway. All freeways have a free flow toll system in an extension that exceeds 200 kilometers.

Furthermore, Santiago has a fleet of 25 thousand taxis and 11 thousand collective taxis. The latter refers to shared cars with a defined route. In recent years, Santiago promotes bicycles through an incipient network of bike-sharing and the investment of cycleways.

Regarding public transportation, Santiago has a transportation system with extensive subway coverage and buses. Moreover, it has a commuter train. The next sub-section presents information about those in detail.

2.2 History of Public Transportation in Santiago, Chile

Until the early 1970s, Chilean State maintained total control in the passenger transportation industry. The privatization of the urban transportation system began in 1975, increasing the bus fleet and, in the same way, the atomization of the system. In the same year, the first subway car operates a short stretch of the first line of the Chilean subway called *Metro*. Three years later (1978), the agency inaugurated a second metro line. By the early 1980s, the Metro was already an extension of 25 kilometers. On the other hand, surface transportation grouped small companies into Gremial Associations allowing a better operation to set fares and service routes (DTPM, 2019).

In 1989, Santiago's Metro became an independent company of the state apparatus. Metro continues to grow in the following years, incorporating a tunneling construction method without opening the surface and altering urban dynamics. The technique allowed the construction of Line 5 in 1997, starting the construction of Line 4 in 2002 and extending other lines.

On the other hand, the bus system has a new regulation process in 1990, unifying the atomized system through the *Yellow Buses* system. The new framework allows the fare integration between Metro and buses through a new service called Metrobus. The latter opened the system incorporating foreign companies in 2003, consolidating integration creating intermodal stations (subway & bus) in 2004.

The year 2003 began the urban transportation project called Transantiago, implemented in two primary stages. In the first phase, in 2005, the system incorporated the first articulated buses transforming transportation labor unions into traditional companies to operate the system. Also, the system created the financial manager (AFT). In a second phase, in 2007, Transantiago launched changes in all buses' network structure and fare integration. Moreover, it incorporates a single means of access and electronic payment called the *Bip* card. Finally, the system created a specialized unit dedicated to plan and coordinate the operation.

Transantiago covers an area of 2,353 km^2 called *Gran Santiago*. Initially, two sub-systems comprise Transantiago. The former is the trunk line network, whose basis is the Metro's network and bus services operating on the city's main roads, including BRT systems. The latter is the bus feeder network, consisting of local bus services operating on local streets of restricted geographical areas.

From 2010, the Chilean government adjusted the Transantiago system negotiating deals of transportation providers and complimentary services. The new deals came into force in 2012, eliminating the structure of trunk-feeder services and route exclusives for a company. Each company forms a business unit of transportation, which has a defined color. Moreover, 1,120 new high-tech buses entered with high levels of safety and comfort for users. In 2017, the suburban train service called Metrotren incorporated a train to Nos, which links Central Train Station with the southern part of the city.

In the following years, the system added new electric buses. Since March 2019, the transit aims to grow in quality by renaming the Metropolitan Mobility Network, known as the "*Red*" system.

3. PUBLIC TRANSPORTATION NETWORK STRUCTURE

Santiago has three modes of public transportation: subway (Metro), buses (BRTs and traditional buses), and a commuter train (*MetroTren*).

3.1 Metro network

Metro's current system has six lines. The opening of the last one (line 3) was in 2017. The future network plan incorporates three new lines and three extensions for old routes. Figure 2 presents the current subway network and the projected lines, including line extensions.

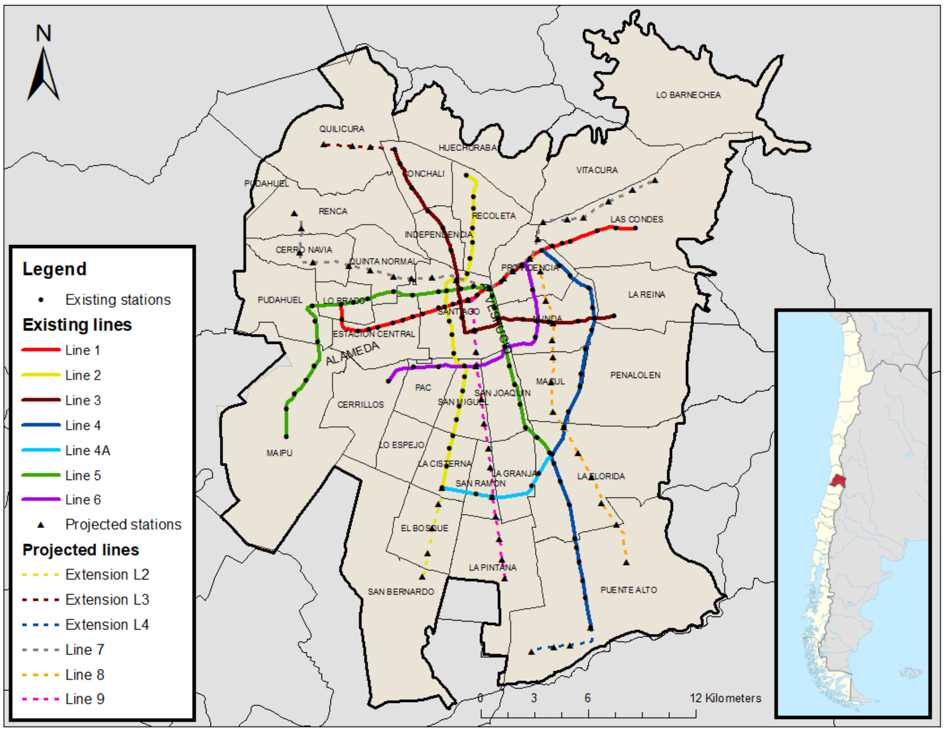


Figure 2: Metro network map: existing lines and future projects.

3.2 Buses network

Transit operators are transportation companies regulated by the National Ministry of Transportation and Telecommunications through the Executive Office called DTPM. Currently, the Red system has six business units, in which a company manages a set of bus services. The service identification is through numbers, letters, and colors. The buses meet the Euro VI emission standard or are electric. The most modern buses are red and white and have WIFI, USB ports and, air conditioning (DTPM, 2019).

The Santiago system has an infrastructure dedicated to bus services. The system has three infrastructure types: corridors, exclusive roads, and bus lanes (FiscalizacionMTT, 2019).

- Bus corridors: Roads include exclusive lanes for buses. These lanes are usually on the central zone of a road, separated from the other lanes. The objective is to increase the commercial speed of buses.
- Exclusive roads: Roads that transit services use exclusively at a schedule.
- Bus lanes: Lanes destined for buses located on the right side of a road, according to the direction of traffic operating at all times and days of the week.

Figure 3 shows the infrastructure dedicated to transit services. Santiago has 19 corridors (red lines), 11 exclusive roads (blue lines), and 53 bus lanes (purple lines). The figure shows that the infrastructure dedicated exclusively to buses has a radial structure from the city center without ring corridors. Moreover, the transit infrastructure reaches neither continuity nor high coverage in the city.

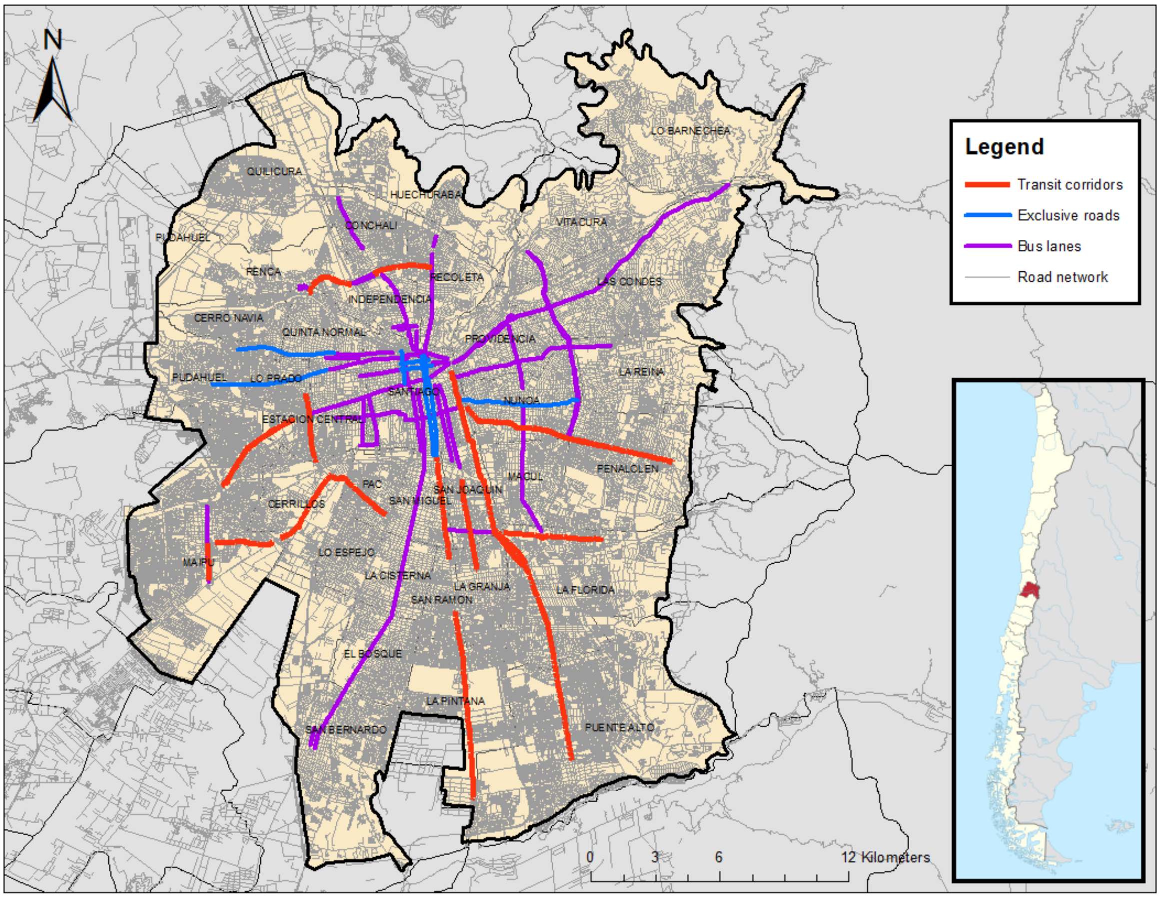


Figure 3: Buses networks: corridors, exclusive streets, and bus lanes.

4. METHODOLOGY

The mathematical model considers the continuous approximation (CA) method proposed by G.F. Newell. The method has applications for transit problems (e.g., Medina-Tapia, Giesen, & Muñoz, 2013; Medina-Tapia, Robusté, & Estrada, 2020, 2021), private transportation issues as well (e.g., Estrada, Salanova, Medina-Tapia, & Robusté, 2021; Medina-Tapia & Robusté, 2018, 2019), and logistics problems (e.g., Pulido, Muñoz, & Gazmuri, 2015).

The region of the modeling is a concentric city of radius R [km]. Santiago is not a perfectly circular city; thus, we adapted the urban area to the modeling but using the real parameters from surveys. The concentric city has ring and radial routes considering the rush hour of the city (P_m) as the period of analysis. We assume non-homogeneous continuous distribution over the city in which each point (r, θ) in polar coordinates has a different density value $D(r_f, \theta_f, r_t, \theta_t)$ in [user/km^4·h] represents the trip density distribution from a point (r_f, θ_f) to (r_t, θ_t).

4.1 Variables

The transit system's network design has four variables: two spatial variables and two temporary variables (Table 4).

Type	Route	Variable	Explanation
Spatial variables	Circular routes	$d^c(r)$	Distance between ring routes with a radius r [km/route]
	Radial routes	$\Phi^r(\theta)$	Distance as an angle between radial routes with an angle θ [radian/route]
Temporary variables	Circular routes	$h^c(r)$	Headway between vehicles at a ring route on r [h/veh]
	Radial routes	$h^r(\theta)$	Headway between vehicles at a radial route on θ [h/veh]

Table 4: Descriptions of decision variables.

4.2 Cost functions

The model formulation contains two components: user (T_T^u in [user·h/P_m]) and agency (C_T^a in [\$/P_m]) costs as show in Equation 1, where can also see that the travel time value (μ in [\$/user·h]) multiplies the user cost function.

$$TC_T = \mu \cdot T_T^u + C_T^a \quad (1)$$

4.2.1 User costs

The total time of users ($T_T^u = T_A + T_W + T_V + T_T$ in [user·h/P_m]) contains four functions (Equation 2): access (T_A), waiting (T_W), trip (T_V), and transfer time (T_T). These equations comes from Medina-Tapia et al. (2021). The time functions in Equation 2 represent the total time for each trip stage of a transit system. The calculation of these functions comes from the integration of the local time function over a circular region:

- Access time: Passengers lose time to get to the closest station or the destination from the origin. First, the demand in rush hour ($f^A(r,\theta) \cdot T$ in [user/km2·P_m]) is the density of users that board and alight at a station/stop during the rush hour. Second, the average accessibility time per user, $t^A(r,\theta)$ in [h], depends on the time perception and the average access time.
- Waiting time: The passenger density that boards a vehicle is $f_l^W(r,\theta) \cdot T$ in direction $l \in L$ during rush hour ([user/km2·P_m]). The average waiting time per passenger at a station is $t_l^W(r,\theta)$ in [h], which depends on the time perception factor and time headway of a service (Medina-Tapia et al., 2013).
- In-vehicle travel time: The total travel time depends on two components: the user load density in rush hour ($f_l^V(r,\theta) \cdot T$ in direction $l \in L$ in [user/km·P_m]), and the travel time per kilometer ([h/km]).

- Transfer time: Two factors comprise this local time function. The user density that transfers at a point (r, θ) to direction $l \in L$ ($f_l^T(r, \theta) \cdot T$ in [user/km2]) and the average transfer time function.

4.2.2 Agency costs

The agency cost has three components (C_T^a in [$/$P_m$]): capital ($C_K$), operational ($C_O$), and infrastructure cost (C_I). The last two costs have sub-components. The operational cost ($C_O = C_G + C_V$) includes the on-vehicle crew cost (C_G), and in-operation vehicle cost (C_V). The infrastructure cost ($C_I = C_P + C_S$) includes the linear (C_P) and nodal infrastructure (C_S). The explanations of Equations 2 are at Medina-Tapia et al. (2021).

- Capital cost: The cost value ($C_K = \sum_{l \in L} F_l \cdot \varphi^k$ in [$/$P_m$]) depends on the fleet in direction $l \in L$ (F_l in [veh]) and the cost per vehicle (φ^k in [$/veh·$P_m$]).
- Operational cost: First, the total salary ($C_G = F \cdot \eta^d \cdot T \cdot \varphi^g$ in [$]) is in proportion to three components: the fleet ($F_l, l \in L$), the number of work shifts on a vehicle (η^d), and the salary in rush hour ($T \cdot \varphi^g$). Second, the total operating cost (C_V in [$]) comprises two components: the number of vehicles that run on a corridor ($2T/h^c(r)$ or $2T/h^r(\theta)$ respectively), the operation cost per unit of distance traveled on a cruising speed (φ^o) considering the width of a transit corridor $d^c(r)$ or $\Phi^r(\theta)$.
- Infrastructure cost: The linear infrastructure cost (C_P) depends on the number of routes and its length of rings and radial routes ($\frac{1}{d^c(r)}$ or $\frac{1}{\Phi^r(\theta) \cdot r}$ in [km·route] in direction $l \in L$), and the unitary cost (φ^p in [$/km·route·$P_m$]). The unitary cost per km in the rush hour has a fixed component and another variable part ($\varphi^p = \varphi^{p(f)} + \varphi^{p(v)} \cdot T$ in [$/km·route·$P_m$]. The nodal infrastructure (C_S) depends on the number of intersections $\frac{1}{\Phi^r(\theta)} \cdot \frac{1}{d^c(r)}$ and the unitary cost φ^s in [$/station·route·$P_m$], considering each intersection has four stations or stops.

4.3 Problem formulation and optimization

The TNDFSP (transit network design and frequency setting problem) minimizes the system's total cost, taking a heterogeneous demand distribution into account. The formulation of the total cost of a transit system (Equation 1) in monetary units ([$/$P_m$] contains two components (Estrada, Roca-Riu, Badia, Robusté, & Daganzo, 2011): the user cost component (T_T^u in [user·h/P_m]), which is multiplied by the travel time value (μ in [$/user·h]), and the second component of agency costs (C_T^a in [$/$P_m$]).

$$Min\, TC_T = \mu \cdot (T_A + T_W + T_V + T_T) + (C_K + C_V + C_I) \quad (2a)$$

$$\max_{\theta, l \in \{c_c, c_a\}} \left(f_l^V(r, \theta) \cdot d^c(r) \cdot h^c(r) \right) \leq K^v \quad \forall\, r \quad (2b)$$

$$\max_{r,l\in\{r_i,r_o\}} \left(f_l^V(r,\theta)\cdot\Phi^r(\theta)\cdot(R+r)/2\cdot h^r(\theta)\right)\leq K^v \quad \forall\,\theta \tag{2c}$$

$$d^c(r)\geq K^{d(c)} \quad \forall\, r \tag{2d}$$

$$\Phi^r(\theta)\geq K^{d(r)} \quad \forall\,\theta \tag{2e}$$

$$h^c(r)\geq K^h \quad \forall\, r \quad (2af$$

$$h^r(\theta)\geq K^h \quad \forall\,\theta \tag{2g}$$

The problem framework is a fixed spatial transit system whose mathematical problem is a nonlinear system that includes inequality constraints.

First, the problem has four decision variables ($d^c(r), \Phi^r(\theta), h^c(r), h^r(\theta)$) according to the spatial and temporal deployment of resources. In this problem, the fixed variables do not change along a corridor. Second, the problem has three sets of constraints. The first of these (Equations 2b and 2c) ensures that occupancy does not exceed the capacity of each vehicle (K^v in [user/veh]). Second, the minimum distance between stations ensures that transit vehicles reach the cruising speed before arriving at the next station and can correctly brake (Equations 2d and 2e).

In the case of radial routes (Equation 2e)), $K^{d(r)} = K^{d(c)}/r_{min}$, where r_{min} is a minimum radius in which this constraint applies in [km/route] or [rad/route], respectively. Finally, the operator requires a minimum separation (time) between consecutive vehicles (TRB, 2013). Equations 2f and 2g ensure that the optimum frequency is feasible (K^h in [h/veh]).

5. RESULTS

The section has three parts. First, the section presents the parameters used in the modeling, including continuous demand density functions. Second, the section also presents the optimal solutions obtained from the model. Third, the section analyzes a comparison between the obtained optimal solutions and the metro network for Santiago, Chile.

5.1 Modeling inputs

5.1.1 Parameters

The modeling considers Santiago's urban shape approaching a concentric city, explained by Medina-Tapia et al. (2021). The modeled city has a radius of 15 km (R), and the rush hour lasts 1.5 hours (T). Table 5 shows the parameters in each stage of a trip, using the time perception from TRB (2013).

Demand parameters							
T [h]	α [dimensionless]	β [dimensionless]	γ [dimensionless]	δ [dimensionless]	v^w [km/h]	χ^T [m]	$v^a(r)$ [km/h]
1.5	2.2	2.1	1.0	2.5	3.0	40	$v^a(r) = 3.0 + 1.4\bar{6} \cdot r$

Operational parameters												
v^t	a^a	a^d	τ	τ'	τ''	τ'''	τ^s	t^f	η^d	K^v	K^d	K^h
[km/h]	[m/s²]		[s/station]					[min]	[shift/veh]	[user/veh]	[km/route]	[s/veh]
80	1.3	1.3	19.2	5	35	0	42.1	6	1	1,494	0.481	123

Economic parameters							
μ	φ^k	φ^g	φ^o	$\varphi^{p(f)}$	φ^p	$\varphi^{s(f)}$	φ^s
[$/user·h]	[$/veh]	[$/shift·h]	[$/km·veh]	[$/km·route·$P_m$]		[$/station·route·$P_m$]	
1.48	135.6	27	3.7	245.1	248.8	169.9	172.4

Table 5: Parameters used for user and agency cost functions.

5.1.2 Trip generation and attraction functions

The proposed model considers a concentric city, which has a public transportation system with two types of transit services: ring and radial routes. Santiago is a concentric city but does not have a perfect circular form; however, the modeling assimilates that the city has this urban form. The last Origin-Destination survey (MTT, 2012) sets over 700 zones for *Gran Santiago* city; however, the modeling simplifies zoning by dividing the city into 9 OD macro-zones: a central zone, four inner zones, and four outer zones (Fig). Table shows the information of subway trips at rush hour comes from the Santiago OD survey (MTT, 2012) using the OD grouping of the nine macro zones.

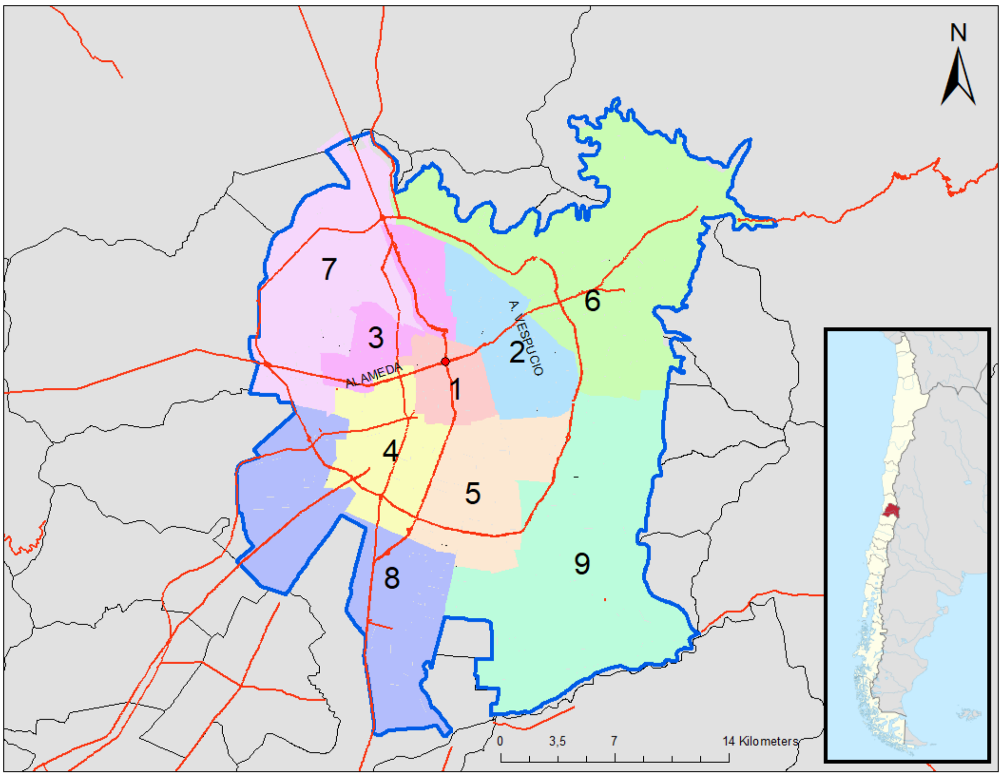


Figure 4: OD macro-zones used for the Santiago of Chile modeling.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
1	10575,5	7440,5	2346,0	1588,0	2728,5	9605,5	1326,4	624,7	1712,3	**37947,4**
2	22458,0	19583,3	1659,0	981,5	2973,0	9652,2	1023,6	609,0	4306,6	**63246,2**
3	12596,8	6248,9	9025,0	2018,6	727,9	3685,2	4103,0	974,6	694,6	**40074,7**
4	17550,9	5922,7	779,9	9656,3	3624,0	3462,8	1702,7	5936,3	2074,1	**50709,7**
5	14958,5	9937,8	494,7	1350,1	16573,4	7533,6	1859,1	1382,2	8933,3	**63022,7**
6	15385,9	16619,7	1985,5	1666,7	3754,5	24629,7	2246,1	334,7	2250,3	**68873,2**
7	20471,6	14257,2	13896,9	1983,4	1533,2	14097,3	32123,3	2548,4	374,4	**101285,8**
8	25495,8	13724,3	3938,1	8662,8	5836,0	7327,9	2766,1	50812,3	7306,0	**125869,4**
9	31559,0	30074,8	4648,4	5759,6	17143,4	18355,3	2062,1	3917,2	66970,2	**180490,0**
Total	**171052,0**	**123809,4**	**38773,5**	**33666,9**	**54893,9**	**98349,6**	**49212,4**	**67139,4**	**94621,9**	**731519,1**

Table 3: Santiago's OD macro-matrix in [trip/P_m] obtained from OD Survey (MTT, 2012).

The method calibrates a continuous function in which the total trips of each origin-destination (Table) is the value in the OD trip matrix (T_{ij} where i is the origin zone, and j is the destination zone), as shown in Equation 3. The coordinates $\theta^i_{f(2)}$-$\theta^i_{f(1)}$ and $r^i_{f(2)}$-$r^i_{f(1)}$ define the origin zone. Meanwhile, the coordinates $\theta^i_{t(2)}$-$\theta^i_{t(1)}$ and $r^i_{t(2)}$-$r^i_{t(1)}$ define the destination zone.

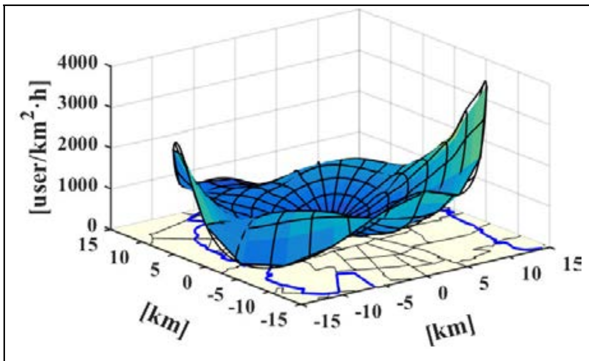
$$T_{ij} = \int_{\theta^i_{f(1)}}^{\theta^i_{f(2)}} \int_{r^i_{f(1)}}^{r^i_{f(2)}} \int_{\theta^i_{t(1)}}^{\theta^i_{t(2)}} \int_{r^i_{t(1)}}^{r^i_{t(2)}} D\left(r_f, \theta_f, r_t, \theta_t\right) r_t \, dr_t \, d\theta_t \; r_f \, dr_f \, d\theta_f \tag{3}$$

Using the function of Equation 3, we obtain the function of generated demand $\lambda(r,\theta)$ at a point (r,θ) in [user/km^2·h] (Equation 4, and attracted demand $\rho(r,\theta)$ at a point (r,θ) in [user/km^2·h] (Equation 5).

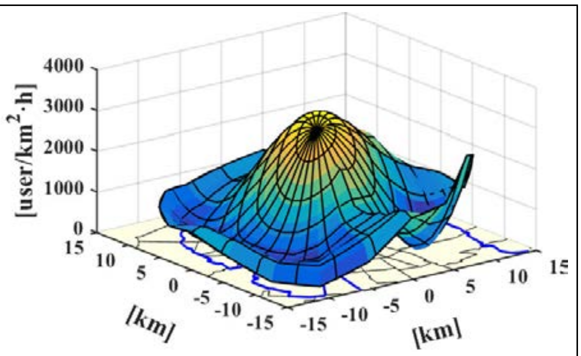
$$\lambda(r,\theta) = \int_0^{2\pi} \int_0^R D(r,\theta,r_t,\theta_t) \, r_t \, dr_t \, d\theta_t \tag{4}$$

$$\rho(r,\theta) = \int_0^{2\pi} \int_0^R D\left(r_f,\theta_f,r,\theta\right) r_f \, dr_f \, d\theta_f \tag{5}$$

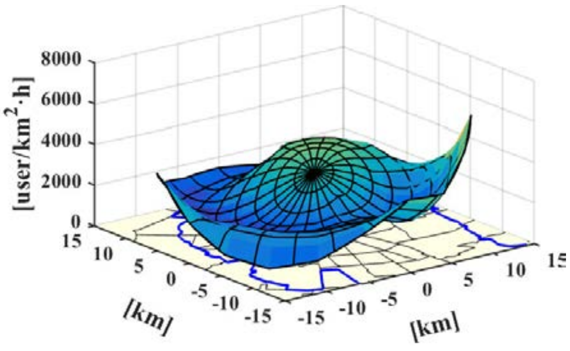
Fig 5 shows the functions of trip generation (Fig (5a)) and attraction (Fig (5b)) obtained from Equations 5. Fig (5c) represents the total trip density function, i.e., the sum of generated and attracted demand functions.



(a) Trip generation function



(b) Trip attraction function

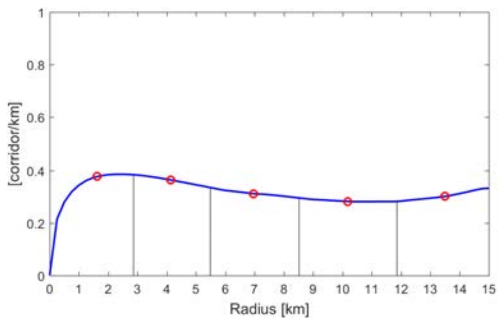


(c) Total trip function

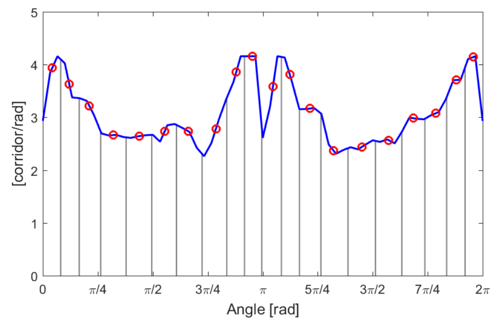
Figure 5: Functions of trip generation and attraction estimated from Santiago's OD matrix (MTT, 2012).

5.2 Optimal solutions obtained from the model

The problem formulation is optimized using KKT conditions. Each point has an optimal solution of density and headway for ring and radial routes. Fig 6 presents the optimal transit density profiles for Santiago, Chile, obtained from the model. The blue line in Fig (6a) represents the optimal ring route density, and Fig (6b) represents the optimal solution for radial routes. The red points represent the optimal location of a route obtained from the discretization process. From optimal transit densities, Fig (7a) shows the macroscopic scheme of transit corridors for Santiago, Chile. Fig (7b) contains the optimal network structure in which a label on each route shows the optimal headway in minutes and the fleet size in trains for rings and radial routes.

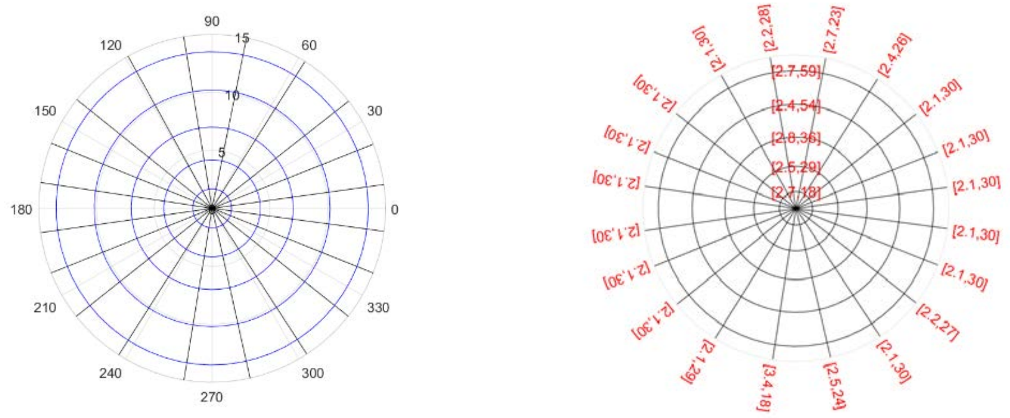


(a) Ring routes



(b) Radial routes

Figure 6: Optimal density profiles for Santiago, Chile.



(a) Optimal transit structure (b) Optimal headways

Figure 7: Optimal transit network scheme for Santiago, Chile.

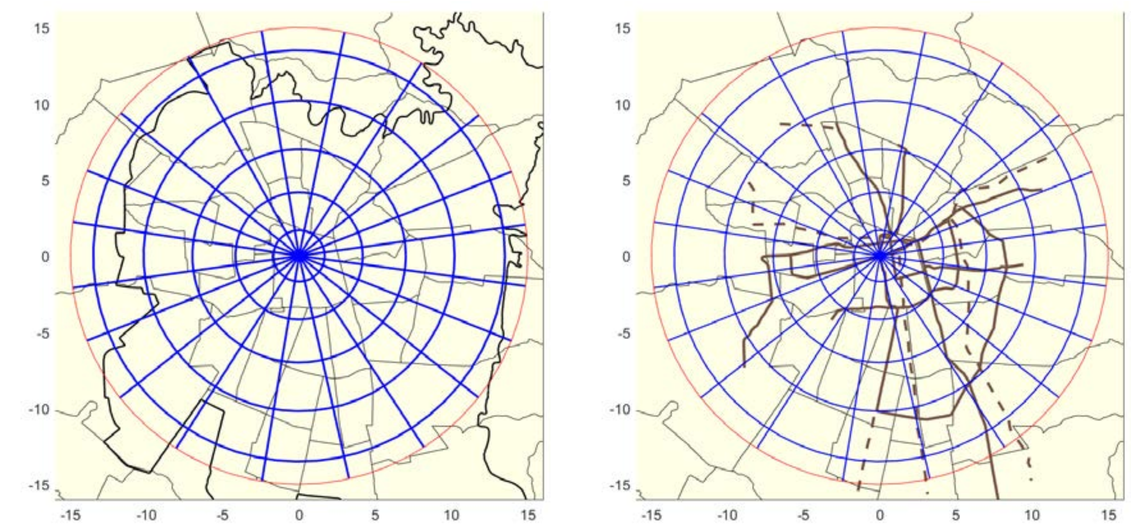
Note: In Fig(b), [X1, X2] in red represents the optimal operation attributes in which X1 is the time headway in minutes and X2 is the fleet size in trains for each route defined optimally.

Regarding ring routes in Fig (7a), the model proposes five transit corridors, whose distribution is slightly higher around the city center. Regarding radial routes in Fig (7a), the model proposes 20 corridors with non-homogeneous distribution with higher density in three zones: East zone (above 0 radians, including Providencia and Las Condes *communes*), West zone (above and below π radians, including Estación Central, Maipú, Pudahuel *communes*), and Southeast (below 0 radians, including La Florida and Puente Alto *communes*). It is worth noting that 20 radial lines could represent ten lines from one side of the city to the opposite.

Regarding ring routes in Fig (7b), headways take on similar values between 2.4 and 2.8 minutes. However, the cycle times on each route are different considering the vehicle-kilometers traveled increases as the route approached the city periphery. Thus, the fleet size that needs a route increases from 18 to 59 trains. Regarding radial routes in Fig (7b), all routes have the same length, but the fleet size depends on the headway and the optimal ring density giving fleet needs from 18 to 30 trains. In a city whose transit vehicles travel long distances, slight headways modify the fleet size significantly.

5.3 Comparison between the optimal solution and Santiago's metro network

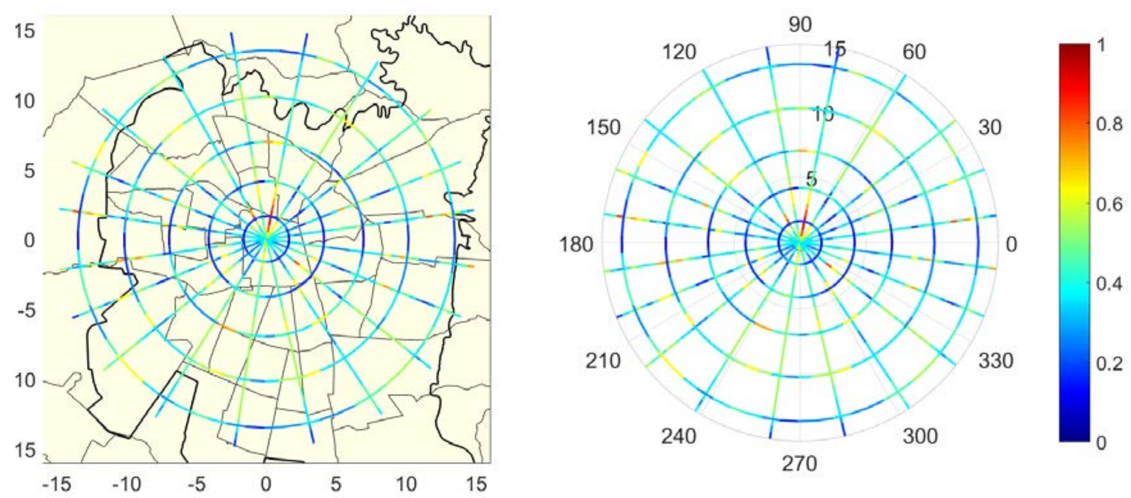
Fig presents a comparison between the subway infrastructure proposal obtained from modeling and future subway projects for Santiago, Chile.



(a) Optimal transit structure (b) Comparison of proposal and subway infrastructure

Figure 8: Comparison between subway infrastructure proposal and current and future projects for Santiago, Chile.

Fig (8a) shows blue lines representing the optimal transit structure, the red circle represents the analyzed area, and the map in the background shows the *communes* of Santiago city, Chile. Fig (8b) also includes the current infrastructure and the future subway projects as brown lines for Santiago, Chile, where continuous lines are existing infrastructure, and dashed lines are the future projects. Currently, Santiago's Metro has seven lines; however, it represents nine existing radial routes, including their extensions; meanwhile, the three new projected lines represent four more radial routes. Globally, the subway mobility plan proposes 13 radial routes, which should increase to 20 radial routes, according to the model. Regarding rings, the transit system only proposes two incomplete rings, which should increase to 5 ring routes.



(a) Santiago and occupation levels (b) Occupation levels

Figure 9: Map of occupation levels obtained from the optimal transit network.

From optimal transit densities, Fig (9a) and (9b) show occupation levels of transit routes for Santiago, Chile. The former overlays the optimal transit network with the map of *communes* of Santiago, Chile. Regarding occupation levels, rings have a maximum occupation of up 75%; however, the average occupation is around 25%. On the other hand, radial routes reach an occupation of up 92% with an average occupation around 37%. Therefore, the global transportation system is not stressed by high occupancy levels.

6. CONCLUSIONS

Santiago, Chile, has a consolidated subway network of more than 50 years with seven lines currently operating. The investment plan considers the extension of some of these lines and the construction of three future projects.

The modeling in the paper uses standard values of operating data. However, some parameters were adapted to the Chilean case, such as the value of time, the train capacity, and the transit demand. In this line, the continuous travel distribution function obtained from the travel matrix origin-destination between macro-zones allowed to represent the generation and attraction of trips. A territory does not have a staggered structure with breaks between two OD-zones boundaries. On the contrary, demand generally varies smoothly from one side of an OD zone boundary to the other side.

The model obtained a macroscopic proposal for subway infrastructure needs, i.e., the modeling applied a theoretical mathematical model previously presented, defining a relevant approach to determine the infrastructure needs for the city of Santiago. The proposed model for Santiago considers 5 rings and 20 radial routes. The comparison between this proposal and the current network plus the planned defines Santiago's infrastructure needs: 13 new radial routes (equivalent to 7 more lines) and four more rings.

Future studies could study complementing these central services with tram services, particularly in Santiago's central commune. It is worth noting that slight headway changes modify the fleet size significantly. The fleet size depends on the headway and the opposite optimal route density or transit stations for the modeling. The latter relates to the time spent due to users boarding, alighting, and others, increasing the cycle time.

The proposal network proposes lower occupation vehicle levels: the maximum occupation of rings is 75%, and radial lines have a maximum occupation of 92%. However, the average occupation of rings is around 25%, and the average radial occupation is 37%.

Therefore, Santiago, Chile, should increase infrastructure supply for the subway network in future strategic planning. The results are considered an interesting preliminary proposal; however, the research approach should be refined through complementary studies. These studies should consider information from all available origin-destination zones, periods, transport purposes, and others. Future studies should also analyze current services with complementary modes (e.g., tram services); and personal mobility modes within a sustainability framework.

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THINKING THE UNTHINKABLE: THE DESIGN OF DISRUPTIVE VISIONS FOR LAND USE AND TRANSPORT INTEGRATION

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ABSTRACT

Transport Scenario-Building is a well-established methodology to investigate strategic decisions for cities and its transport systems. It is often used to examine different futures where there is considerable uncertainty or where the business-as-usual is no longer appropriate. While the use of participatory approaches in Transport Scenario-Building has resulted in more democratic and implementable outcomes, the usefulness of those approaches is limited when the generation of disruptive transport futures and unusual policy solutions are considered.

This paper addresses the abovementioned issue by presenting a participatory approach aimed to obtain disruptive visions on land use and transport by 2050. The context of the Metropolitan Area of Madrid (Spain) is taken as case study. The novel approach incorporates disruptive factors about city futures - “wild cards”- during the participatory visioning process, triggering an unconventional thinking from participants. First, a total of 139 people were engaged by using semi-structured interviews on the future of land use and transport in the case study. Each semi-structured interview explored the desired future for each participant as well as disruptive futures according to “wild cards” previously established. Second, responses were transcribed, coded, and analysed resulting in seven different future narratives.

Third, a group of 20 experts in innovation and strategic thinking evaluated the disruptive level of each future narrative with respect to a business-as-usual scenario. The paper shows the methodological process, the future narratives obtained, and reflects on the capacity of this participatory approach to generate disruptive future visions for land use and transport.

1. INTRODUCTION

Cities and transport systems are changing faster than ever, which is a fertile ground for the emergence of sudden, unique, anomalous, and low predictable incidents (Barber et al., 2006; Dammers, 2010). In this apparently changing age, transport planning experiences challenging times, in which instrumental rationality has come under attack (Innes and Booher, 2018) and deep uncertainty must be treated when supporting decision-making (Lyons and Marsden, 2019; Marchau et al., 2019; Navarro-Ligero et al., 2019). The incorporation of low predictable incidents/processes into decision-making remains a challenge that strongly limits the options for non-linear policy pathways. Those low predictable incidents/processes are here called wild cards: sporadic events or long-lasting processes that are assumed to be improbable, but would have large consequences for cities, transport systems, and social trends if they finally take place (Mendoça et al., 2004; Smith and Dubois, 2010).

Transport scenario building is a well-established methodology that can effectively address the challenge of incorporating wild cards in decision-making (Hickman and Banister, 2014; Soria-Lara and Banister, 2017a; Van Drunen et al., 2011). Transport scenario building investigates strategic and long-term futures marked by considerable uncertainty (e.g., the role of street space in cities) and/or situations where business-as-usual is no longer appropriate (e.g., transport emissions). The visioning phase is a crucial methodological step in transport scenario building, where a series of explorative and/or normative visions are constructed about the city's future and its transport systems (Banister and Hickman, 2013). This methodological phase is seen as a democratic exercise where "all voices" should be heard (Wangel, 2011), engaging the widest variety of actors: members from the public, practitioners, policymakers, etc. (Soria-Lara and Banister, 2017b; Tuominen et al., 2014).

Although there has been a burgeoning application of participatory visioning approaches in the transport field (Zimerman et al., 2012; Wangel, 2011; Hickman et al., 2011; Schade and Schade, 2005; Olsson et al., 2015), limited attention has been paid to deal with non-linear thinking. The implementation of participatory visioning has usually followed consensus-based techniques (e.g., Delphi methods), which limits the capacity to add outlier views into future visions (Shiftan, 2003; Melander et al., 2019). Experts-guided processes have been predominant in participatory visioning exercises, and those experts are usually trained to visualise futures linearly (Hickman and Banister, 2014). Visionary participants are also heavily influenced by current social and technological trends, making outside-the-box thinking a challenge (Soria-Lara and Banister, 2018a). If those barriers persist, the social, democratic, and participatory value of visioning processes will be curtailed, and their strategic value for decision-making will be drastically reduced, due to the limited capacity to incorporate disruptive views. As a result, linear thinking will continue to dominate, reducing the usefulness of transport scenario building.

To address these challenges, this paper aims to explore the following research question: To what extent can the use of wild cards stimulate a more disruptive thinking in participatory visioning? To explore potential answers, a specific region in the Metropolitan Area of Madrid (the Henares Corridor) provides the empirical focus. In a first step, a total of 129 participants were engaged via semi-structured interviews to construct a desirable future vision on transport and land use by 2050. In a second step, the same participants were asked to distort their desired future vision according to six context-based wild cards, guiding participants to visualise additional endpoints outside of their comfort zone. The visioning exercise resulted in seven 2050 visions: one desired vision plus six wild card visions. Then, the level of disruptive thinking reached during the visioning process was evaluated by a group of 21 experts.

The remainder of the paper is organised as follows. Section 2 outlines the theoretical background and the working hypothesis. Section 3 provides details on the research design, including a description of the case study. Section 4 summarizes the main results. Finally, Section 5 closes with concluding remarks and reflections.

2. THEORETICAL BACKGROUND AND WORKING HYPOTHESIS

Current participatory approaches in transport scenario building usually do not generate radical, anomalous, and low predictable visions. A group of authors have used workshops and focus groups to stimulate open and deliberative visioning processes (Banister and Hickman, 2013; Hickman and Banister, 2007; Hickman et al., 2009), rather than implementing more-restricting methods (e.g., questionnaires). However, the obtained long-term visions are still very close to the business-as-usual (BAU) projection, being strongly focused on linear thinking. To overcome this limitation, Tuominen et al. (2014) involved young participants during the visioning stage, resulting in more “original” visions. Soria-Lara and Banister (2017b) also evidenced the higher capacity of younger and non-expert participants to visualize more disruptive visions compared to highly experienced professionals, adults, and seniors.

Traditionally, Delphi techniques, in-depth interviews, and workshops have been used for participatory visioning. The dominance of a consensus-based approach limits the chance to incorporate outliers and divergences. Delphi techniques usually build future visions by carrying out several rounds of questions, where experts are informed about the main agreements reached in past participatory rounds (Mason and Alamdari, 2007; Melander, 2018; Shiftan et al., 2003; Zimmerman et al., 2012). When other more open participatory methods are used (e.g., in-depth interviews and workshops), only highly frequent and common thoughts remain in the obtained visions, limiting the incorporation of “outside-the-box” thinking into the process (Soria-Lara and Banister, 2018b). Other aspects impeding disruptive thinking are the use of BAU projections to orient participants during visioning processes (Julsrud and Uteng, 2015; Piecyk and McKinnon, 2010; von der Gracht and Darkow, 2016), and the construction of a single long-term vision instead of a wide range of options (Mason and Alamdari, 2007; Schuckmann et al., 2012; Trolley et al., 2001).

It is believed that utilizing wild cards –low probability and high impact processes- in participatory visioning processes can break down the abovementioned barriers and stimulate inventive, non-traditional outcomes in participatory visioning exercises. Traditionally, wild cards have been used to analyse unexpected future trends (Barber et al., 2006) as well as to test the stability of future visions in light of external and internal interferences (Steinmuller, 2004). For example, four different wild cards are used to test the robustness of long-term visions in the framework of the European Spatial Planning Cohesion Policies (Dammers, 2010). In the particular context of transport scenario building, Hauphman et al. (2015) explore fourteen technological, geopolitical, and societal wild cards, analysing their likelihood of occurrence and potential effects. Walsh et al. (2015) also use wild cards as a destructive test to evaluate the behaviour of future transportation infrastructure systems. Finally, Von der Gracht and Darkow (2010) extract wild cards from a Delphi process and deploy them to visualise long-term transport logistics futures by using divergent views in combination with desk work. However, the mentioned authors do not test the level of disruptive thinking reached for each vision.

The basic hypothesis underlying this paper is that wild cards can be used to stimulate thinking outside of the BAU zone during participatory visioning processes. Specifically, wild cards could be useful for interrupting linearity in the participants’ visioning processes, resulting in more-disruptive outcomes (Figure 1). The confirmation of this hypothesis –even partially- can show useful and practical lessons for decision-making and planning processes.

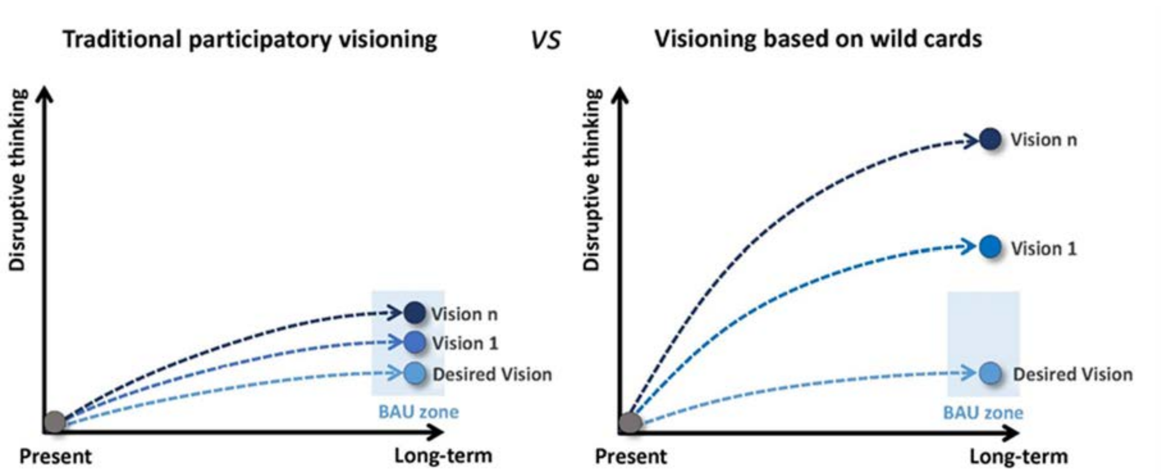

Figure 1: Working hypothesis

3. RESEARCH DESIGN

Our participatory visioning approach entailed three-stages:

- Case study and wild cards selection:
- Construction of 2050 visions and sample characteristics:
- Evaluation of disruption of 2050 visions.

3.1 Case study and wild card selection

The Henares Corridor (approx. 50 km) is located in the east part of the Metropolitan Area of Madrid (MAM) in Spain, connecting the cities of Madrid (3,223,334 inhabitants) and Guadalajara (255,336 inhabitants). More than a million people live in the 17 municipalities located in the Henares Corridor (INE, 2021). It is one of the most industrialised places in the MAM, originating a relevant number of commuters (Barreira-González et al., 2019; Cantergiani and Gómez-Delgado, 2018).

A set of context-based wild cards have been identified to confirm/deny our working hypothesis. Specifically, the research team identified six wild cards (table X) that would disrupt the BAU projections in official planning documents for the case study. The level of context-based surprise originated by those six wild cards was also discussed, identifying two different types:

- imaginable processes: possible surprises in the short and long term
- unimaginable processes: highly improbable surprises in both the short and long term.

Imaginable processes	Unimaginable processes
Zero-emission vehicles: Fossil fuel–powered vehicles will be fully prohibited in the case study, including individual and collective transport modes.	*Shared motorized mobility dominates:* Individual car ownership will be fully prohibited, and only shared motorized mobility can be used in the case study.
Non-motorized city centres: City centres along the corridor will be exclusively limited to active mobility (walking and cycling) and certain collective transport modes. Access to city centres by car will be fully prohibited.	*Overpopulation:* Natural disasters triggered by climate change will originate strong migratory movements from other geographical latitudes to European countries, resulting in a 200% population increase in the Henares Corridor.
E-working dominates: E-working will be implemented for all jobs where physical presence is not required.	*High levels of insecurity in urban areas:* The public space will become very insecure due to high social inequality rates. Walking, cycling, and motorbiking are not advisable actions.

Table 1: Wild cards selected.

3.2 Construction of 2050 visions

Semi-structured interviews were conducted to construct 2050 visions on transport and land use, totalling 129 valid interviews. Each semi-structured interview consisted of four-time blocks. In the first block participants provided socio-economic details (e.g., age, gender, frequent transport mode). In the second block participants shared their desired 2050 vision on transport and land use for the case study. They were asked to visualise an ideal workday in 2050. According to that imaginary day, they had to openly respond to the following questions:

- How do you see covering your daily travels to work, leisure, and shopping on this imaginary day?
- How does the neighbourhood you live in look like?

The third block of the interview focused on distorting the 2050 desired vision generated in the second block, by using the imaginable processes detailed in Section 3.1. First, participants had to select the most disruptive of the three imaginable processes (Table 1), according to their individual opinion. Second, participants had to respond to the same questions from the second block of the interview, conditioned by this imaginable process. Finally, the fourth block of the interview focused on distorting the 2050 desired vision generated in the second block of the survey, by using the unimaginable processes detailed in Section 3.1. First, participants had to select the most disruptive of the three unimaginable processes previously presented. Then, participants had to respond to the same questions from the second block, conditioned by this unimaginable process.

In summary, each semi-structured interview provided a total of three individual visions per participant: desired vision (block 2); vision based on one imaginable process previously selected by the interviewee (block 3); vision based on one unimaginable process previously selected by the interviewee (Block 4). Then, those individual visions were codified and added to other individual visions to obtain collective 2050 visions. Each collective vision was translated into a specific narrative, with seven narratives in total: the 2050 desired vision plus six 2050 wild card visions (three visions based on imaginable processes and three visions based on unimaginable processes). To provide legitimacy over the process, the sample target included members from both the public and professionals from a wide range of sectors. All selected participants were younger than 32 years old, i.e., those who would be at most 65 years old by 2050, the visioning horizon.

3.3 Evaluation of disruption of 2050 visions

To analyse to what extent this participatory approach can stimulate non-linear thinking, the seven 2050 visions were evaluated by a group of 21 experts in innovation, strategic decision-making, and creative thinking. The aim of the evaluation was to grade the seven 2050 visions according to their disruptive thinking level. The evaluation was completed via an on-line questionnaire, based on asking the expert to indicate whether the 2050 visions were:

- non-disruptive
- somewhat disruptive
- disruptive
- very disruptive
- highly disruptive.

Descriptive analysis based on the frequency of responses were used to evaluate the level of disruptive thinking reached by each 2050 vision.

4. RESULTS

4.1 The desired collective vision for 2050

Based on participant responses, the narrative for the desired vision could be formulated as follow:

> *This vision relies on decreasing the level of transport emissions; however, the daily modal split remains largely unaltered. Cleaner private vehicles dominate work commutes, while fossil fuel–powered vehicles are not fully replaced. E-working is seen as a marginal option and walking and cycling are the preferred modes for shopping and leisure activities. A relevant percentage of vehicles are autonomous. Cities have reduced the distances between residential, shopping, and leisure places – by high levels of mixed-use planning and by connecting amenities in a dense network of green corridors. However, workplaces are far away from residential areas and are still mainly located in the city's periphery. Both residential and work areas are connected by car infrastructures and efficient public transport services.*

4.2 Visions based on imaginable processes

Based on participant responses, the narrative for the "zero-emission vehicles" 2050 vision could be formulated as follows:

> *The vision relies on a fundamental technological change – the prohibition of motorized vehicles that are not zero-emission vehicles. However, it does not bring about a drastic change in the daily modal split. Zero-emission vehicles (collective and private) are the main mode for reaching daily work destinations. E-working is seen as a marginal option, while walking and cycling are the desired mode for reaching shopping and leisure activities. A relevant percentage of vehicles are autonomous. Also, car-sharing has a substantial share in personal mobility. Cities should provide for shorter distances between residential, shopping, and leisure places, requiring areas with a high mix of those activities and connected each other by a dense network of green corridors. Workplaces are mainly located in the city's periphery and far away from residential places. Both residential and working areas would be connected by car infrastructures and efficient collective transport services.*

According to participant responses, the following narrative was constructed for the imaginable process “non-motorized city centres”:

> *This 2050 future is fundamentally based on the full restriction of private vehicles access to city centres. All public space in city centres is recovered for active mobility – with the exception of public transport road space and platforms – and for the creation of socialization spaces (e.g., parks, leisure areas). That would increase walking and cycling levels to all daily destinations (work, shopping, and leisure activities). E-working is seen as a marginal option. The restriction of private vehicles access to city centres would severely limit both the rollout of autonomous vehicles and the promotion of car-sharing services. There would be a preference for cities that offer a high mix of residential, shopping, leisure, and working places, reduce the distances between those activities and foster active mobility patterns. Consequently, working places would be transformed into more mixed-use areas. A dense network of green corridors will connect different places of the case study.*

The following 2050 vision can be generated according to the wild card “e-working generalization”:

> *This 2050 future is distinguished by the e-working generalization, with all jobs not requiring physical presence. That would initiate a change in modal split patterns, increasing walking and cycling levels for daily destinations such as shopping and leisure activities. Car ownership rates would drastically decrease in favour of car-sharing solutions. Moreover, a percentage of vehicles would become autonomous. People would still prefer to live in the city’s periphery, but in mixed use neighbourhoods marked by shorter distances between residential, shopping, and leisure places, triggering an increase of active mobility. A dense network of green corridors will connect residential, shopping, and leisure activities. Current workplace destinations would be transformed into mixed use locations, as most of workplaces would be located at individual households or other community (co-working) locations.*

4.3 Visions based on unimaginable processes

Based on participant responses, the following narrative has been elaborated according to the wild card “Overpopulation”:

> *This 2050 vision would trigger changes in modal split patterns, with increased use of collective modes for work commuting and increased walking and cycling rates to shopping and leisure locations. Car ownerships rates would decrease in favour of a generalization of car-sharing habits. E-working would be seen as a marginal option. There would be a preference from high-income families to live in the city periphery and in low density places, but with a high land use mix. Current work areas – located in the city’s periphery – would be transformed into more multifunctional places. Low-income*

families would prefer to live in high-density areas in city centres. A dense green network of corridors would connect different places along the case study.

The 2050 vision based on the unimaginable process “shared motorized mobility dominates”, could be formulated as follows:

The future vision relies on a fundamental travel behaviour change, based on the prohibition of individual car ownership and the generalization of shared motorised mobility. Public modes would be the preferred option for reaching daily destinations – working, shopping, and leisure activities. Walking and cycling would be also a preferred mode, fundamentally for shopping and leisure trips. The use of car would be drastically limited to shared services. E-working would be seen as a marginal option. There would be a preference for living in city centres with shorter distances between residential, shopping, and leisure places. The built environment would provide these activities in mixed use location, connected by a dense network of green corridors. Workplaces – mainly located in the city’s periphery – would remain far away from residential areas. Both residential and work areas would be connected by efficient collective transport services.

Finally, the third unimaginable process, “high level of insecurity in urban areas”, led to the following vision:

The visualised transport future is strongly affected by a high level of insecurity in urban areas. Walking and cycling are not advisable. The modal split would be drastically altered, with the private car dominating all daily trips –work, shopping, and leisure. There would be also preferences for increasing the level of car sharing, as well as for the promotion of clean and autonomous vehicles with zero emissions. Public green areas would be removed and recovered for car infrastructures. There would be a preference by high-income families for living in the city periphery in private communities. Land uses would be highly segregated in homogenous areas connected by motorized infrastructure. City centres would be mainly transformed into work destinations, with most employees commuting from the city’s periphery. Low-income families would also tend to live in those insecure city centres.

4.4 Evaluation of disruptive thinking

The expert evaluation provides new insights into the basic hypothesis underlying this research, i.e., that different types of wild cards can be used to stimulate thinking outside of the BAU zone during participatory visioning processes. This working hypothesis was confirmed when unimaginable processes were used; however, some problems were noted in the 2050 visions based on imaginable processes.

The evaluation shows how the most disruptive 2050 visions – compared to the common 2050 desired vision – were those generated by using the following unimaginable processes "high level of insecurity in urban areas" and "shared motorised mobility dominates" (Figures 2 and 3). More than 90% of experts find that the 2050 vision "high level of insecurity in urban areas" is disruptive, very disruptive, and highly disruptive. Additionally, almost 70% of experts indicate that the 2050 vision "shared motorised mobility dominates" is disruptive and very disruptive. However, different results are found for the third vision generated through the other unimaginable process "overpopulation", where only 43% of experts signal this vision as disruptive and very disruptive.

Although multiple reasons can explain the previous results, one relevant aspect should be emphasized. The two most disruptive visions ("high level of insecurity in urban areas" and "shared motorised mobility dominates") were obtained from smaller portions of the sample of participants who selected those unimaginable processes during the interview process. Moreover, the socio-economic characteristics of these two sub-samples are highly homogenous unlike the population that selected "overpopulation". For example, employed people older than 25 years who travel daily along the corridor in public transport modes were the group that selected "shared motorised mobility dominates" during the interview. In the case of "high level of insecurity in urban areas", it was a majority of women younger than 25 years who travel daily along the corridor in public transport modes. In both cases, these sub-samples had divergent opinions regarding those participants selecting "overpopulation" during interviewed. In other words, smaller population sub-groups seem better equipped to generate divergences and disruptive thinking.

In the experts' opinion, the level of disruption reached by those visions generated on imaginable processes is more similar to the disruption level perceived for the 2050 desired vision (Figures 2 and 3). In all the three cases (non-motorized city centres; zero-emission vehicles; e-working dominates), only a percentage of experts lower than 52% signal these 2050 visions as disruptive, very disruptive, and highly disruptive. Even, the 2050 vision generated by the imaginable process "e-working dominates" is recognised as disruptive by a lower percentage of experts (33%) in comparison with the desired vision (43%). These assessments can indicate higher probability to generate disruptive thinking among participants when highly surprising factors (as unimaginable processes) are incorporated in the process, as participants are largely used to visualize short-term futures and are strongly affected by linear thinking. Nevertheless, it is worth mentioning that the most disruptive level of thinking has been found for the vision generated through the imaginable process "non-motorised city centres", which is selected by a minority of participants during the interview process (20% of participants). That reinforces the findings obtained for the visions generated through unimaginable processes, smaller sample sub-groups can have more divergent opinions on transport and land use futures.

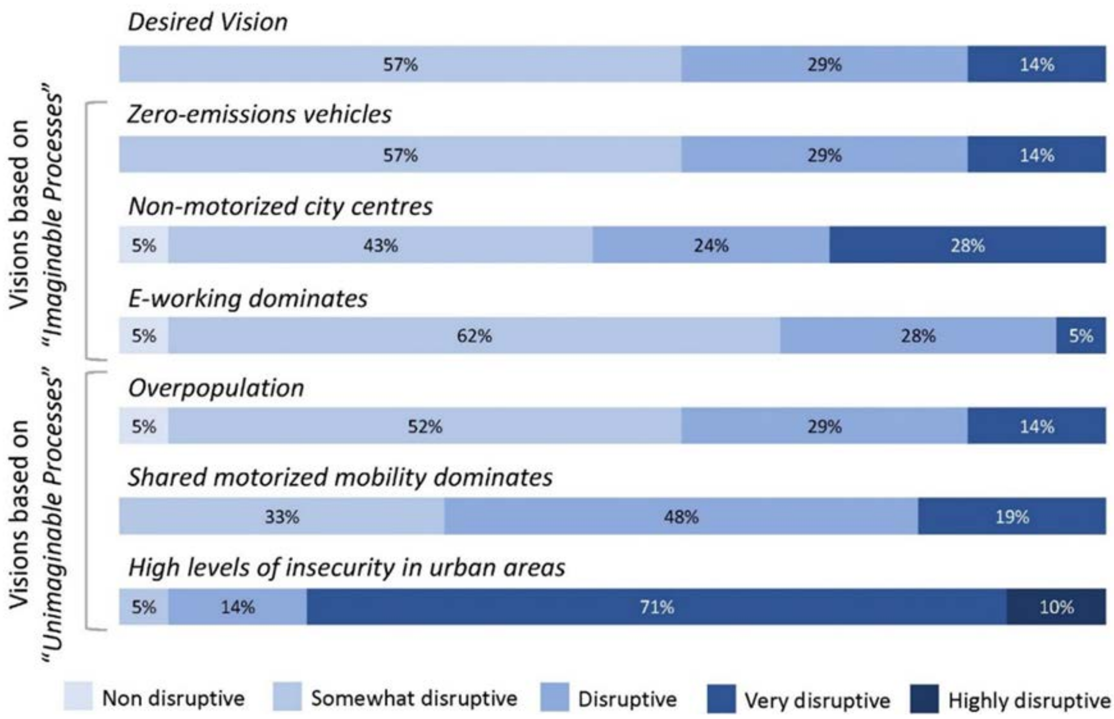

Figure 5: Percentage of experts identifying levels of disruptive thinking.

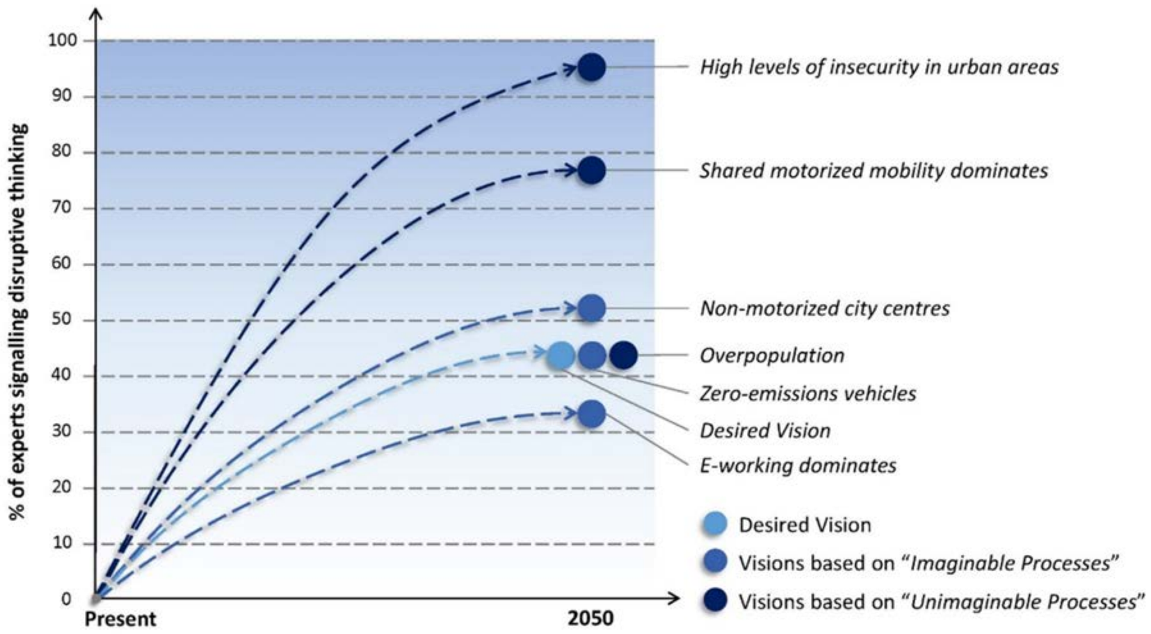

Figure 6 – Level of disruption identified by experts for each 2050 visions.

5. CONCLUSIONS AND DISCUSSION

In the reminder of this Section, a set of issues, limitations, and emerging questions are presented, discussing which elements of the visioning process have worked well (or not), and why. The purpose is to comment on what has been learned to distil some "prescriptions" for research and decision-making.

The visionary participants were local people between 18 and 32 years old. That is a convenience sample that allows the research team experimenting with a group of participants that can initially have more willingness to visualise futures under wild cards conditions. The limitation is that it would be impossible using the obtained 2050 visions in a real decision-making process, because it is unknown of what population this sample is representative. However, this convenience sample provides the research team with a more controlled environment to prove causality associated with the working hypothesis. Of course, further research steps are needed to distil usable "prescriptions" for thinking disruptively in decision-making, in which the control level of the research environment decreases, and the visionary participants are engaged according to the canons of probability sampling.

The research design opted for larger samples, engaging one of the highest number of participants in the field of transport scenario building. Larger samples would facilitate the emergence of smaller groups of participants with divergent views able to select the widest range of wild cards. For both imaginable and unimaginable processes, the most disruptive thinking (compared to the desired common vision) was obtained for those visions triggered by wild cards selected by a minority of participants. Moreover, those smaller sample sub-groups have tended in our context to be homogeneous regarding certain socio-economic characteristics. In this respect, most of participants selecting "shared motorised mobility generalization" were older than 25 years old, employed, and frequently used public transport modes to travel along the case study. The unimaginable process "high level of insecurity in urban areas" was mostly selected by women younger than 25 years old that frequently use public transport modes to travel along the case study.

The main limitation of semi-structured interviews is the null capacity of participants to interact with each other, missing the opportunity to activate learning processes. Both the structure and further analysis of semi-structured interviews in different blocks and phases, including multi-options to add several wild cards, facilitated the capture of minority views and their translation into narratives. It was seen how these minority views usually brought by homogenous group of populations resulted in higher level of disruptiveness. The comparison of a 2050 desired vision vs six wild cards visions has been conducted in this study. An alternative option is to run several visioning exercises separately, some of which had wild cards and some of which did not (control group). That would facilitate to gain additional and stronger insights into the capacity of wild cards to add non-linear thinking.

The use of wild cards proved useful for generating disruptive thinking between participants when unimaginable processes were used. However, imaginable processes provided 2050 visions with similar level of disruption as the common desired vision. This finding implies that highly surprising factors are needed to generate disruptions and break linear thinking. In this respect, using a wide range of wild cards can be crucial for two main reasons. First, the probability to generate disruption is higher as a larger number of highly surprising factors will be on the table. Second, larger numbers of wild cards can increase the chances to generate divergences between participants. In this respect, it is key that participants are forced to choose between wild cards rather than to visualize futures for all of them. Having to choose between wild cards triggers divergences, as proved during the participatory visioning presented in this research. Moreover, the choice of participants between different types of wild cards have served to incorporate outlier views from participants, represented by those wild cards selected by a minority of participants.

This participatory visioning provides decision-making with the option to incorporate unexpected incidents/processes but high impact in planning processes. It can contribute to define a more strategic vision of planning goals that include possible threats and/or accelerators originated by wild cards visions. For example, the COVID-19 crisis during 2020 underlines the importance of incorporating more diverse and non-linear visions into decision-making. Further steps are still needed to distil useful practice tools by using wild cards. This participatory approach that engages the widest range of participants provides legitimacy over planning processes. However, it must be said that each participatory process should be customized for each particular situation. Legal barriers and the low commitment of politicians to those participatory visioning exercises are also seen as obstacles to overcome in real practice.

Finally, this research presents a participatory visioning process aimed at evaluating the capacity of wild cards to stimulate disruptive thinking. The results are encouraging – especially when introducing wild cards. Further research could inform how to deploy wild cards more effectively used during transport visioning processes. In this respect, new challenges are related to the development of efficient methods to generate and identify wild cards as well as the design of effective mechanisms to assess the level of disruption generated through the visioning process.

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QUANTIFICATION OF TRANSPORT OFFER LINKED TO A EUROPEAN HYPERLOOP NETWORK

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ABSTRACT

Hyperloop is the modern and environmentally friendly update of an idea that has been in people's head for more than 200 years, since Medhurst presented the first patents. When "Hyperloop Alpha" was published by Elon Musk in August 2013, the best trained labour force, the most capable financial capital and the bravest governments and institutions, moved forward to make it a reality.

Currently, there isn't any scientific publications that address with enough detail, and without self-bias, the transport offer linked to specific networks of this new mode. This paper presents an approach to an operational plan in the exploitation phase for a specific Hyperloop network in Europe.

About the proposed network, with an extension over 12,000 kilometres, the authors will analyse its social and economic benefits based on GDP and the directly connected population, describe its design parameters (radii of curvature, acceleration, deceleration and constant speed zones), outline the demand using simple gravity models, propose an annual service calendar with schedules and frequencies differentiated by country, and present the main magnitudes associated with its operation.

In addition, the presentation will show the results of the research carried out on the main obstacle that the Hyperloop implementation will pose in the future: the number of tubes needed per direction vs. the transport capacity of each capsule or pod.

1. INTRODUCTION

Hyperloop is the update of an idea that has been in men's head for more than 200 years, from Medhurst's first patents related to the atmospheric train (Medhurst, 1810).

Launching a pressurised capsule, loaded with goods or people, through a tube whose inner pressure has been considerably reduced, is nothing but the next evolutionary step of magnetic levitation trains.

Since its inception, railway speed has been related to different aerodynamic designs of trains and different traction typologies. Since the first horse-drawn and guided carriages, rail transport has known first the steam traction, then diesel traction and later electric traction. It was with high-speed railways (first with electric traction and then with magnetic levitation) that the aerodynamic design of trains began to gain importance, reaching top speeds of 600 km/h, as in the case of the Maglev.

The physical barrier that has so far prevented the achievement of better high-speed rail speeds has always been air friction. That is why the next step to achieve higher limit-speeds is to necessarily reduce the atmospheric pressure around the train, as proposed by Hyperloop concept. To help better understand the process being described, note anecdotally that a tube without pressure inside, and whose temperature is close to absolute zero, is conceptually very close to the representation of a particle accelerator, where the speed of particles is close to the speed of light.

Taking this idea as a backbone, in August 2013, Elon Musk and his support teams at SpaceX and Tesla published ‘Hyperloop Alpha’ (Musk, 2013). A document that, with a modern and ecological format, brought to the present the original ideas of Medhurst and many others who came after him, such as Lamson (1908), Goddard (1924), Salter (1972) or Olster (2010-2015).

The challenges posed by this new mode of transport are very diverse. There are obvious physical risks, but also economic, financial, legal, regulatory, budgetary, and even socio-political risks, taking into consideration that Hyperloop will be able to "deform" the territory, turning countries into neighbourhoods.

Regardless of this, in just 8 years, Musk's initiative has sparked the birth of a very dynamic new industry. Despite its notable shortcomings, ‘Hyperloop Alpha’ has become the dragging engine capable of bringing together the best trained human force, the most capable financial capital and the boldest governments and institutions.

The prospect of a new mode of land transport with the huge potential to bring closer together regions separated by long travel times, has attracted the interest of governments such as India or United Arab Emirates, which have shown their interest in hosting this type of infrastructure. At the level of countries and supra-national entities under the influence of the OECD, receptiveness to the Hyperloop project has also been high, although the approach is taking place in a more cautious manner.

In order to analyse the financial viability of such an investment project and, where appropriate, the sustainability of the public accounts of the region in which it is located, it is necessary to have certainly about the amounts of capex and opex linked to it. In this sense, this document provides information on a plausible Hyperloop network serving the European

Union, using different methodologies to capture its design characteristics and the amount of transport it would provide annually if all its lines were put into service in the same year.

2. BIAS PROBLEMS IN THE FACE OF THE NECESSARY SOCIETAL ENDORSEMENT OF A NEW TECHNOLOGY

In September 2020, Gkoumas and Christou published ‘A Triple-Helix Approach for the Assessment of Hyperloop Potential in Europe’ (Gkoumas and Christou, 2020), a paper which referred to the relative abundance of research devoted to capsules and operations, but the paucity of research on safety issues. This document refers to other research advocating that the commercial potential and financial viability of Hyperloop has yet to be demonstrated (Walker , 2018). Gkoumas and Christou also index an inconclusive study published in 2016 by the US Department of Transportation (Taylor et al., 2016) on the commercial viability of Hyperloop, and a more recent research that questions the financial viability of the system in a potential deployment in the Great Lakes environment (USA) (Transportation Economics & Management Systems, Inc, 2019).

The main problem with financial feasibility studies for disruptive technologies such as Hyperloop, which are not based on concrete applications, is always the lack of detail. This matter is even more striking when feasibility studies carried out on specific infrastructures and with well-proven technologies are observed, duties that usually have the support of the developer industry itself.

The risk of self-serving bias in innovations of this scale is something that infrastructure planners and policy makers need to be aware of from the earliest stages. Assuming this, it is worth remembering that Hansen (2020) has already warned of the risks of polarising the opinion of the different interest groups that could benefit from a transport solution such as Hyperloop.

This is something that has already happened in the past, and it was a step prior to the failure of a project of similar characteristics as was ‘ARAMIS’. Referring to this event, in 1993 the French philosopher Bruno Latour published a book (Latour and Poter, 1996) in which he described how technological passion for a concept can have a double detriment: on the one hand it can blind some of the promoters to the technical feasibility of the project, and on the other hand it can make others irrational denialists.

During the 1970s, in Paris, ARAMIS was the latest attempt to create a rapid passenger transport system whose concept had emerged in the United States a decade earlier. The goal was to develop an automatic-guided public transport system, in which the transport elements would resemble the private car in size and comfort. These elements would be hooked to each other forming trains of variable length, as the ‘carriages’ would be temporarily attached until the destination turnout of each other was reached. The project never materialised.

In 1994, Latour, in an article derived from his book and entitled ‘Ethnography of a case of ‘high technology’: on Aramis’ (Latour, 1993) put the spotlight on the different currents that in his opinion caused the project to fail: “Aramis is technically ready for homologation”, ... , “Aramis was technically ready, but would have been so costly that it would have been unsalable politically”, ... , “the Aramis cabin was not technically ready because the RATP (Regional Transport Authority of Paris requested that Matra respect specifications completely unsuited to such an innovative experimental prototype”, ... , “nothing can be gained from the Aramis, it produced no technical or cultural results, it was a false innovation from the outset, an impracticable idea”, ... , “the question of the technical feasibility of the Aramis should not be raised”.

In this context, two milestones can make the difference between Hyperloop and ARAMIS:

- February 2020: CEN-CENELEC announced the launch of a new joint technical committee, CEN/CLC/JTC20. Its purpose is the standardisation of Hyperloop systems. As several European and international industries are investing in Hyperloop systems supported by the interest of public and private actors, European standardisation is crucial to achieve a coherent deployment of this new mobility tool (CEN-CENELEC, 2020).
- October 2020: Shift2Rail, a body of the European Commission, promotes the financing of a new project called Hypernex. Led by the Polytechnic University of Madrid (UPM), it tries to identify the main challenges facing Europe in terms of research, innovation, and infrastructures. The objective is to lead the development of this new means of transport and seek the most appropriate solutions (Universidad Politécnica de Madrid, 2020).

But regardless of the above, and although there is a broad consensus on the viability of this subsystem-level technology, it is clear that it will be necessary to carry out prognosis exercises in which all of them operate in a joint and coordinated manner. These exercises should be extremely detailed and applied to concrete realities.

Today, the simulation possibilities in multiple fields allow, for example, to emulate the design characteristics of transport networks using artificial intelligence algorithms. Through specific commercial software, it is also possible to emulate the annual operation of the rolling stock linked to these networks. And through sophisticated spreadsheets it is possible to simulate the commercial life of a vehicle company project. The information derived from such tasks, properly processed and integrated, would be the first step to advance in a solid understanding of the financial viability and future budgetary sustainability of a concept like Hyperloop.

With the design of a transport network for Europe, connecting the main cultural and economic nodes, from which detailed physical information can be extracted, and on which a reasonable plan of operations can be projected, it will be possible to calculate the capex and opex that allows to advance in the knowledge of the economic viability of the system as a whole.

As a tangential result, this document provides the necessary inputs to calculate the volume of investment in infrastructure of a hypothetical network. As the main result, this paper provides the quantification of the transport supply linked to it. The measurement of the transport offer is the necessary input to calculate the volume of investment in rolling stock, as well as to calculate most of the operating costs.

3. A PROGNOSTIC EXERCISE THROUGH THE PROPOSAL FOR A EUROPEAN HYPERLOOP NETWORK

The land deformation effect that the speed of certain modes of transport generates is behind the positive socio-economic effects that occur when these modes come into operation.

The figure below shows what a European Hyperloop Transport Network would look like. In addition to others, the fundamental design premise has been to connect the capitals of the states over which it is deployed, as directly as possible.

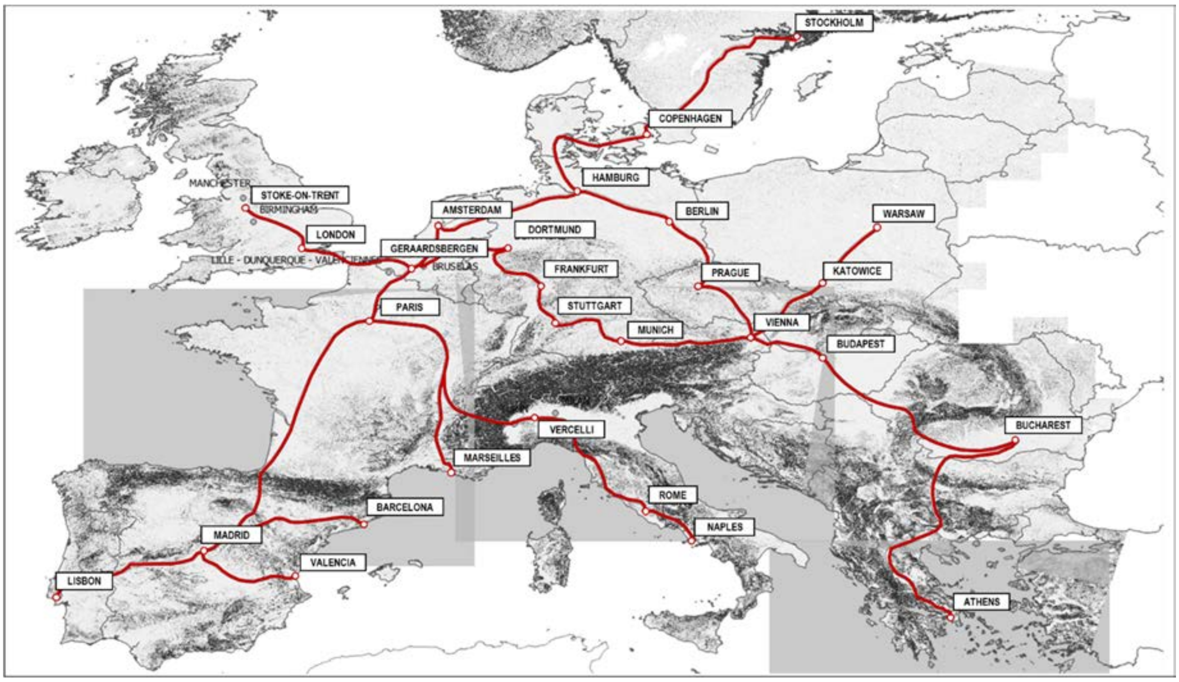

Figure 1: Lines of the proposed European Hyperloop Network

The name of the network lines and their length is shown in the table below.

Transport line name	Length [km]	Transport line name	Length [km]
01 LISBON - MADRID	537.66	15 MUNICH – STUTTGART	236.62
02 VALENCIA - MADRID	360.02	16 STUTTGART - FRANKFURT	169.32
03 MADRID - BARCELONA	544.65	17 FRANKFURT – DORTMUND	240.14
04 MADRID - PARIS	1,108.71	18 DORTMUND – GERAARDSBERGEN	274.62
05 MARSEILLE - PARIS	787.92	19 HAMBURG - COPENHAGEN	464.36
06 PARIS - GERAARDSBERGEN	247.53	20 COPENHAGEN – STOCKHOLM	595.13
07 GERAARDSBERGEN - LONDON	317.56	21 VIENNA – KATOWICE	304.38
08 LONDON - STOKE-ON-TRENT	238.33	22 KATOWICE - WARSAW	260.25
09 GERAADSBERGEN – AMSTERDAM	198.93	23 BUDAPEST – VIENNA	229.06
10 HAMBURG – AMSTERDAM	391.34	24 BUCHAREST – BUDAPEST	746.49
11 BERLIN – HAMBURG	262.40	25 ATHENS – BUCHAREST	1,079.47
12 PRAGUE – BERLIN	306.67	26 NAPLES – ROME	198.12
13 VIENNA – PRAGUE	280.89	27 ROME – VERCELLI	561.18
14 VIENNA – MUNICH	364.96	28 VERCELLI - PARIS	760.58

Table 1: Length between network nodes

The design of this network has been established within the framework of a research project linked to the University of the Basque Country.

3.1 Utility offered

In addition to the connection of state capitals, the European Hyperloop network includes the physical connection of European metropolitan regions with a census population of more than two million people.

The network thus consists of 28 lines with 28 nodes or stations (15 of which are located in state capitals). Three grouped nodes are suggested. The first of these would be in the Italian town of Vercelli, which would cover Milan and Turin. The second node would be located in Geraardsbergen, a Belgian town which would cover both Brussels and the Lille-Dunkerque-Valenciennes area. The third such node would be located in Stoke-on-Trent to cover both the Manchester and Birmingham agglomerations in the UK.

Starting from a Central European ring of 10 stations, the network extends to the rest of the continent via four branches. The northern branch would connect Hamburg with Stockholm. The southern branch would connect Geraardsbergen with the southern countries (Portugal, Spain, France and Italy). The eastern branch would connect Vienna with the peripheral countries of Poland, Romania and Greece. Finally, the north-west branch would also connect Geraardsbergen with the United Kingdom.

As an example, based on the latest available census data, the network would host seven super-nodes, defined as stations with the capacity to connect more than 15 million people (Geraardsbergen, Madrid, Paris, London, Stoke-on-Trent, Vienna and Marseille) through a single journey stage.

The proposed design would also allow direct access to the new high-speed mode of transport for 1/4 of the EU-28 population (120 million people), 1/3 of its GDP, 1/4 of its workforce, and 1/5 of all goods moved.

3.2 Methodology for the characterisation of the network layout.

Once the utility of the network has been described, the layout of the network should follow criteria that minimise the amount of investment required for its implementation. Following this premise, the layout process begins with the viewing of the slope map of Europe. Knowing the orography of a territory makes it possible to draw lines connecting cities through the flattest areas, and to use large radii of curvature.

After defining the layout of the network, the next step would be to determine its characteristics. In terms of capex, a linear infrastructure connecting two points through 15.45% of singular works (tunnels and viaducts) is not the same as another infrastructure with 18.76% of this type of works for the same connection.

3.3 Fundamentals of transport services operation

The stock of public capital allocated to transport services only achieves social utility when it is used to design a reasonable operational plan that makes it possible to present a specific transport offer to users. In order to determine the amount of transport that should be produced in a typical year in a network such as the one proposed, any planning office in the service of a public administration would have to go through a series of very well-defined phases.

3.3.1 About the radii of curvature

Firstly, the radii of curvature that apply on each section of each of the 28 lines must be known. This makes it possible to determine the maximum speed of the capsules on each of the aforementioned sections by means of equation (1), which is derived from ADIF's General Project Instruction IGP-3 (ADIF, 2011).

$$V = 6{,}4692 \times R^{0{,}4481} \qquad (1)$$

In this equation, R refers to the applicable radius of curvature expressed in metres and V to the speed of the capsule expressed in km/hour.

Figure 2: Curvature radii for a European Hyperloop Network

The radii of curvature recorded in the design of the proposed lines range from the 2.64 km in the vicinity of Athens (line 25 linking this city to Bucharest) to the 260.74 km in line 24 (Bucharest - Budapest). According to equation (1), when the proposed radius is 60,000 metres, the curve speed is 895.24 km/hour.

3.3.2 About acceleration, deceleration, and maximum speed

Although Hyperloop's maximum speed is theoretically 1,220 km/hour, the operational plan described here puts this figure at 850 km/hour. A sufficiently high speed, which does not rigidify the physical-technical boundary conditions of the system as much. In the same way, the acceleration and deceleration of the capsules is maintained at all times at values of 0.1G, coinciding, for example, with the hypotheses used by HTT in its own studies (Transportation Economics & Management Systems, Inc., 2018), but far from the value of 0.5G shown in the 'Hyperloop Alpha'. Under these conditions of movement, the time and space consumed by a capsule to reach a speed of 850 km/hour from 0 would be 240.766 seconds and 28,423.80 metres.

Adopting these assumptions, which could at some point be described as conservative, will allow the formulation of a reasonable financial viability analysis, which the industry could gradually beat with the introduction of more solid technical innovations.

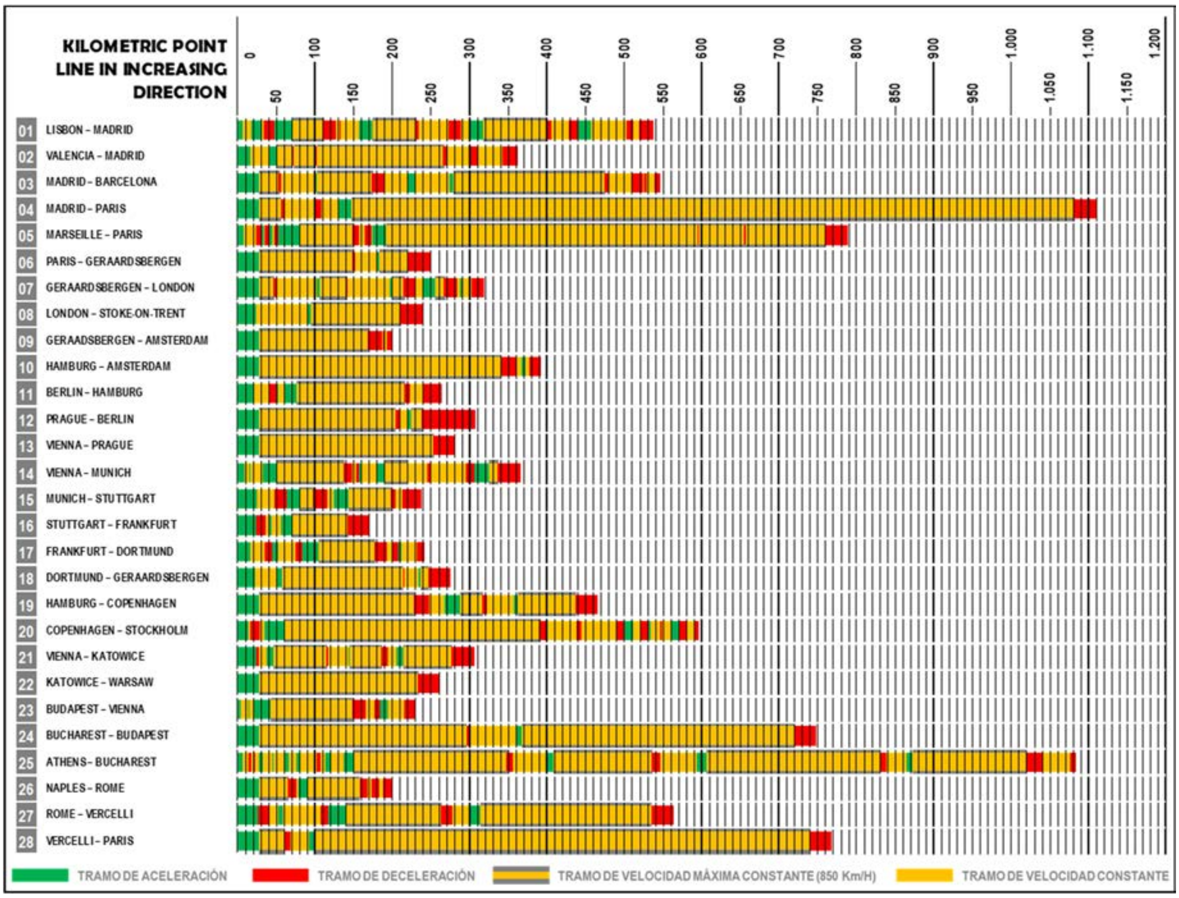

Figure 3: Overview of pod movement characteristics in the network

The figure above shows the acceleration, deceleration, constant speed and maximum constant speed zones, linked to each of the lines of the proposed European Hyperloop Network.

3.3.3 About time consumed in pre- and post-travel related tasks

A Hyperloop station or Hyperloop gateway will have many operational similarities to a high-speed rail station, but physically it will have two well distinct zones, as is the case in any airport. In this sense, while an airport differentiates between 'land side' and 'air side', a Hyperloop station will have to differentiate between an 'atmospheric pressure side' and a 'low pressure side'.

Under these conditions, the process of transporting a person or a load between the origin and destination of any line in the network would be affected by certain unalterable milestones and fix time consumptions. This is due to the need for persons or objects under atmospheric pressure to transit to a state where they maintain atmospheric pressure inside a capsule, but which, when it enters the tube through a lock, must be under low pressure.

The table below shows in a schematic way what should be the orderly process of access of users to the transport capsules. It also shows how the capsules access to the tubular infrastructure, the process of arrival of the capsules at the stations, and finally the disembarkation process.

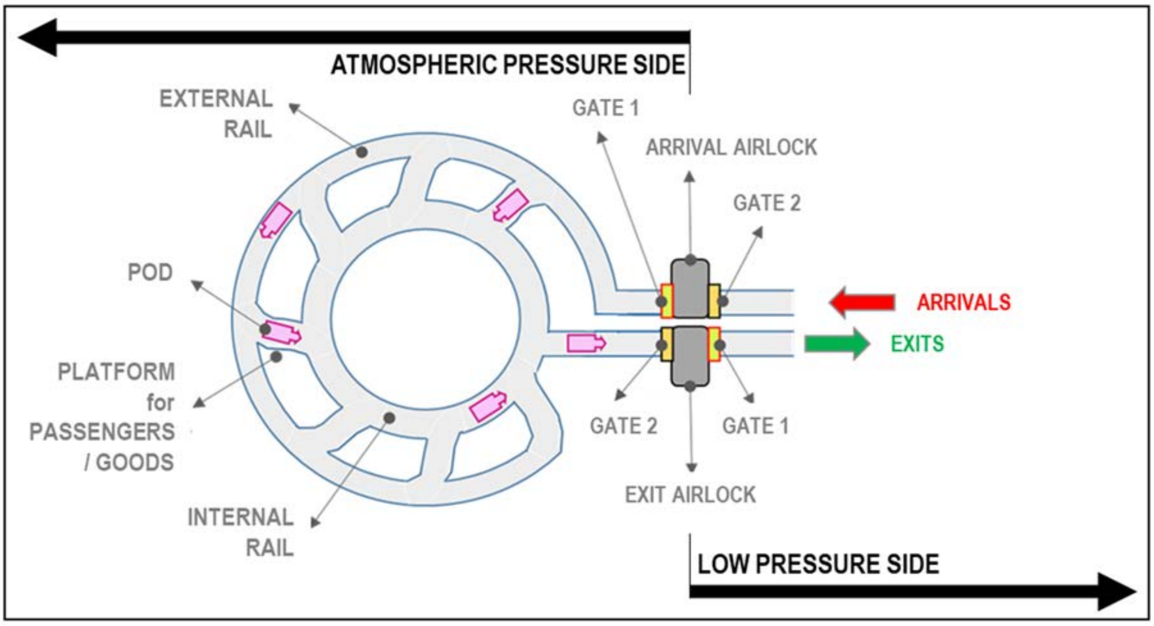

Figure 4: Approach to a Hyperloop station scheme

	Milestone	Duration [min]
1	Pod transition from platform to entrance to exit airlock (gate 1)	3.50
2	Pod entrance at departure airlock	0.75
3	Gate 1 closing in the exit airlock	0.58
4	Air extraction in the exit airlock	2.50
5	Gate 2 opening of the exit airlock	0.83
6	Pod movement towards the propulsion zone in the tube	0.42
7	Gate 2 closing in the exit airlock	0.83
8	Pod movement inside the tube to its destination	VARIABLE
9	Gate 1 opening at arrivals airlock	0.83
10	Pod entry at the arrival airlock	0.75
11	Gate 1 closing at the entrance to the arrival’s airlock	0.83
12	Pressurisation of the arrival’s airlock	0.67
13	Gate 2 opening at arrivals airlock	0.58
14	Pod movement from the arrival’s airlock to the platform by external rail	3.50
15	Pod reposed on platform	0.33
16	Uncoupling operation of passenger / cargo	1.50
17	Pod doors opening and orderly departure of passengers/cargo from the capsule interior	2.00
18	Equipment for sanitisation rapid intervention / pod condition checking	4.00
19	Battery replacement (or partial recharging if necessary)	5.00
20	Pod on standby until passenger/cargo occupancy starts	VARIABLE
21	Passenger/cargo occupancy	2.50
22	Anchoring of passengers/cargo and approval by a supervisor	2.00
23	Pod closure and automatic safety check	1.50
24	Transition of pod from platform to entrance to exit airlock (gate 1)	MILESTONE 1 AGAIN

Table 2: Description of milestones in pre and post trip operations and times allocation

The sum of the times of the above milestones amounts to 35.42 minutes (0.5903 hours). This amount could be equated to the boarding and alighting times for passengers boarding and alighting high-speed rail services.

The above table refers to both passengers and cargo. In the case of cargo, with the right logistics, these times could be even shorter.

3.3.4 About the commercial speed of the transport system

According to the Royal Academy of Engineering of Spain, commercial speed is defined as the "average travel speed used by public transport vehicles to complete a full circle of a route, including all delays and waiting time at terminals" (Real Academia de Ingeniería, 2012).

Transport line name	**(a)** Length [km]	**(b)** Variable time [hours]	**(c)** Fixed time [hours]	Commercial speed [km/hour] **(a) / (b)**	Commercial speed [km/hour] **(a) / (b+c)**
01 LISBON – MADRID	537.66	0.8069	0.5903	666.33	384.81
02 VALENCIA – MADRID	360.02	0.5129	0.5903	701.93	326.34
03 MADRID – BARCELONA	544.65	0.7628	0.5903	714.01	402.52
04 MADRID – PARIS	1,108.71	1.4006	0.5903	791.6	556.89
05 MARSEILLE – PARIS	787.92	1.0856	0.5903	725.79	470.15
06 PARIS – GERAARDSBERGEN	247.53	0.3614	0.5903	684.92	260.09
07 GERAARDSBERGEN – LONDON	317.56	0.4700	0.5903	675.66	299.5
08 LONDON – STOKE-ON-TRENT	238.33	0.3561	0.5903	669.28	251.83
09 GERAADSBERGEN – AMSTERDAM	198.93	0.3032	0.5903	656.1	222.64
10 HAMBURG – AMSTERDAM	391.34	0.5447	0.5903	718.45	344.79
11 BERLIN – HAMBURG	262.40	0.3951	0.5903	664.14	266.29
12 PRAGUE – BERLIN	306.67	0.4303	0.5903	712.69	300.48
13 VIENNA – PRAGUE	280.89	0.3979	0.5903	705.93	284.24
14 VIENNA – MUNICH	364.96	0.5449	0.5903	669.77	321.49
15 MUNICH – STUTTGART	236.62	0.3770	0.5903	627.64	244.62
16 STUTTGART – FRANKFURT	169.32	0.2844	0.5903	595.36	193.57
17 FRANKFURT – DORTMUND	240.14	0.4236	0.5903	566.9	236.85
18 DORTMUND – GERAARDSBERGEN	274.62	0.3974	0.5903	691.04	278.04
19 HAMBURG – COPENHAGEN	464.36	0.6526	0.5903	711.55	373.61
20 COPENHAGEN – STOCKHOLM	595.13	0.9241	0.5903	644.01	392.98
21 VIENNA – KATOWICE	304.38	0.4342	0.5903	701.01	297.1
22 KATOWICE – WARSAW	260.25	0.3744	0.5903	695.11	269.77
23 BUDAPEST – VIENNA	229.06	0.3984	0.5903	574.95	231.68
24 BUCHAREST – BUDAPEST	746.49	0.9563	0.5903	780.6	482.67
25 ATHENS – BUCHAREST	1,079.47	1.5699	0.5903	687.6	499.71
26 NAPLES – ROME	198.12	0.3141	0.5903	630.75	219.06
27 ROME – VERCELLI	561.18	0.7936	0.5903	707.13	405.51
28 VERCELLI – PARIS	760.58	0.9775	0.5903	778.09	485.13

Table 3: Detail of commercial speed on each line of the network

The table 3 shows the commercial speed that Hyperloop would offer on each of the lines of the proposed European network, taking into account both the time of the exclusive movement of the capsule on the so-called 'low pressure side' of the system (variable time), as the time resulting from the sum of the previous time and the fixed time defined in the previous section.

These data allow us to state that the commercial speed linked to the network would be 699.56 km/h when considering only the travel time of the capsules (variable time). If the predefined fixed time (0.5903 hours) is added to this time, the commercial speed would be 357.25 km/h.

3.3.5 About the monthly, weekly, and daily organisation of the transport services

The transport offer made available to users of the new European transport network should be designed according to values of frequency of departure of the capsules from the originating stations expressed in reasonable terms. The time that elapses at a station between the departure of one capsule and the next, may vary depending on the time of day, the day of the week, the season, and the country in which the station is located.

In view of this reality, it is proposed that there should be three annual seasons, quantifiable by months. During the so-called working season, the system's service offer will be mainly oriented to meet the demand generated from Monday to Friday. During the tourist season, the service offer will try to meet the demand generated on weekends. The so-called intermediate season is the period of time when the service supply transitions between the working and tourist season.

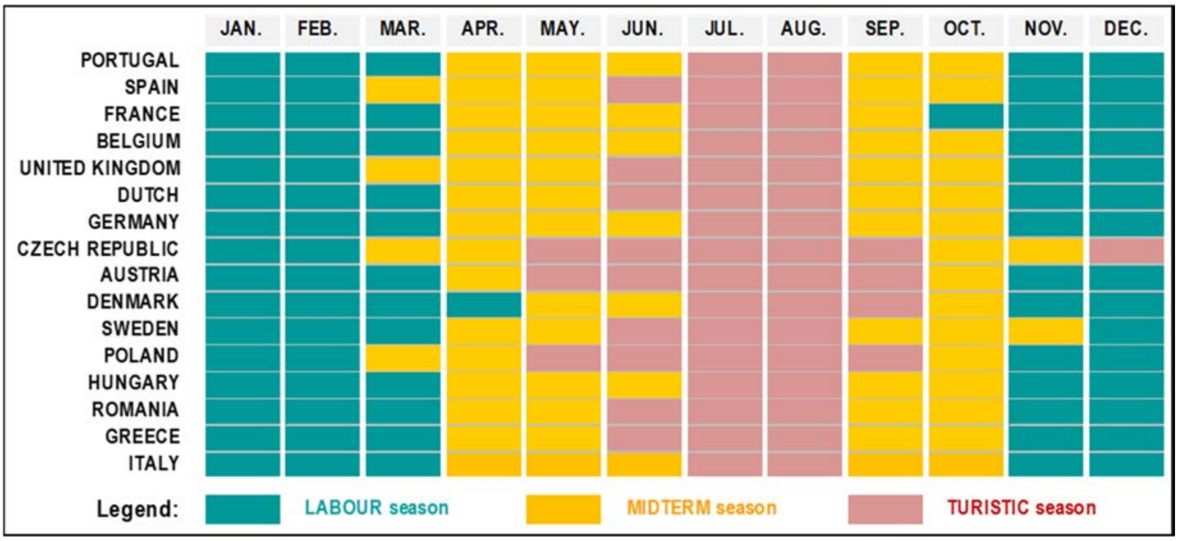

Figure 5: Variation of transport offer by season and country type

Within each season, the transport offer will vary according to the country and each of the four standard days to be considered. This research has considered the existence of 15 standard days.

	MON.	TUES.	WED.	THURS.	FRI.	SAT.	SUN. / HLDY.
WEEK of LABOUR SEASON	LS1				LS2	LS3	LS4
WEEK of MIDTERM SEASON	MS1				MS2	MS3	MS4
WEEK of TURISTIC SEASON	TS1				TS2	TS3	TS4

Figure 6: Acronym for each standard day within the annual transport offer

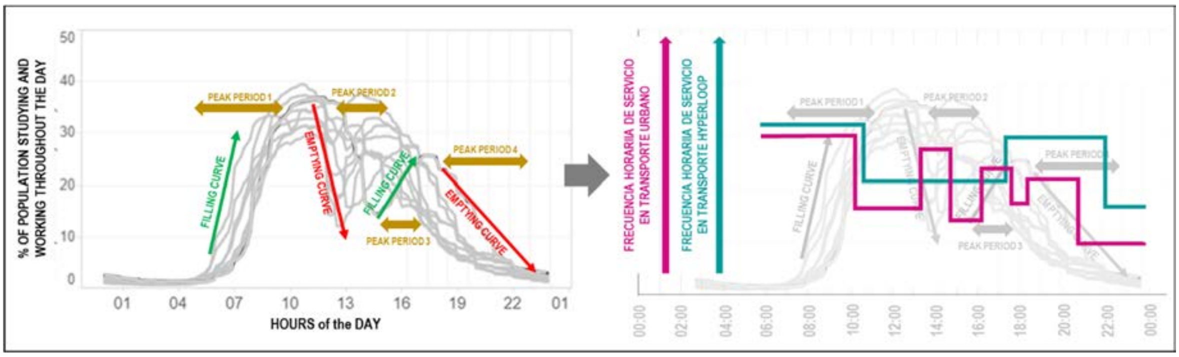

Figure 7: Transport service frequencies linked to people's time use on labour days

FREQUENCY TIMETABLE	PERIOD 1 [MIN] since ... until [MAX]	PERIOD 2 [MIN] since ... until [MAX]	PERIOD 3 [MIN] since ... until [MAX]	PERIOD 4 [MIN] since ... until [MAX]
on labour days	MIN: 5 am MAX: 11 am	MIN: 9 am MAX: 17 pm	MIN: 13 pm MAX: 22 pm	MIN: 18 pm MAX: 0 am
LS1	3 minutes	6 minutes	4 minutes	7 minutes
LS2	3 minutes	6 minutes	3 minutes	7 minutes
MS1	3 minutes	5 minutes	4 minutes	6 minutes
MS2	3 minutes	5 minutes	3 minutes	6 minutes
TS1	5 minutes	7 minutes	5 minutes	10 minutes
TS2	4 minutes	6 minutes	3 minutes	5 minutes
on Saturday day	MIN: 6 am MAX: 10 am	MIN: 9 am MAX: 22 pm	MIN: 21:00 MAX: 1 am	MEANING of the FREQUENCY
LS3	10 minutes	5 minutes	10 minutes	
MS3	8 minutes	5 minutes	8 minutes	POD 2 POD 1
TS3	15 minutes	10 minutes	15 minutes	
on Sunday / Holiday day	MIN: 6 am MAX: 16 pm	MIN: 15 pm MAX: 22 pm	MIN: 21:00 MAX: 1 am	
LS4	8 minutes	4 minutes	6 minutes	
MS4	7 minutes	4 minutes	5 minutes	X minutes
TS4	6 minutes	3 minutes	4 minutes	

Figure 8: Pod frequency from stations (expressed in minutes between exits)

The idiosyncrasies of each country shape different patterns of how people spend their time. In the context of the working season, the number of people working and studying throughout the day in the different countries of the European Union tends to be distributed in a similar way, with two clearly differentiated peaks, especially on the days from Monday to Thursday. In terms of urban transport, the existence of these peaks leads to the existence of four peak periods of demand. One before and one after each peak.

There is a tendency to compare the utility of a Hyperloop network with the utility provided by any metro network in any urban agglomeration. Due to the very nature of the trips to be offered by this new transport system, this document will only consider the existence between Monday and Thursday of two peak periods when the frequency of the services offered should be higher.

The figure 7 shows, on the one hand, the time use curves of people on a working day in various European countries according to Eurostat (Madrid (Edizíones) - Europa Press, 2018), and on the other hand, the differentiated frequency periods that must be established within each day.

The figure 8 shows the time in minutes that should elapse in each period (of variable duration depending on the country) linked to each standard day between the departure, from the same station, of two consecutive capsules established in the operational plan. It is this information that defines the final transport offer made available to users of the network.

The amount of service offered for passenger transport ranges from a minimum of four capsule departures per hour and direction (15 minutes frequency) to a maximum of 20 capsule departures per hour and direction (3 minutes frequency).

It is proposed to provide a supplementary cargo service in addition to the passenger service, which will be provided on timetable sections of each standard day where the frequency is more than three minutes.

3.3.6 About inter-core travel, network usage demand and design demand for each line

Newton's gravity equation has served for many years as the basis for explaining the demand for travel between two distant points in the territory. This simple conceptual tool is based on the assumption that traffic between two population centres is proportional to the population of the two centres and inversely proportional to the square of the distance between them, i.e. a point is as attractive as its mass is important and vice versa.

Equation (2) allows the calculation of the displacements between two points i and j with population p_i and p_j and separated by a given physical distance.

$$\text{Total trips F}_{i,j} = K_F \times (p_{i \times} p_j)/(dF_{i,j}{}^2) \quad (2)$$

Equation (3) allows the calculation of the displacements between two points i and j with population p_i and p_j and separated by a given distance in time.

$$\text{Total trips T}_{i,j} = K_T \times p_{i \times} p_j)/(dT_{i,j}{}^2) \quad (3)$$

In both equations, K is a coefficient to be estimated that allows calibration. In this research, the calibration has been carried out considering the reality of population censuses, usage demands, and physical and temporal distances in the Iberian Peninsula, between the Madrid-Barcelona and Madrid-Valencia connections.

Proceeding in the manner described allows two types of displacements to be quantified. One comes from the consideration of an exclusively physical distance (kilometres) between two points, and the other comes from the consideration of an exclusively temporal distance (minutes).

The demand for use of the new system will come from the amount of journeys it is able to capture from other modes (air, rail, bus, car and motorbike), as well as the amount of journeys it is able to induce. Under these assumptions, it has been hypothesised here that 80% of any travel decision on the European Hyperloop network will be influenced by the time variable, while only 20% of that decision will be influenced by the physical distance variable.

Transport line name	Gravitational model total trips (TTGM) and demand for use of the European Hyperloop Network (DUEHN)					Demand for design in …	
	by distance criterion …				DEHN yearly 20% P + 80% T [000.000 pax]		
	… physical (P)		… temporal (T)				
	TTGM [000.000 pax]	DUEHN [000.000 pax]	TTGM [000.000 pax]	DUEHN [000.000 pax]		… average working day [pax]	… rush hour [pax]
01 LISBON – MADRID	5.40	4.67	4.94	4.27	4.35	15,032	2,029
02 VALENCIA – MADRID	2.95	2.14	7.08	6.13	5.33	18,404	2,485
03 MADRID – BARCELONA	10.22	8.84	10.22	8.84	8.84	30,525	4,121
04 MADRID – PARIS	5.49	4.75	10.51	9.09	8.22	28,407	3,835
05 MARSEILLE – PARIS	5.21	4.50	7.10	6.14	5.81	20,082	2,711
06 PARIS – GERAARDSBERGEN	23.86	16.12	15.16	10.99	12.02	41,499	5,602
07 GERAARDSBERGEN – LONDON	16.87	12.23	34.13	29.52	26.06	90,017	12,152
08 LONDON – STOKE-ON-TRENT	33.91	22.91	20.19	14.63	16.29	56,270	7,596
09 GERAADSBERGEN – AMSTERDAM	8.27	5.59	3.85	2.79	3.35	15,041	2,031
10 HAMBURG – AMSTERDAM	1.37	0.99	3.67	3.17	2.73	12,291	1,659
11 BERLIN – HAMBURG	5.81	3.92	3.87	2.80	3.02	13,591	1,835
12 PRAGUE – BERLIN	3.39	2.46	2.88	2.08	2.16	9,698	1,309
13 VIENNA – PRAGUE	2.18	1.47	1.66	1.20	1.25	5,637	761
14 VIENNA – MUNICH	1.42	1.03	3.31	2.87	2.50	11,221	1,515
15 MUNICH – STUTTGART	3.32	2.24	1.86	1.35	1.53	6,866	927
16 STUTTGART – FRANKFURT	6.01	4.06	2.11	1.53	2.04	9,154	1,236
17 FRANKFURT – DORTMUND	5.55	3.75	2.92	2.12	2.45	10,972	1,481
18 DORTMUND – GERAARDSBERGEN	8.14	5.50	5.91	4.28	4.52	20,319	2,743
19 HAMBURG – COPENHAGEN	2.62	2.27	2.26	1.95	2.01	6,962	940
20 COPENHAGEN – STOCKHOLM	1.10	0.95	1.05	0.91	0.92	3,172	428
21 VIENNA – KATOWICE	1.93	1.40	1.60	1.16	1.21	4,161	562
22 KATOWICE – WARSAW	3.16	2.13	2.16	1.56	1.67	5,796	782
23 BUDAPEST – VIENNA	3.76	2.54	1.90	1.37	1.60	5,551	749
24 BUCHAREST – BUDAPEST	1.05	0.91	1.51	1.31	1.23	4,247	573
25 ATHENS – BUCHAREST	0.63	0.55	0.98	0.84	0.78	2,711	366
26 NAPLES – ROME	8.06	5.45	3.63	2.63	3.19	11,037	1,490
27 ROME – VERCELLI	7.79	6.74	7.91	6.84	6.82	23,560	3,181
28 VERCELLI – PARIS	11.88	10.28	17.26	14.93	14.00	48,350	6,527

Table 4: Displacements according to different gravity model criteria. Demand for network use and design demand

Under the above assumptions, if the proposed network design had been fully implemented and operational in 2020, it would have registered an annual usage demand of 145.9 million passengers. Similarly, in the same year, the network would have served 530.6 thousand passengers on an average weekday, and 6,153.5 thousand passengers in a rush hour.

3.3.7 About the carrying capacity of each capsule

The proposed passenger transport demand should be satisfied by a transport supply that allows mobility without bottlenecks at the busiest time of the year (rush hour).

The existence of bottlenecks depends not only on the number of tubes in each direction on each line of the network, but also on the transport capacity of each capsule.

The first hypothesis on capsule capacity adopted by Musk's Alpha document was 28 people per transport unit. However, since 2013, the different studies that have been published have been raising this hypothetical capacity, and it is now beginning to be suggested in a very timid way that this figure, in the case of capsules intended for passenger transport, could even be as high as 200 passengers (European Hyperloop Week Mailbox, 2021). Notwithstanding the above, this document sets the limit for passenger capsules at 100 seats.

Under these conditions, as will be explained below, the new network will assign capsules with transport capacities of 40, 50, 60, 60, 80, 90 or 100 persons (in the case of passenger transport), and capsules with transport capacities of 5, 6.25, 7.5, 10, 11.25 or 12.5 tonnes (in the case of freight transport).

3.3.8 About the amount of tubular infrastructure per direction that will be necessary

The design demands on some of the lines in the proposed network can hardly be met with considerations of a maximum departure frequency of 3 minutes, a capsule capacity of 28 persons, and one tube per direction of travel.

This analysis was already carried out by Egea et al. (2016) when in a study entitled "Comparative analysis of the viability between Hyperloop and AVE means of transport in the Madrid-Barcelona corridor" (Egea et al., 2016), under the consideration of capsules with a capacity for 28 passengers, and operating conditions different from those proposed in this research, they already demonstrated the need for the existence of two Hyperloop tubes in each direction on a hypothetical Madrid - Barcelona route that would serve the current high-speed rail demand at rush hours in the corridor.

In this context, if the capsule capacity is brought to its maximum value of 100 seats, but the maximum frequency of passenger capsule departures from stations remains unchanged at 20, in the 2020 standard year, there will be two lines on the network that will need to have more than one tube per direction to meet the weekday design demand. Specifically, the

Geraardsbergen - London connection (line 7) will require three tubes in each direction, and the London - Stoke-on-Trent connection (line 8) will require two tubes in each direction.

Despite the above, the need for three tubes in each direction on line 7 results in unsatisfied demand at rush hour. This situation of unsatisfied demand at rush hour is repeated on three other lines in the network (line 3 Madrid - Barcelona, line 6 Paris - Geraardsbergen, and line 28 Vercelli - Paris), which quantify the number of tubes required in each direction at one. The existence of small bags of unsatisfied demand in some cases is justified by the rational need to ensure that there is no under-utilised stock of public capital at any point in the life cycle of any infrastructure.

3.3.9 About the relation between the transport capacity of each capsule and the amount of tubular infrastructure per way

The weekday and rush hour design demands provided for each line of the new network in section 3.3.6 are linked to the year 2020. There is a large body of research that attempts to link the annual growth in demand for any mode of transport to the evolution of the GDP of the countries in which it is generated. Thus, if no technical progress is made on the existence of capsules that overcome the self-imposed limitation of 100 seats, the need for more than one tube per direction will end up affecting more lines than initially enunciated.

The 2018 Ageing Report (European Commision, 2018), one of a series of reports regularly published by the European Commission, provides very long time series quantifying GDP growth by country. Similarly, through equation (4), which is the result of research led by Judith Fernández (2015) in the framework of the Optired project (Fernández Jáñez, J., 2012), it is possible to make prognoses on the growth of demand for a transport system according to the evolution of GDP linked to the territory that hosts them.

$$\%\triangle \text{ Demand} = 0{,}11698 \times (\%\triangle GDP - 0{,}8817)^2 + 1{,}906 \times (\%\triangle GDP - 0{,}8817) \quad (4)$$

Transport line name	Need of tubes per direction in the pods operation …									
	100 pax.									200 pax.
	2020	2030	2040	2050	2060	2070	2080	2090	2098	2098
07 GERAARDSBERGEN – LONDON	3	3	4	5	5	6	7	8	9	4
08 LONDON – STOKE-ON-TRENT	2	2	2	3	3	4	4	5	6	3
06 PARIS – GERAARDSBERGEN	1	1	1	2	2	3	3	3	4	2
02 VALENCIA – MADRID	1	1	1	1	1	1	2	2	3	1
03 MADRID – BARCELONA	1	1	1	1	1	2	2	3	3	2
04 MADRID – PARIS	1	1	1	1	1	2	2	2	3	1
28 VERCELLI – PARIS	1	1	1	2	2	2	2	3	3	2
01 LISBON – MADRID	1	1	1	1	1	1	2	2	2	1
05 MARSEILLE – PARIS	1	1	1	1	1	1	2	2	2	1
09 GERAADSBERGEN – AMSTERDAM	1	1	1	1	1	1	2	2	2	1

Table 5: Evolution of the need for tubes by direction due to increases in demand in two pod capacity scenarios

Based on the approaches described above, table 5 is provided showing those lines which in the period 2020-2098 will gradually increase their need for tubes per direction by more than one. The table shows the values for the need for tubes both in the case where the capacity limit of the passenger capsules is 100 or 200 seats.

As an abacus, the figure below shows the results of a simulation relating the capacity of passenger capsules to the need for tubes per direction on five of the 28 lines in the network.

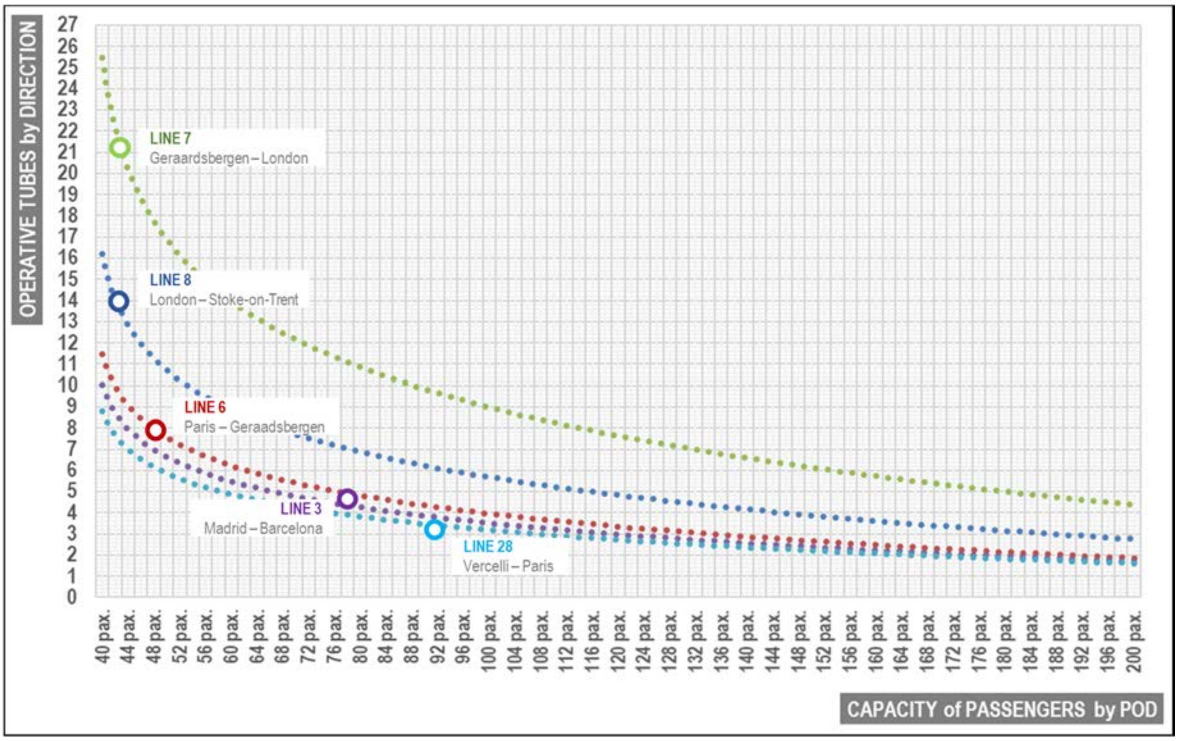

Figure 9: Relation between pod passenger capacity and the need to operate two tubes or more per direction

In any case, for reasons of space, the configuration of the line does not seem reasonable to exceed 3 operational tubes per direction and 1 additional tube as a backup. It is environmentally unacceptable to create tracks in the terrain that are more than 60 metres wide.

4. QUANTIFICATION OF THE TRANSPORT SUPPLY LINKED TO THE EUROPEAN HYPERLOOP NETWORK IN 2020

European Hyperloop Network		01 LISBON – MADRID	02 VALENCIA – MADRID	03 MADRID – BARCELONA	04 MADRID – PARIS	05 MARSEILLE – PARIS	06 PARIS – GERAARDSBERGEN	07 GERAARDSBERGEN – LONDON	08 LONDON – STOKE-ON-TRENT	09 GERAADSBERGEN – AMSTERDAM	10 HAMBURG – AMSTERDAM
Length	[Km]	537.66	360.02	544.65	1,108.71	787.92	247.53	317.56	238.33	198.93	391.34
Trip time	[Hours]	1,4	1,1	1,35	1,99	1,68	0,95	1,06	0,95	0,89	1,13
Qy. of tubes	Depart	1	1	1	1	1	1	3	2	1	1
	Spare	1	1	1	1	1	1	1	1	1	1
	Arrive	1	1	1	1	1	1	3	2	1	1
Seats pod		60	80	100	100	90	100	100	100	60	50
Qy. of pods	Pax.	62	52	62	88	76	44	150	84	40	52
	Freight	22	18	22	32	28	16	54	32	14	18
000 expeditions	Pax.	167	167	167	164	164	164	508	339	165	182
	Freight	28	28	28	32	32	32	114	76	34	32
000 trip hours	Pax.	259	210	258	360	310	180	579	349	163	223
	Freight	54	46	55	83	68	41	143	75	37	40
000,000 km travelled	Pax.	89.6	60.1	90.9	181.7	129.1	40.5	161.6	80.7	32.8	71.4
	Freight	14.9	9.9	15.0	35.5	25.2	7.8	35.8	18.0	6.8	12.3
Transport offer	000,000 seats	10.01	13.35	16.68	16.40	14.76	16.40	50.85	33.90	9.92	9.12
	000 tn.	206.76	275.68	344.60	399.10	359.19	399.10	1,421.28	947.52	256.35	197.09

European Hyperloop Network		11 BERLIN – HAMBURG	12 PRAGUE – BERLIN	13 VIENNA – PRAGUE	14 VIENNA – MUNICH	15 MUNICH – STUTTGART	16 STUTTGART – FRANKFURT	17 FRANKFURT – DORTMUND	18 DORTMUND – GERAARDSBERGEN	19 HAMBURG – COPENHAGEN	20 COPENHAGEN – STOCKHOLM
Length	[Km]	262.40	306.67	280.89	364.96	236.62	169.32	240.14	274.62	464.36	595.13
Trip time	[Hours]	0,99	1,02	0,99	1,14	0,97	0,87	1,01	0,99	1,24	1,51
Qy. of tubes	Depart	1	1	1	1	1	1	1	1	1	1
	Spare	1	1	1	1	1	1	1	1	1	1
	Arrive	1	1	1	1	1	1	1	1	1	1
Seats pod		60	40	40	50	40	40	50	90	40	40
Qy. of pods	Pax.	44	48	44	52	44	40	48	44	56	70
	Freight	16	16	16	18	16	14	16	16	20	26
000 expeditions	Pax.	182	182	171	182	182	182	182	182	182	170
	Freight	32	32	37	32	32	32	32	32	32	38
000 trip hours	Pax.	191	202	179	223	191	174	202	191	240	275
	Freight	36	37	42	40	36	31	37	36	44	66
000,000 km travelled	Pax.	47.8	55.8	47.9	66.4	43.1	30.9	43.7	50.1	84.6	100.9
	Freight	8.2	9.7	10.5	11.5	7.4	5.4	7.5	8.7	14.6	22.6
Transport offer	000,000 seats	10.94	7.29	6.83	9.12	7.29	7.29	9.12	16.40	7.29	6.79
	000 tn.	236.51	157.67	186.67	197.09	157.67	157.67	197.09	354.77	157.67	189.22

Table 7a: Quantification of the offer transport linked to a previously justified amount of infrastructure and pods

European Hyperloop Network		21 VIENNA – KATOWICE	22 KATOWICE – WARSAW	23 BUDAPEST – VIENNA	24 BUCHAREST – BUDAPEST	25 ATHENS – BUCHAREST	26 NAPLES – ROME	27 ROME – VERCELLI	28 VERCELLI – PARIS	TOTAL	
Length	[Km]	260.25	229.06	746.49	1,079.47	198.12	561.18	760.58	464.36	12,067	
Trip time	[Hours]	0,96	0,99	1,55	2,16	0,9	1,38	1,57	1,24	--	
Qy. of tubes	Depart	1	1	1	1	1	1	1	1	31	90
	Spare	1	1	1	1	1	1	1	1	28	
	Arrive	1	1	1	1	1	1	1	1	31	
Seats pod		40	40	40	40	40	50	100	100	--	
Qy. of pods	Pax.	44	44	70	98	42	62	72	56	1,68	52
	Freight	16	16	26	36	16	22	26	20	604	18
000 expeditions	Pax.	171	172	172	163	168	168	164	182	5,333	182
	Freight	37	34	34	32	30	30	32	32	1,027	32
000 trip hours	Pax.	178	184	288	392	171	258	288	240	6,907	223
	Freight	42	39	59	92	39	55	66	44	1,48	40
000,000 km travelled	Pax.	44.4	39.4	128.6	176.0	33.2	94.1	124.7	84.6	2,201.9	71.4
	Freight	8.2	9.7	10.5	11.5	7.4	5.4	7.5	8.7	423.6	
Transport offer	000,000 seats	10.94	7.29	6.83	9.12	7.29	7.29	9.12	16.40	355,3	
	000 tn.	236.51	157.67	186.67	197.09	157.67	157.67	197.09	354.77	8,631.76	

Table 7b: Quantification of the offer transport linked to a previously justified amount of infrastructure and pods.

5. CONCLUSIONS

The information set out in this document would already allow an approximation of the capex of network implementation and the opex linked to the operation of transport services. It will also make it possible to establish revenue scenarios based on assumptions of passenger and freight capsule occupancy for each of the proposed journeys.

Based on the above, it can be stated that the average length of a line in the network is 430.96 km, and the average journey time is 1.21 hours. 23% of the tubular infrastructure would correspond to backup tubes. This type of tube should have a pressure inside it such that, should it be necessary, due to an incident in the rest of the pipes, the service pressure would be reached in a short space of time.

The carrying capacity of the passenger capsules would range from 40 to 100 seats per trip. If each seat is assigned an equivalent payload of 125 kg, the carrying capacity of the cargo capsules would range from 5 to 12.5 tonnes. The cargo activity is envisaged as a complementary service to passenger transport and should be focused on high value-added and/or perishable cargo.

The need for passenger pods is quantified at 1,680 (73.5% of the total), and they would operate on a daily average of 8.70 journeys (4.35 journeys per direction). The average operating time of this type of capsule would be 4,111 hours per year (11.26 hours per day).

The average annual km travelled by each passenger capsule would be around 1.3 million (3,591 km per day).

The need for cargo capsules is quantified at 604, and they would operate on a daily average of 4.66 expeditions (2.33 expeditions per direction). The average operating time of this type of capsule would be 2,450 hours per year (6.71 hours per day). The average annual km travelled by each passenger pod would be around 0.70 million (1,921 km per day).

From the gravity demand models, a demand for the use of the network of 145.9 million passengers can be surmised for the year 2020. The calculation of this usage demand in a planning phase is particularly useful to obtain the design demands for an initial dimensioning of the number of tubes required in each direction.

The setting of operating timetables per line on each of the 14 predefined standard days, and of time slots within each day with differentiated service frequencies, would make it possible to offer a potential transport capacity of 355 million passengers per year and 8.7 million tonnes from 2020 onwards.

As a reference taken from Eurostat (2021), it is worth noting that in terms of air transport alone, the volume of passengers generated in 2019 by 47 European airports (providing a service equivalent to that provided by the 28 stations of the European Hyperloop Network) to any other airport in the European Union amounted to 256 million. These values show the possibility of growth in demand for use over a reasonable period of time during which it would not be necessary to undertake work to expand the capacity of the network.

6. NEXT STEPS

If the final decision on the part of governments is to provide this type of infrastructure through public-private partnership contracts, there must necessarily be Special Purpose Companies of a mercantile nature to make them a reality. In this sense, it is essential to determine the number of companies that will be necessary to carry out the investment projects, as well as to describe the corporate purpose of each.

In the process of technical, economic, financial, and legal structuring of this type of agreement between public and private agents, the amount of obligations to be met by the companies will emerge on the one hand, and the amount of rights on the other. The final balance resulting from the balancing of these rights and obligations will make it possible to quantify, where appropriate, the need for the contribution of public resources and their typology.

In this context, one of the most relevant obligations in the opex structure of the new operating companies will be electricity consumption.

As stated at the beginning of this paper, Hyperloop has been presented to the world as a new green mode of transport, and the existing proposals to date all advocate that the renewable energy source should be solar. Since 2009, the price of solar power generation has been gradually decreasing from USD 0.359 per kWh to USD 0.037 per kWh today. Similarly, in 2009 the cost of wind power generation was USD 0.135 per Kwh to USD 0.040 today (Schneider, 2021). Despite the relatively low prices on exhibit, and the technical availability of battery backup is becoming more and more feasible, there is still a problem of stable availability of this type of energy source.

It would therefore be worth exploring the possibility of linking Hyperloop with novel energy sources that are potentially more beneficial than solar and wind. In 2016, the European Patent Office approved the patent application for a Spanish invention called the Ionic Electric Power Station (Santana Ramirez, 2016), which, in addition to promising to generate electricity at a production cost of around USD 0.020 per kWh, has also been classified by the same body as a renewable energy source that mitigates climate change under the heading (Y02P20/133).

Keep going through further progress in the search for sustainable energy sources with more stable generation profiles will advance the financial viability of Hyperloop.

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LOCALIZACIÓN BAJO DOS PERSPECTIVAS ENFRENTADAS: ¿CERCANÍA O REPARTO JUSTO?

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RESUMEN

En este trabajo abordamos un problema de localización que, a pesar de su gran interés y aplicabilidad en situaciones reales, ha sido poco estudiado en la literatura. No obstante, cada vez más empresas se enfrentan a él a la hora de determinar la localización óptima de sus instalaciones. Generalmente, cuando queremos localizar un conjunto de instalaciones, ya sean estaciones de bicicletas, centros comerciales u hospitales, entre muchas otras, se intenta que estén lo más cerca posible de sus puntos de demandas, esto es, usuarios de la bicicleta, clientes o pacientes. Pero, a su vez, se desea también que la carga de trabajo (la demanda) esté repartida de forma homogénea.

Así, los objetivos a optimizar serían: minimizar la mayor distancia entre las instalaciones y los puntos de demanda y balancear la carga de trabajo de las instalaciones que se localicen, entendiendo como carga de trabajo el número de puntos de demanda a los que una instalación presta servicio. Por tanto, se consideran dos objetivos que, habitualmente están en conflicto, esto es, si se trata de localizar instalaciones favoreciendo que los puntos de demanda estén lo más cerca posible de la instalación que le presta el servicio, podría conllevar que haya instalaciones que tengan una carga de trabajo más elevada que otras. Igualmente, si nos centramos en optimizar el balanceo de la carga de trabajo de las instalaciones, podría conllevar que los puntos de demanda estén más alejados. Debido a la complejidad del problema de optimización combinatoria bi-objetivo que sea plantea, los métodos exactos hacen que su resolución sea costosa o inviable. Esto nos lleva a proponer un algoritmo metaheurístico capaz de resolverlo rápidamente obteniéndose soluciones de gran calidad. Concretamente, se propone un algoritmo híbrido basado en Oscilación Estratégica combinado con Path Relinking capaz de ofrecer diferentes soluciones eficientes de gran calidad.

1. INTRODUCCIÓN

En general, los problemas de localización son problemas clásicos de optimización que consisten en encontrar la mejor localización para situar un conjunto de instalaciones, que deben servir a su vez a un conjunto de puntos de demandas. El término *mejor* dependerá de la función que se considere a la hora de resolver el problema de localización específico que tengamos entre manos. Normalmente, esta función suele definirse basándonos en la distancia o en el coste que hay entre los puntos de demandas y las instalaciones.

Además, en términos generales un problema de localización puede clasificarse como discreto o continuo, ponderado o sin ponderar, con capacidades o sin capacidades, determinístico o estocástico, y esto dependerá de las características que tengan asociados tanto los puntos de demanda a los que haya que dar servicio como las instalaciones a localizar. Por otro lado, cuando estamos resolviendo un problema real es común que se consideren más de un objetivo a la vez cuyos objetivos están en conflicto, es decir, es imposible mejorar uno de ellos sin empeorar otro, convirtiéndose el problema en un problema de optimización multi-objectivo ya que, en lugar de obtener una solución óptima, se debe obtener un conjunto de soluciones eficientes (también conocidas como soluciones no dominadas o soluciones Pareto). Diremos que una solución es eficiente cuando no exista ninguna otra solución posible que la mejore en, al menos, uno de los objetivos, igualando los niveles de los demás.

En este trabajo pretendemos resolver un problema de localización bi-objectivo, discreto, no ponderado, sin capacidades y determinístico conocido como el problema del k-centro balanceado, en adelante, k-BCL (por sus siglas en inglés, k-Balanced Center Location). Este problema fue estudiado por primera vez por Davoodi (2019) y su objetivo es localizar un k de instalaciones, seleccionadas de un conjunto m de posibles instalaciones candidatas, con $k<m$, para servir a un conjunto de n puntos de demanda de forma que se minimice la máxima distancia entre cada punto de demanda y su instalación más cercana, para que todos los puntos de demandas puedan tener las instalaciones que le prestarán el servicio lo más cerca posible, y al mismo tiempo minimizar el máximo número de puntos de demandas asignados a cada instalación para balancear la carga de trabajo de cada instalación.

Para abordar el problema del k-BCL se ha diseñado un algoritmo metaheurístico basado en la construcción soluciones usando un algoritmo GRASP (Festa y Resende, 2009). Estas soluciones se incluyen en un algoritmo de Oscilación Estratégica (Glover, 2000) combinado con Path Relinking (Ribeiro y Resende, 2012) capaz de ofrecer diferentes soluciones eficientes de gran calidad.

2. ALGORITMO

Como se introdujo anteriormente el problema del k-BCL pretende: minimizar la máxima distancia entre cada punto de demanda y su instalación más cercana, y al mismo tiempo, minimizar el máximo número de puntos de demandas asignados a cada instalación.

Teniendo estos dos objetivos en cuenta, a continuación, se detalla el algoritmo diseñado para obtener soluciones eficientes para este problema.

2.1 Construcción: GRASP

Para construir soluciones factibles usaremos una metodología GRASP (Festa y Resende, 2009) que es un algoritmo multi-arranque que se compone de dos fases: fase de construcción y fase de mejora. La fase de construcción es la encargada de construir soluciones factibles desde cero y la fase de mejora es la encargada de mejorar las soluciones aplicando una búsqueda local. Por tanto, para construir soluciones partimos de una solución vacía y se elige aleatoriamente la primera instalación que se va a localizar y a continuación se ordenan en una lista el resto de las instalaciones basándonos en una medida de contribución que dependerá de la función a optimizar. Este algoritmo en lugar de seleccionar siempre la mejor instalación elegirá aleatoriamente una instalación de las mejores hasta que se haya construido una solución completa, es decir, hasta que se hayan seleccionado (o abierto) *k* instalaciones. Esto se repite *N* veces para tener una población inicial de soluciones. Como estamos tratando con un problema con dos objetivos que están en conflicto, tendremos que quedarnos con todas aquellas soluciones que sean eficientes. Como es usual en un algoritmo GRASP, se intentarán mejorar las soluciones aplicándoles una búsqueda local. En este caso, hemos optado por una búsqueda local muy sencilla que consiste simplemente en intercambiar una instalación que haya sido incluida en la solución con otra que no lo haya sido y ver si somos capaces de mejorarlas haciendo este simple intercambio.

2.2 Oscilación Estratégica

Las soluciones eficientes obtenidas en la fase anterior serán incluidas en un procedimiento de oscilación estratégica (Glover, 2000) que consiste en explorar nuevas regiones del espacio de soluciones gracias a movernos entre la factibilidad y la infactibilidad de las soluciones.

En la Figura 1 puede observarse gráficamente como funciona la oscilación estratégica. Partimos de una solución factible obtenida en la Sección 2.1, S_i y añadiremos y eliminaremos instalaciones para obtener soluciones infactibles, S_i^a y S_i^r. En la mitad del camino obtendremos otra solución factible, S_i^c. Este procedimiento se repetirá un número de veces que denotaremos *Iter*.

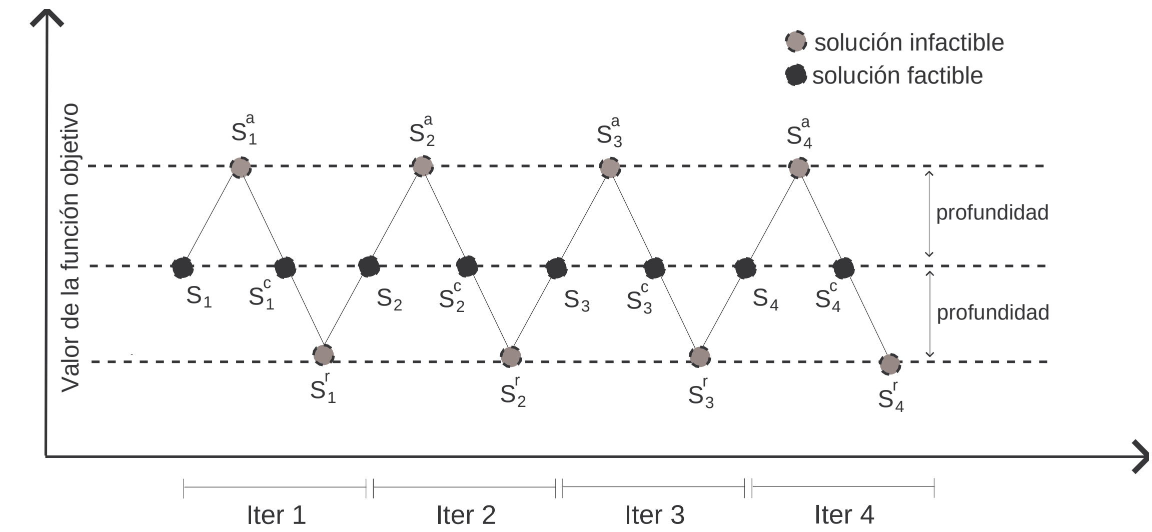

Figura 1: Oscilación estratégica

Recordemos que de nuevo, cada vez que obtengamos una solución factible, S_i y S_i^c, para *i=1,…,Iter,* debemos comprobar si es una solución eficiente, comparándolas con las previamente obtenidas.

2.3 Path Relinking

Para finalizar, exploraremos más soluciones uniendo trayectorias de soluciones que conecten dos soluciones infactibles cualesquiera obtenidas en la Sección 2.2 gracias a la oscilación estratégica, S_i^a y S_i^r.

En la Figura 2, se muestra un ejemplo en el que hay que localizar 6 instalaciones y partimos de dos soluciones infactibles con 2 instalaciones más (solución de partida) y 2 instalaciones menos (solución final). La metodología de Path Relingking va eliminando de la solución de partida las instalaciones que no estén en la solución final. A continuación, se eliminan instalaciones que estén en la solución de partida y se van sustituyendo por instalaciones que estén en la solución final. De esta forma se obtiene un camino para llegar de una solución a la otra que compartirán atributos de ambas soluciones y que además, convierte a estas soluciones en factibles.

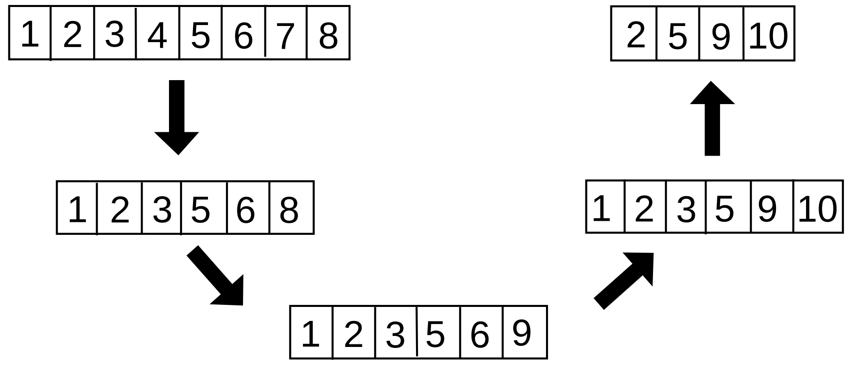

Figura 2: Ejemplo de Path Relinking entre dos soluciones infactibles

Una vez más, cada vez que obtengamos una solución factible debemos comprobar si es una solución eficiente, comparándolas las obtenidas con anterioridad.

3. RESULTADOS

En esta sección se muestran los resultados que se han obtenido al resolver 40 problemas del repositorio OR-lib (http://people.brunel.ac.uk/\textasciitilde mastjjb/jeb/info.html) con el algoritmo propuesto en este trabajo y con otros propuestos en la literatura: NSGA-II (Deb *et al.*, 2002), MOEA/D (Zhang y Li, 2007) y SPEA2 (Zitzler *et al.*, 2001).

Las soluciones eficientes obtenidas por los cuatro algoritmos han sido representadas para cada problema por separado pudiéndose observar que nuestro algoritmo denominado SO+PR es capaz de obtener en una mayoría de los problemas mejores soluciones eficientes.

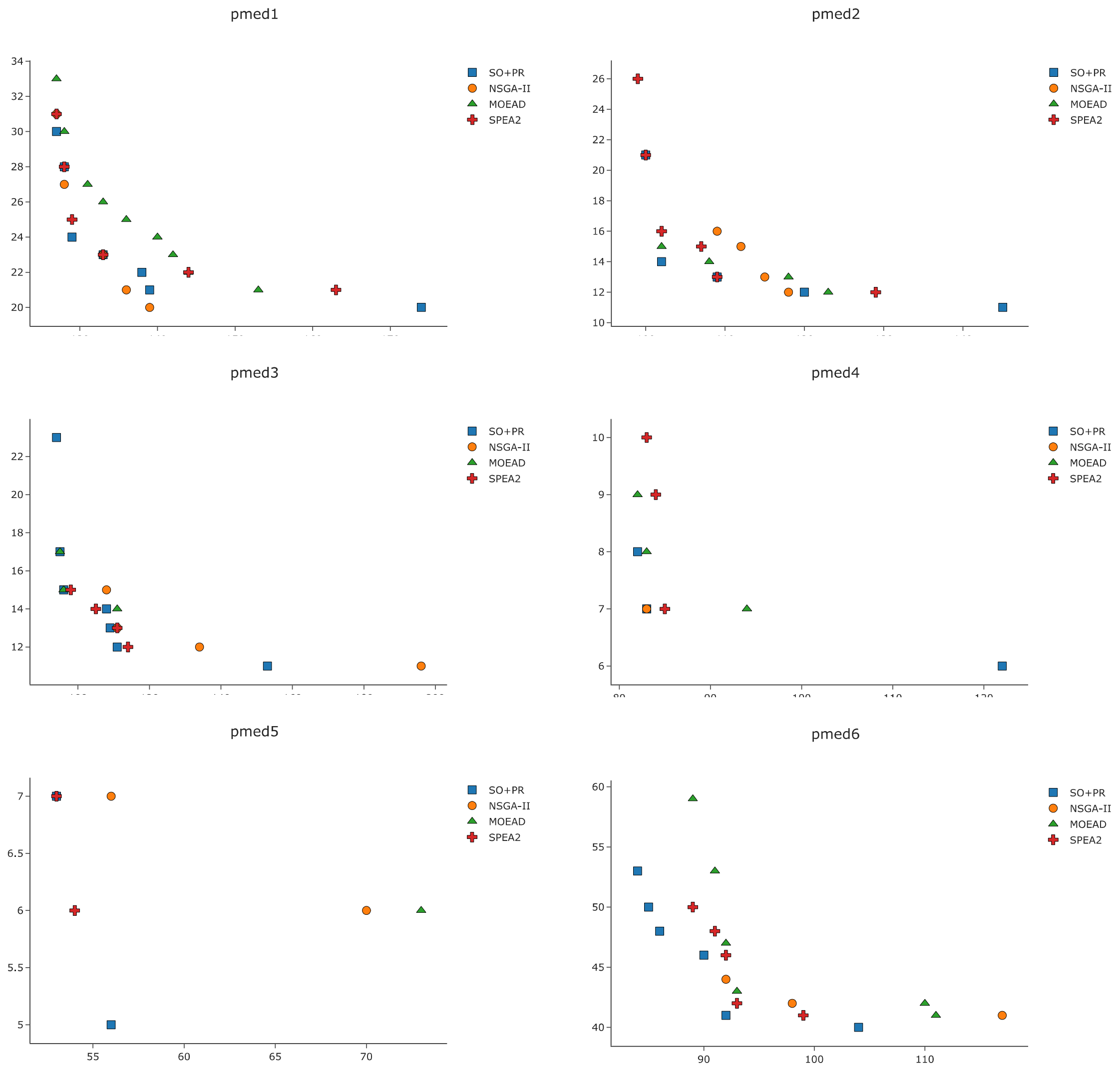

Figura 3: Soluciones eficientes 1-6.

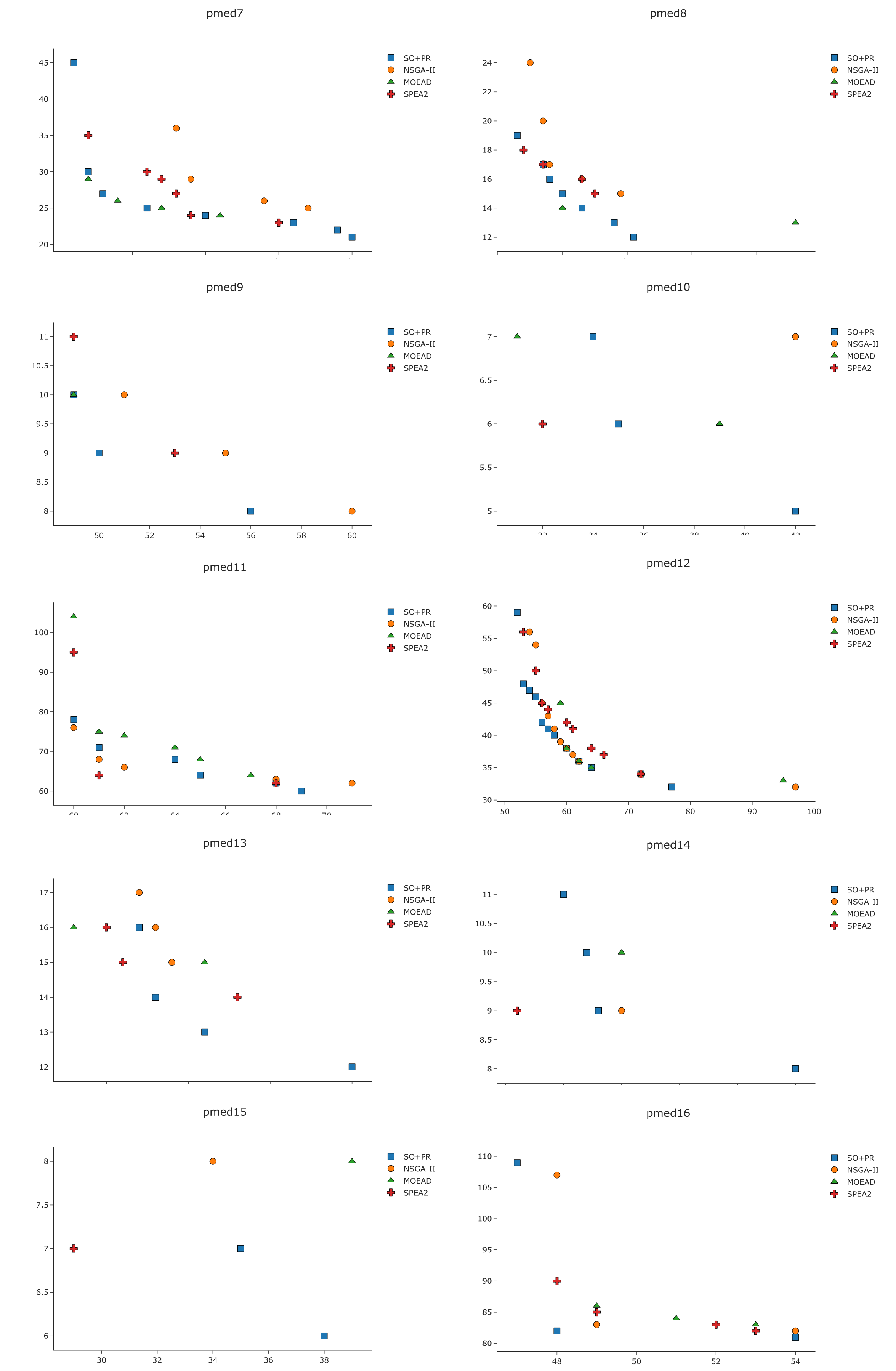

Figura 4: Soluciones eficientes 7-16.

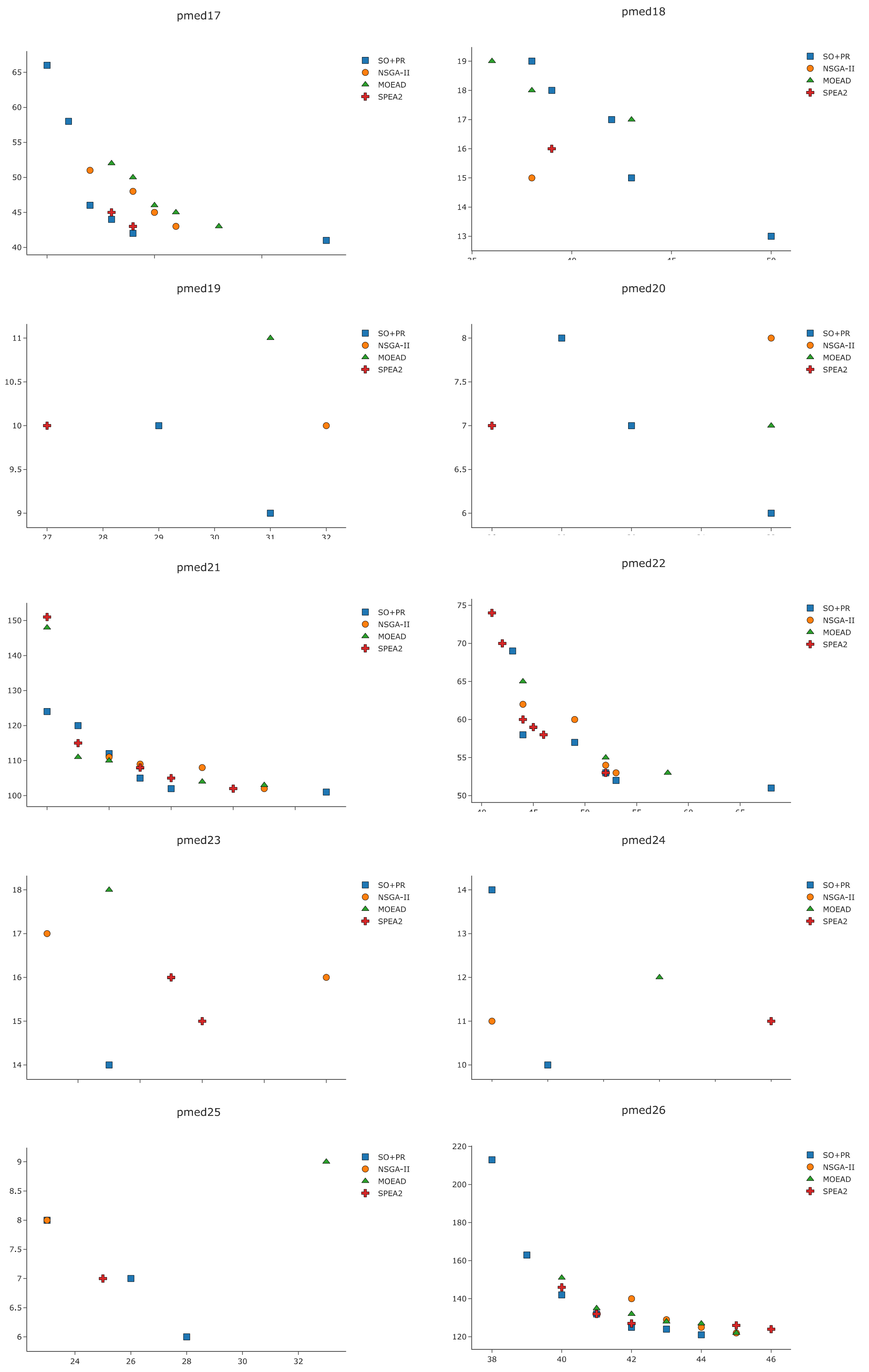

Figura 5: Soluciones eficientes 17-26.

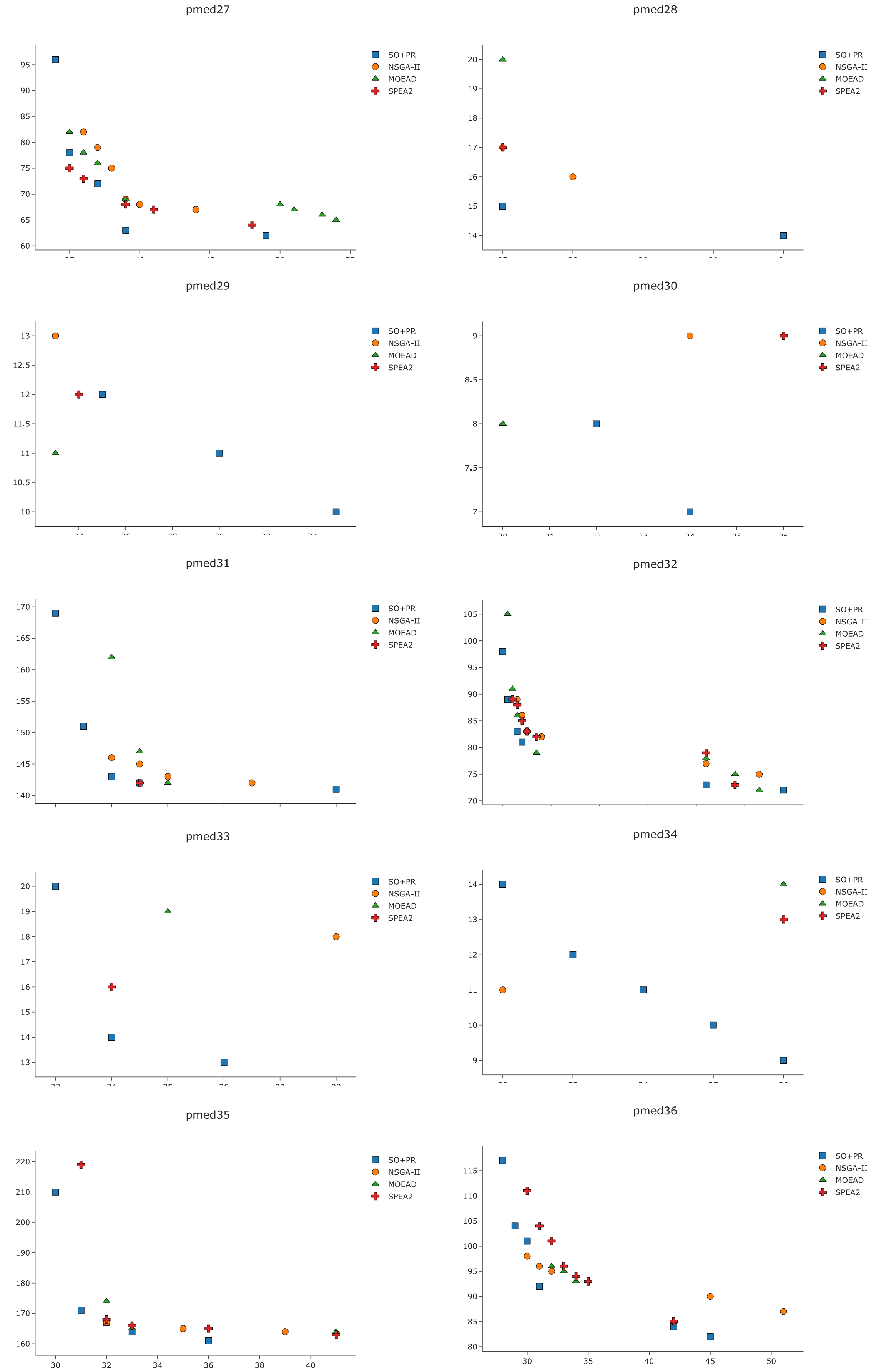

Figura 6: Soluciones eficientes 27-36.

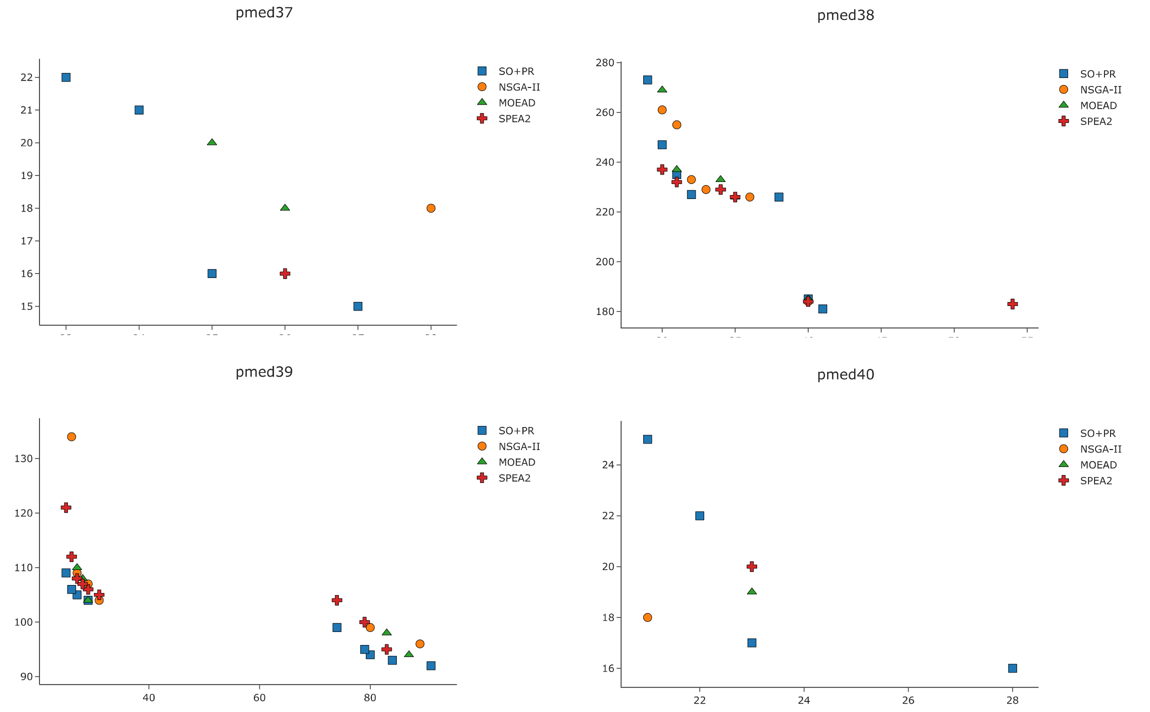

Figura 7: Soluciones eficientes 37-40.

4. CONCLUSIONES

En este trabajo se propone un algoritmo que es capaz de resolver de forma eficiente un problema de localización con dos objetivos que aparece en muchas situaciones reales, el problema que consiste en localizar cualquier tipo de instalaciones asegurando que todos los puntos de demandas puedan tener las instalaciones que le prestarán el servicio lo más cerca posible, y todas las instalaciones tenga una carga de trabajo similar para evitar desigualdades entre ellas.

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CUANDO EL MÁS CERCANO NO ES EL PREFERIBLE

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RESUMEN

En este trabajo presentamos un problema de localización de instalaciones que aparece en múltiples situaciones reales y que, por tanto, es de gran interés para diversos sectores. Generalmente, cuando se desea localizar un conjunto de centros logísticos o de distribución que van a prestar un servicio tanto a empresas minoristas como mayoristas, se intenta que estén situados lo más cerca posible de estas empresas.

Además, se suele asumir que cada empresa recibirá el servicio del centro logístico más cercano. Esto se traduce en que el objetivo o criterio a optimizar sea situar los centros logísticos en aquellos lugares que minimicen la máxima distancia entre las empresas y su centro logístico, asegurando así que la empresa más alejada de su centro de distribución estará lo más cerca posible y, por tanto, todas las demás empresas recorrerán una distancia inferior.

Sin embargo, aparecen situaciones en las cuales algún o algunos centros logísticos podrían quedar inhabilitados debido, por ejemplo, a una catástrofe natural. En este caso, las empresas que son servidas por los centros logísticos afectados tendrán que recibir el servicio desde otro punto. Este otro centro podría ser el segundo más cercano o, si éste también estuviera no disponible, desde el tercero más cercano o, si éste tampoco pudiese dar servicio, desde el cuarto más cercano, y así sucesivamente. Este problema no ha sido muy estudiado en la literatura, pero cada vez se aplica más en situaciones reales propias, por ejemplo, de la Logística Humanitaria. Debido a su complejidad, los métodos exactos no permiten resolver este problema en tiempos razonables.

Por ello, proponemos un algoritmo metaheurístico capaz de resolverlo rápidamente obteniéndose soluciones de gran calidad. Concretamente, se propone un algoritmo GRASP combinado con una Búsqueda Tabú y una Oscilación Estratégica.

1. INTRODUCCIÓN

Existen muchas situaciones reales en las que hay que instalar un conjunto de instalaciones (hospitales, centros comerciales, estaciones de bicicleta, centros logísticos, etc.) para dar un servicio a un conjunto de puntos de demanda (pacientes, clientes, usuarios de bicicleta, empresas, etc.). Hay multitud de problemas de localización según la función que se desee optimizar, algunos de los más conocidos son el problema del p-centro, el problema del p-mediana o el problema de la máxima cobertura. Una característica común que la mayoría de los problemas de localización tienen es que cada punto de demanda será servido por su instalación más cercana ya que así se reduce el coste o el tiempo en el que se obtiene el servicio.

Sin embargo, podría ocurrir que algunas de las instalaciones se queden inhabilitadas debido a algún fallo y que haya que acudir a otra instalación para que preste el servicio requerido por los puntos de demanda. Podemos distinguir entre dos situaciones, que no se conozca de antemano qué instalaciones están inhabilitadas o que si se conozcan. En el primer caso, el cliente debe acudir a la instalación para poder comprobar que no puede obtener el servicio requerido, y una vez allí se dirigirá a la siguiente instalación más cercana a ésta. Este problema se conoce como el problema del próximo p-centro (Albareda-Sambola et al., 2015 o López-Sánchez et at., 2019) y el objetivo es minimizar la máxima distancia entre los puntos de demanda y las instalaciones más cercanas mas la distancia entre las instalaciones y las instalaciones más cercanas a éstas. En el segundo caso, el cliente sabe a priori qué instalaciones no están disponibles y en lugar de ir la instalación más cercana, si ésta no estuviese disponible, se dirigirá directamente a la segunda o si esta no estuviera disponible, se dirigirá a la tercera, y así sucesivamente. Este problema se conoce como el problema del $\propto$-ésimo p-centro (Chen y Chen, 2013) y el objetivo es minimizar la máxima distancia entre los puntos de demanda y la $\propto$-ésima instalación más cercana. En este trabajo se resolverá esta versión del problema, el $\propto$-ésimo p-centro que como se ha indicado su objetivo es localizar un conjunto p de instalaciones, seleccionadas de un conjunto m de posibles instalaciones candidatas, con $p<m$, para servir a un conjunto de n puntos de demanda de forma que se minimice la máxima distancia entre cada punto de demanda y su $\propto$-ésima instalación más cercana, para que todos los puntos de demandas puedan tener, no sólo una única instalación cercana sino $\propto$ instalaciones cercanas asegurando que en el caso de que alguna instalación quedase inhabilitada, poder dirigirnos a la siguiente y que ésta siga estando cerca.

Para abordar el problema se ha diseñado un algoritmo metaheurístico basado en un algoritmo GRASP (Festa y Resende, 2009) para construir soluciones y mejorarlas usando en lugar de una búsqueda local tradicional, una búsqueda Tabú (Glover y Laguna, 1998) Estas soluciones se incluyen en un algoritmo de Oscilación Estratégica (Glover, 2000).

2. ALGORITMO PROPUESTO

Como se introdujo anteriormente el problema del ∝-ésimo p-centro pretende: minimizar la máxima distancia entre cada punto de demanda y su ∝-ésima instalación más cercana. Teniendo este objetivo, a continuación, se detalla el algoritmo diseñado para obtener soluciones para este problema.

2.1 GRASP

Para construir soluciones factibles usaremos una metodología GRASP (Festa y Resende, 2009) que es un algoritmo multi-arranque con dos fases: fase de construcción, que es la encargada de obtener soluciones factibles desde cero y fase de mejora, que es la encargada de mejorar las soluciones obtenidas en la fase de construcción.

En la fase de construcción partimos de una solución vacía y se elige aleatoriamente la primera instalación que se va a localizar y a continuación se ordenan en una lista el resto de las instalaciones basándonos en una medida de contribución que dependerá de la función a optimizar. Este algoritmo en lugar de seleccionar siempre la mejor instalación elegirá aleatoriamente una instalación de las mejores instalaciones hasta que se haya construido una solución completa, es decir, hasta que se hayan seleccionado p instalaciones. Esto se repite N veces para tener una población inicial de soluciones.

Una vez construidas N soluciones factibles y como es usual en un algoritmo GRASP, se intentarán mejorar las soluciones aplicándoles una búsqueda local. Una búsqueda local sencilla consistiría simplemente en intercambiar una instalación que haya sido incluida en la solución con otra que no lo haya sido y ver si somos capaces de mejorarlas haciendo este simple intercambio. Sin embargo, en esta fase en lugar de optar por una búsqueda tradicional hemos implementado una búsqueda tabú (Glover y Laguna, 1998) puesto que uno de los inconvenientes de la búsqueda local tradicional es que la mejora de la solución depende fuertemente de la solución de partida, pudiendo quedar fácilmente en un óptimo local. La búsqueda tabú tiene dos características importantes, memoria adaptativa y aceptación o no de movimientos. En este caso, dispondremos de una memoria a corto plazo que almacenará los últimos movimientos que se hayan realizado, de esta forma no podrán repetirse movimientos mientras que estén almacenados en la memoria, con el fin de restringir los movimientos disponibles y se permitirá empeorar el valor de la función objetivo para evitar quedar atrapado en un óptimo local. La búsqueda tabú termina cuando no se encuentren mejoras después de un número determinado de iteraciones.

2.2 Oscilación estratégica

Las soluciones obtenidas en la fase anterior serán incluidas en un procedimiento de oscilación estratégica (Glover, 2000) que consiste en explorar nuevas regiones del espacio de soluciones gracias a movernos entre la factibilidad y la infactibilidad de las soluciones.

Partimos de una solución factible obtenida en la Sección 2.1, y añadiremos las δ instalaciones para obtener soluciones infactibles con $p + \delta$ instalaciones. A continuación, para recuperar la factibilidad se eliminan δ instalaciones. Se han seguido los siguientes criterios para incluir y eliminar instalaciones:

Insertar	**Eliminar**
Voraz	Voraz
Voraz	Aleatoriamente
Aleatoriamente	Voraz
Aleatoriamente	Aleatoriamente

Tabla 1: Estrategias para insertar y eliminar instalaciones en la oscilación estratégica.

3. RESULTADOS

En esta sección se muestran los resultados que se han obtenido al resolver 37 problemas del repositorio TSP-lib (http://elib.zib.de/pub/mp-testdata/tsp/tsplib/tsplib.html) con el algoritmo propuesto y hemos realizado una comparación con el estado del arte. Concretamente se ha resuelto el problema para $\alpha = 1,2,3$, siendo un total de 111 instancias. En las tablas 2, 3 y 4 se muestran los valores medios de la función objetivo (FO) y el tiempo de ejecución en segundos (CPU) para cada problema solucionado. Se muestra una comparativa de nuestro algoritmo propuesto denominado (SO) y el estado del arte (SOTA) y además se incluyen los límites inferiores (LB) para cada problema.

Como puede observarse en las tablas 2, 3 y 4, el algoritmo propuesto presenta un comportamiento robusto como mostraron las 30 ejecuciones independientes que se realizaron, independientemente del valor de $\propto$ seleccionado.

	LB		SOTA		SO	
Instance	**FO**	**CPU (s)**	**FO**	**CPU (s)**	**FO**	**CPU (s)**
att48_48_10	836.34	0.09	1401.71	0.09	1203.18	1.85
att48_48_20	474.65	0.11	921.43	0.11	710.77	0.65
att48_48_30	251.07	0.08	921.43	0.08	462.08	0.22
att48_48_40	186.95	0.07	331.05	0.07	319.85	0.06
ch150_150_10	122.55	8.59	177.64	8.59	141.53	82.96
ch150_150_100	18.91	1.78	45.25	1.78	33.47	1.50
ch150_150_110	16.48	1.83	48.22	1.83	30.18	0.95
ch150_150_120	13.77	1.73	40.72	1.73	27.36	0.55
ch150_150_130	11.91	1.76	33.40	1.76	22.45	0.26
ch150_150_140	8.80	1.46	36.68	1.46	17.58	0.11
ch150_150_20	76.80	14.33	133.37	14.33	97.13	39.97
ch150_150_30	55.72	9.55	118.75	9.55	79.56	18.01
ch150_150_40	47.41	6.14	93.49	6.14	68.23	12.22
ch150_150_50	38.01	3.94	79.66	3.94	60.94	7.74
ch150_150_60	31.98	3.95	68.02	3.95	49.64	6.29
ch150_150_70	27.06	2.11	68.02	2.11	46.48	4.38
ch150_150_80	24.99	1.72	49.64	1.72	41.46	3.28
ch150_150_90	20.73	1.83	45.95	1.83	38.38	2.18
eil101_101_10	12.14	2.72	18.68	2.72	14.32	26.04
eil101_101_100	0.71	0.18	1.41	0.18	1.41	0.05
eil101_101_20	7.53	5.78	12.73	5.78	10.30	8.50
eil101_101_30	5.76	2.06	12.04	2.06	8.25	4.75
eil101_101_40	4.61	1.16	11.18	1.16	7.28	2.89
eil101_101_50	3.64	1.00	10.82	1.00	7.07	1.80
eil101_101_60	3.35	0.65	7.62	0.65	6.32	1.08
eil101_101_70	2.69	0.35	7.21	0.35	5.00	0.55
eil101_101_80	2.24	0.28	6.71	0.28	4.12	0.25
eil101_101_90	1.58	0.20	6.32	0.20	3.16	0.08
pr439_439_10	1716.51	42.85	2580.94	42.85	1971.83	3790.85
pr439_439_20	1029.71	120.01	2958.57	120.01	1200.26	1566.51
pr439_439_30	739.19	279.80	1630.38	279.80	886.71	761.30
pr439_439_40	580.01	319.76	1530.52	319.76	728.87	490.00
pr439_439_50	468.54	368.89	1570.03	368.89	600.00	294.52
pr439_439_60	400.20	370.46	1654.73	370.46	548.29	230.09
pr439_439_70	357.95	271.50	1630.38	271.50	500.00	175.29
pr439_439_80	312.50	264.24	1630.38	264.24	475.66	155.71
pr439_439_90	280.90	93.01	1144.83	93.01	416.08	131.18

Tabla 2: Resultados computacionales para $\alpha = 1$

	LB		SOTA		SO	
Instance	**FO**	**CPU (s)**	**FO**	**CPU (s)**	**FO**	**CPU (s)**
att48_48_10	1377.53	0.20	2334.17	0.20	1592.12	5.14
att48_48_20	820.45	0.22	1910.06	0.22	1130.85	1.21
att48_48_30	601.59	0.22	1849.16	0.22	936.38	0.42
att48_48_40	474.65	0.19	1267.89	0.19	532.08	0.07
ch150_150_10	184.06	0.95	241.53	0.95	205.66	223.16
ch150_150_100	38.01	3.61	91.90	3.61	53.21	2.35
ch150_150_110	33.24	3.46	77.13	3.46	51.65	1.36
ch150_150_120	31.98	3.20	77.13	3.20	50.30	0.72
ch150_150_130	29.55	2.49	87.22	2.49	46.63	0.31
ch150_150_140	27.06	2.23	71.82	2.23	42.30	0.14
ch150_150_20	122.55	13.20	194.37	13.20	141.53	94.75
ch150_150_30	93.98	26.27	161.82	26.27	112.51	55.58
ch150_150_40	76.38	20.94	118.83	20.94	96.42	31.74
ch150_150_50	65.42	19.11	166.24	19.11	87.69	18.10
ch150_150_60	55.72	8.02	129.57	8.02	78.42	12.24
ch150_150_70	50.78	5.97	117.58	5.97	68.23	8.20
ch150_150_80	47.41	4.22	98.11	4.22	64.45	5.57
ch150_150_90	41.28	4.14	103.50	4.14	62.04	3.63
eil101_101_10	19.46	0.45	25.94	0.45	21.21	68.12
eil101_101_100	3.64	0.68	6.32	0.68	2.83	0.05
eil101_101_20	12.14	7.98	19.10	7.98	14.14	28.27
eil101_101_30	9.22	7.22	18.68	7.22	12.00	10.63
eil101_101_40	7.53	9.60	15.13	9.60	9.43	6.19
eil101_101_50	6.36	4.05	15.81	4.05	8.60	3.19
eil101_101_60	5.76	2.85	13.60	2.85	8.25	1.94
eil101_101_70	5.00	1.61	13.60	1.61	7.28	0.96
eil101_101_80	4.53	1.43	12.04	1.43	6.32	0.43
eil101_101_90	4.03	1.06	9.43	1.06	5.00	0.11
pr439_439_10	2752.64	0.37	3779.05	0.81	3146.63	12960.97
pr439_439_20	1716.51	0.84	2440.54	26.27	2226.26	6158.89
pr439_439_30	1271.83	0.94	3222.19	24.36	1500.21	3982.18
pr439_439_40	1008.17	3.40	3300.00	76.85	1253.99	2587.24
pr439_439_50	874.27	4.53	2432.33	183.53	1068.00	1327.63
pr439_439_60	739.19	7.90	2037.31	487.18	975.00	918.13
pr439_439_70	621.74	25.81	2575.12	1271.12	905.54	639.50
pr439_439_80	580.01	24.80	2277.06	497.79	731.86	509.87
pr439_439_90	530.48	49.18	2432.33	291.78	715.89	405.64

Tabla 3: Resultados computacionales para $\alpha = 2$

	LB		SOTA		SO	
Instance	**FO**	**CPU (s)**	**FO**	**CPU (s)**	**FO**	**CPU (s)**
att48_48_10	1965.63	0.01	2755.07	0.01	2186.31	6.72
att48_48_20	1179.16	0.35	2011.66	0.33	1374.48	1.61
att48_48_30	829.38	0.54	1628.44	0.50	1011.66	0.54
att48_48_40	676.75	0.22	1374.48	0.22	675.00	0.08
ch150_150_10	295.81	0.15	330.21	0.16	298.56	398.03
ch150_150_100	52.60	5.76	109.42	7.79	69.35	3.23
ch150_150_110	48.80	6.83	134.29	8.85	67.22	1.85
ch150_150_120	47.41	4.79	108.78	5.18	61.29	0.95
ch150_150_130	42.59	4.62	104.00	4.43	57.50	0.41
ch150_150_140	40.01	4.82	77.13	4.33	52.20	0.16
ch150_150_20	168.41	19.58	203.04	13.83	179.71	150.94
ch150_150_30	122.55	26.00	211.07	35.26	146.41	78.08
ch150_150_40	103.43	25.38	167.28	25.21	119.22	52.10
ch150_150_50	87.13	26.36	161.82	27.68	108.03	26.70
ch150_150_60	76.38	21.82	164.50	26.16	97.46	17.78
ch150_150_70	69.37	31.32	134.29	30.88	92.82	13.10
ch150_150_80	61.58	17.73	131.63	17.82	83.38	8.34
ch150_150_90	55.72	9.74	133.65	12.64	79.81	4.75
eil101_101_10	30.22	0.11	33.24	0.10	29.43	92.44
eil101_101_100	5.17	2.24	10.20	2.15	2.83	0.05
eil101_101_20	16.32	2.70	20.81	3.41	18.03	43.73
eil101_101_30	12.14	4.77	16.28	5.61	14.14	19.37
eil101_101_40	10.31	10.51	21.40	11.04	12.04	9.71
eil101_101_50	9.01	6.60	21.54	7.03	10.63	4.74
eil101_101_60	7.53	8.05	13.60	8.47	9.06	2.22
eil101_101_70	6.71	8.09	14.42	8.72	8.54	1.06
eil101_101_80	6.08	4.06	15.13	4.49	7.28	0.44
eil101_101_90	5.76	2.50	10.77	2.95	6.08	0.11
pr439_439_10	3989.30	0.49	4601.22	0.09	4076.23	16272.47
pr439_439_20	2347.51	6.27	3220.64	29.76	2726.03	11827.09
pr439_439_30	1716.51	2.01	3390.06	18.51	2231.73	5679.48
pr439_439_40	1407.62	3.21	3222.19	67.48	1644.88	4102.42
pr439_439_50	1226.02	3.23	3486.58	38.89	1467.35	3039.05
pr439_439_60	1019.99	5.76	2622.26	105.76	1340.01	2033.03
pr439_439_70	946.46	17.48	3222.19	102.37	1231.11	1316.50
pr439_439_80	853.03	54.00	3390.06	402.48	1217.58	955.74
pr439_439_90	739.19	21.18	2982.03	491.31	986.47	723.38

Tabla 4: Resultados computacionales para $\alpha = 3$

4. CONCLUSIONES

En este trabajo hemos abordado un problema de optimización conocido como el problema $\propto$-ésimo p-centro y que aparece cuando fallan las $\propto -1$-ésimas instalaciones más cercanas teniendo que ir a la $\propto$-ésima instalación más cercana. Aquí se han abordaddo situaciones con $\propto = 1,2,3$ puesto que en situaciones reales suele ser improbable que fallen más de 3 instalaciones. El algoritmo que se propone es capaz de obtener soluciones independientemente del valor de $\propto$ que se indique y esa flexibilidad es una de las fortalezas del algoritmo propuesto.

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PREMIOS A JÓVENES INVESTIGADORES - FINALISTAS
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ANALYSIS OF PUBLIC-PRIVATE PARTNERSHIP MODELS IN HIGH-SPEED RAILWAY TRANSPORT IN PORTUGAL

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ABSTRACT

European railway transportation is not as efficient as it could be. Several factors contribute to this absence of efficiency, including a lack of private investment and exclusively public railway administrators and enterprises. Public-private partnerships can yield higher efficiency in railway transport. Within the high-speed railway sector there are a few implemented infrastructures through public-private partnerships and, in many of them, the result has not been the expected one. Hence, the purpose of this research is to develop a list of recommendations and good practices that allow governments, private investors, and railway stakeholders to take better and more efficient decisions on the implementation of new high-speed rail lines. Consequently, this research has analysed the Portuguese high-speed rail network called Rede Ferroviária de Alta Velocidade (RAVE) designed through public-private partnership. The research methodology is based on exploratory case study and on the identification of critical success factors. This article has made it possible to develop the following list of recommendations and good practices, cross-border cooperation for international sections, unique contracts for substructure and superstructure and an independent contract for signalling and communication systems.

1. INTRODUCTION

Exclusively public railway managers and operators, an absence of cost-reducing competition, and a lack of private investment can be classified as the historical factors that have not allowed railway transport to be as efficient as it might be (European Parliament, 2016). The European Union initiated railway transport liberalisation in 2006 with international freight transport, in 2007 with domestic freight transport, continued in 2010 with international passenger transport, and finished the 14th December 2020 with domestic passenger services (Diario Oficial de la Unión Europea, 2004b, 2007, 2016). These measures represent the initial actions taken toward an efficient railway system in Europe.

The most efficient railway transport management and development can be obtained through public–private partnership (PPP) contracts. PPP offers a reduction in public financing, mobilises private investment, and grants access to advantages connected with the private sector like skilled project management and innovation. Public services such as road transport have implemented this partnership successfully, but it is not a common model in high-speed railway transport. A limited number of high-speed railway lines have been constructed using PPP contracts. However, in many cases, the result has not been optimal. The following situations illustrate these facts (European PPP Expertise Centre 2020; World Bank, 2017, 2020).

Since 2007, a high-speed railway line has connected the Channel Tunnel with London. Formerly known as the Channel Tunnel Rail Link, this line is currently called High Speed 1. The PPP contract had to be restructured during the construction period due to two obstacles: difficulties in obtaining private financing and the British Government's opposition to augmenting the direct grants. High Speed 1's income came from the track access payments of Eurostar, the international railway enterprise that operates passenger rail services between France and the United Kingdom through the Channel Tunnel. The concession contract included the purchase of British public participation in Eurostar. Nevertheless, the Eurostar services were merely a third of what was forecasted, and the concessionaire had to sell its participation in Eurostar (Butcher, 2011; National Audit Office, 2001, 2005, 2012, 2015).
Since 2010, a cross-border high-speed line has connected the towns of Figueras (Spain) and Perpignan (France) through the Pyrenees. The PPP contract was awarded to the company TP Ferro. The Figueras-Perpignan line should receive traffic from the Spanish Barcelona-Figueras high-speed line. However, when the cross-border line was ready to begin operation, the Barcelona-Figueras line was under construction and the Figueras-Perpignan line had no rail traffic. The concession period was extended to solve this inconvenience, but ultimately, the PPP contract was terminated early. Currently, the Spanish and French national railway managers are operating this Spanish-French international section (Boletín Oficial del Estado, 2004, 2016; Eiffage 2013; Ministerio de Fomento, 2009, 2011; Sanz Gandásegui, 2005; Secretario de Estado de Relaciones con las Cortes, 2015).

These experiences reveal the need for a deep study of the reasons that high-speed railway PPP contracts fail, so that such failures can be avoided. In both cases, the failures proceeded from the decisions of public administrators and private investors. Hence, this article examines the RAVE Portuguese high-speed railway line which was designed through PPP contracts. Through this high-speed rail network, Portugal not only connected their capital with that of the neighboring country, but also connected with the European high-speed rail network. The RAVE Portuguese high-speed railway network was designed through six PPP contracts in 2004. However, it was only awarded the contract for the Poceirão and Caia section. Because of the 2008-2010 international financial crisis, which deeply affected Portugal, the PPP contract for the Poceirão-Caia section was rescinded during the design phase and the project for the whole network was discarded (Diário da República, 2011; Direcção-Geral do Tesouro e Finanças, 2010; Rede Ferroviária de Alta Velocidade, 2007; Tribunal de Contas, 2014).

In the general context of PPPs for high-speed railways, several economic aspects have already been studied. First, Bonnafous (1987) concluded that the first European high-speed railway line, which connected Paris and Lyon, generated direct economic benefits in the tourism and industry sectors. An extended article on railway PPPs was published by Dehornoy (2012), who deduced that the most successful concessions were those focussing on integrated traffic (for airport links) and availability traffic (for high-speed infrastructure). Moreover, Crozet (2016) concluded that PPPs permit the construction and opening of new high-speed lines in a timely fashion; however, public financial rescues are needed to solve financial problems. The relationship between investment and social benefits of high-speed rail transportation experiences in Europe (and worldwide) has been investigated by multiple researchers (De Rus, 2009; De Rus and Nash, 2009; Campos, de Rus and Barrón, 2009). They concluded that it was better than alternative modes of transport in terms of time savings, reliability, comfort, safety, and reduced pollution. Koppenjan and Leijten (2005, 2007) and Priemus (2011a, 2011b) analysed the Dutch sector in detail – the Hogesnelheidslijn Zuid (HSL-Zuid) high-speed line in particular – to assess the participation of private investors in railway infrastructure. They established that the Dutch government was not able to implement innovative contracts successfully due to its limited knowledge about PPP.

The RAVE Portuguese high-speed railway network has been developed in consideration of the interests of the Republic, politicians, private investors, and construction companies. De Azevedo Isidoro, Marat-Mendes, and Regina Tângari (2018) realised that the network’s layout has not suffered from large changes from 1845 to 2015 and that developments were successfully made during social and economics transformations. Despite its limited budget, Portugal has led the European Union in development new transport infrastructure through PPP. However, Macário, Ribeiro and Duarte Costa (2015) found several pitfalls related to PPP regulation. Through a huge study on Portuguese road and railway PPPs, Pereira (2016) explains that most of the projects overestimated the demand forecast. On the contrary, while exploring the advantages of PPP, Rolland Sobral and Neves Cruz (2011) noted the success of private financing, adherence to a budget and deadlines, and the know-how of private investors in Portugal.

The Portuguese public-private high-speed rail model has been analysed by many authors. Besanko and Tenreiro Gonçalves (2013) concluded that the state-owned company RAVE should have described how the social and economic benefits were higher than the infrastructures costs. Pedro, De Abreu e Silva and Brookes (2015) described the influence of the external stakeholders. Oliveira Cruz, Kokkaew, and Cunha Marques (2017) issued recommendations to reduce risks (e.g., construct initially only one line to test the PPP model, split the infrastructure and operation management, or re-bid the operation contract within 5 to 10 years). Regarding the financial implementation and management of the Portuguese high-speed railway network, De Abreu e Silva, Silva and Sussman (2011) also determined that PPPs must be adapted to each project and it is necessary to pay attention to the interface generated from the split between substructure and superstructure works.

The failures that appeared during implementation (as previously described) could be repeated, even if the conclusions of the studies reviewed were applied to new high-speed rail lines contracted by PPPs. Therefore, the present research aims to develop a list of recommendations and good practices that can serve as a tool for governments, private investors, and railway stakeholders to make the best decisions before the construction of a new line. For that reason, this study analyses the RAVE Portuguese high-speed railway network.

2. RESEARCH METHODOLOGY

Case study theory was applied to this research in accordance with Stake (1995) and Yin (2009), the most relevant authors in this area. A case study was defined by Stake (1995) as a “study of the particularity and complexity of a single case, coming to understand its activity within important circumstances” (p. 7) and by Yin (2009) as “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evidence” (p. 9). These authors identified two groups of three case study types. According to the reason for selecting a case study, Stake (2003) identified intrinsic, instrumental and collective case studies, and according to the purpose of the research, Yin (2009) identified explanatory, descriptive and exploratory case studies. This research is classified as exploratory case study due to the novelty of the RAVE Portuguese high-speed network examination. This case study is analysed to identify the critical success factors (CSFs) in high-speed railway infrastructure contracted by PPPs. Rockart (1982) defined CSFs as “the few key areas of activity in which favourable results are necessary for a particular manager to reach his or her goals” (p. 4).

This methodology was proven in research related with PPP transport infrastructures (Koppenjan, 2005; Liyanage and Roumboutsos, 2016; Liyanage and Villalba-Romero, 2015; Liyanage, Njuangang and Villalba-Romero, 2016; Ribeiro, Couchinho, Macário and Liyanange, 2016; Voordijk, Liyanage and Temeljotov Salaj, 2016; Macário et al., 2015).
The research methodology steps applied to this article consisted of five sequential actions: (a) collection of a wide range of data for the RAVE Portuguese high-speed railway network from the railway infrastructure concessionaire, railway infrastructure manager, railway undertaking, public administrations and railway-specific publications; (b) classification of the data into six areas: project, infrastructure, transport service, contract, corporate structure and investment; (c) identification and analysis of the CSFs; (d); discussion of the CSFs and (e) development of a list of recommendations and good practices for governments, private investors, and railway stakeholders.

3. DESCRIPTION OF THE CASE STUDY

In 1988, Portugal launched the construction of a high-speed rail network in coordination with Spain; they agreed to design the lines with Union Internationale de Chemins de Fer (UIC)-gauge (1,435 mm) (Diário da República, 1988). RAVE was established as a company in 2000. This company was comprised of the Portuguese State (60%) and Rede Ferroviária Nacional (REFER) (40%), the Portuguese national railway infrastructure manager, whose aim was to analyse and prepare for implementation of the RAVE Portuguese high-speed railway network. In 2001, Portugal and Spain created a European economic interest group called Spain-Portugal high-speed—or, in Portuguese and Spanish, Alta Velocidade Espanha-Portugal and Alta Velocidad España-Portugal. Both nations were responsible for the cross-border sections. This group was made up of RAVE and Administrador de Infraestructuras Ferroviarias (ADIF), the Spanish national railway infrastructure management organization (Rede Ferroviária de Alta Velocidade, 2004; Tribunal de Contas, 2014).

In a binational summit between Portugal and Spain in 2003, the following cross-border sections were defined: Porto-Vigo, Lisbon-Madrid, Aveiro-Salamanca, and Faro-Huelva. In 2004, Portugal unveiled its high-speed railway network, which comprised the agreed-upon sections with Spain and a domestic section between Lisbon and Porto. The European Union included the Lisbon-Porto, Lisbon-Madrid, and Aveiro-Salamanca sections in the high-speed railway axis of its southwestern Europe priority project; and the Porto-Vigo section in the Iberian Peninsula priority project. The Lisbon-Madrid section was classified as one of the five highest-priority axes for the European Union (Diário da República, 2004; Diario Oficial de la Unión Europea, 2004a; Rede Ferroviária de Alta Velocidade, 2004; Tribunal de Contas, 2014).
Following various Portuguese-Spanish summits up to 2009, the Portuguese high-speed rail network was designed with the features described in Table 1:

Axis	Journey time	Traffic	Length	Maximum speed	Stations
Lisbon-Madrid	2 hours and 45 minutes	Passengers and freight	206 km	350 km/h	Lisbon, Évora and Elvas/Badajoz
Lisbon-Porto	1 hour and 15 minutes	Passengers	314 km	300 km/h	Lisbon, Ota, Leiria, Coímbra, Aveiro and Porto
Porto-Vigo	60 minutes	Passengers and freight	100 km	250 km/h	Porto, Sá Carnerio Airport, Braga and Valença/Tuy
Aveiro-Salamanca	2 hours and 45 minutes	Passengers and freight	70 km	250 km/h	Aveiro, Viseu and Guarda
Évora-Faro-Huelva	Lisboa-Faro 1 hour and 30 minutes Faro-Huelva 30 minutes	Passengers	200 km	300 km/h	Évora and Faro

Note: Data from Rede Ferroviária de Alta Velocidade (2006, 2008, 2009).

Table 1 – Portuguese high-speed rail network.

There is a high cross-border mobility between Portugal and Spain due to cultural, linguistic, economic and cultural relations. However, it exists an important deficit in public transport. The new high-speed railway axis benefits to Portugal and Spain, and specially to the Spanish regions of Galicia, Castilla y León, Extremadura and Andalucía, due to its geographical location (Gutiérrez Gallego, Naranjo Gómez, Jaraíz-Cabanillas, Ruiz Labrador, and Su Jeong, 2015; Chen, Correia and de Abreu e Silva, 2015; Carvalho, Partidario and Sheate, 2017; Varela Cornado, 2018).

The Portuguese government decided to start contracting only for the axes considered to be a priority for Portugal. Theses axes were Lisbon-Madrid, Lisbon-Porto, and Porto-Vigo's 1st Phase, which was designed with polyvalent sleepers in 1,668 mm Iberian gauge. These sections are summarised in Table 2.

Axis	Journey time	Traffic	Length	Maximum speed	Stations
Lisbon-Madrid	2 hours and 45 minutes	Passengers and freight	206 km	350 km/h	Lisboa, Évora and Elvas/Badajoz
Lisbon-Porto	1 hour and 15 minutes	Passengers	314 km	300 km/h	Lisboa, Ota, Leiria, Coímbra, Aveiro and Oporto
Porto-Vigo 1st Phase Braga-Valença	60 minutes	Passengers and freight	55 km	250 km/h	Braga and Valença/Tuy

Note: Data from RAVE (2006, 2007, 2008, 2009).

Table 2 – Portuguese high-speed rail network priority axes

The Portuguese government justified the construction of these three Portuguese high-speed rail priority axes mainly through the socioeconomic benefits introduced by the connection with the Spanish and European passenger and freight railway networks (Diário da República, 2010).

In 2010, due to the international financial crisis that affected Portugal in 2008 and especially in 2009, an economic program dedicated to stability and growth was established. This program included a delay on the contracting for the Lisbon-Porto and Porto-Vigo axes (Ministério das Finanças e da Administração Pública, 2010). In 2011, the Portuguese government published a strategic transport plan for the 2011-2015 period in which the Lisbon-Madrid high-speed railway line project was abandoned (Diário da República, 2011). That year, the RAVE society was extinguished and integrated into REFER, which assumed the role of RAVE in the Spain-Portugal high-speed European economic interest group (Tribunal de Contas, 2014).

4. ANALYSIS AND DISCUSSION OF THE CSFs

This research examines the PPP model developed for the RAVE Portuguese high-speed network. In this section are analysed and discussed the CSFs.

4.1. Cross-border cooperation for international sections

For the RAVE Portuguese high-speed network cooperation between Portugal and Spain is ongoing through the various binational summit meetings and involved the creation of a European economic interest group, in which both countries were responsible for the cross-border connection of the Lisbon-Madrid axis (Diário da República, 1988; Tribunal de Contas, 2014). Spain has experience in this type of cross-border cooperation, since the international high-speed rail section between Figueras and Perpignan that links the high-speed rail networks of Spain and France was built through a public-private collaboration model involving a joint agreement between the two countries. As with the connection between Portugal and Spain, these two countries principally made their decisions in bilateral summits to define the characteristics of the international section between Figueras and Perpignan. On October 10th, 1995, as a result of the Spanish-French summit meeting held in Madrid, Spain and France signed the so-called Madrid Agreement, the purpose of which was to establish the grounds for the construction and operation of a high-speed connection between Spain and France through Figueras and Perpignan. Subsequently, in the same way as Portugal and Spain, a European economic interest group was also set up between Spain and France to control and enable the development of the project (Boletín Oficial del Estado, 1998; López Pita, s.f.; Ministère de l'écologie, du développement durable, des transports et du logement, 2011). Another infrastructure that should be highlighted in terms of cross-border railway cooperation is the Channel Tunnel between France and the United Kingdom. This infrastructure was also developed through public-private collaboration, in a joint project between France and the United Kingdom enacted by the Treaty of Canterbury on February

12th, 1986 (Secretary of State for Foreign and Commonwealth, 1986). All these cross-border agreements and cooperation accords between different countries contrast with the case of the HSL-Zuid line where the Netherlands had to pay compensation to Belgium to agree and finalise the route for the cross-border connection (Omega Centre, 2011).

Currently in Europe, cross-border cooperation is an undeniable reality since it contributes to cohesion, sustainable social development, and facilitates increased economic activity in cross-border territories. Transport infrastructures play a fundamental role in cross-border cooperation and common planning policies are increasing in Europe. To provide cross-border projects with continuity and durability, it is necessary to create an alliance between cross-border territories, which must be institutionalised through an agreement. For this alliance to be robust, it is necessary to ensure the participation of interest groups, guarantee a coherent objective for all participants, and ensure that the results of the cooperation involve similar benefits on both sides of the border (Galko and Volodin, 2016; Castanho, Vulevic, Fernández, Fernández-Pozo, Gómez and Loures, 2017; Kurowska-Pysz, Castanho and Loures, 2018).

4.2. Unique contracts for substructure and superstructure

The infrastructure works were divided into the six PPP contracts displayed in Table 3:

Axis	Section	PPP Contract	Scope
Lisbon-Madrid	Poceirão-Caia	PPP1	Substructure and superstructure. Évora station. Conventional freight railway line between Évora and Caia.
	Lisbon-Poceirão	PPP2	Substructure and superstructure. Tejo new bridge, Terceira Travessia do Tejo (TTT).
Lisbon-Porto	Lisbon-Pombal	PPP3	Substructure and superstructure. Leiria station.
	Pombal-Porto	PPP4	Substructure and superstructure. Aveiro station.
Porto-Vigo	Braga-Valença	PPP5	Substructure and superstructure.
All axes	All sections	PPP6	Signalling and communications systems.

Note: Data from Rede Ferroviária de Alta Velocidade (2007) and Tribunal de Contas (2014).

Table 3 – PPP contract scope for the Portuguese high-speed rail network

Substructure and superstructure works were included in the same PPP contracts. The PPP1, PPP2, PPP3, PPP4, and PPP5 contracts had the following scope: design, construction, finance and maintenance for 40 years; during operation, the payments were based on availability, traffic, and maintenance. The PPP6 contract was for the signalling and

communications systems on the whole high-speed railway network. For the Lisbon-Madrid axis, Portugal was responsible for the connection between Lisbon, Poceirão and Caia, which was divided into 2 contracts. The first (contract PPP1) included the high-speed section between Poceirão and Caia. Contract PPP1 also included the construction and operation of Évora station and a conventional freight railway line between Évora and Caia. Contract PPP2 included the high-speed section between Lisbon and Poceirão and a new bridge in Lisbon called Terceira Travessia do Tejo. Contract PPP1 was signed in 2010 with ELOS–Ligações de Alta Velocidade. Contract PPP2, which connected Lisboa and Poceirão in the second Portuguese section of the Lisbon-Madrid axis, was launched in 2009. The consortiums called ELOS–Ligações de Alta Velocidade, ALTAVIA ALENTEJO–Infraestruturas de Alta Velocidade, and TAVE TEJO presented bids. In 2010, due to the financial crisis, the Portuguese government discarded this construction (Direcção-Geral do Tesouro e Finanças, 2008, 2009, 2010; Rede Ferroviária de Alta Velocidade, 2007; Tribunal de Contas, 2014).
For the RAVE Portuguese high-speed network, both the substructure and superstructure were included within the same contract (Rede Ferroviária de Alta Velocidade, 2007; Tribunal de Contas, 2014). This is also the case of the other high-speed lines contracted through public-private partnerships in Europe, namely, the High Speed 1 line, connecting the Channel Tunnel with London, in the United Kingdom, the French Bretagne-Pays de la Loire line, which links the towns of Le Mans and Rennes, the Sud-Europe Atlantique line, which links the towns of Tours and Bordeaux, the Contournement Nîmes-Montpellier bypass, and the international Figueras-Perpignan section between Spain and France (Boletín Oficial del Estado, 2016; ERE Eiffage Rail Express and Réseau Ferré de France, 2013; LISEA and SNCF Réseau, 2017; National Audit Office, 2001; OC'VIA and Réseau Ferré de France, 2012).

It is not a coincidence that all these lines, except for the Dutch HSL-Zuid line, combined the substructure and superstructure activities into a single contract. This need is justified by the following technical reasons. Firstly, it is necessary to indicate that the substructure supports the superstructure and transmits the loads to the foundation. Secondly, the superstructure is the area above ground level that receives the loads from the trains which are then transferred to the substructure. It is clear, therefore, that there is an interaction between the substructure and superstructure; for this reason, it is necessary for the design to take into account the factors that influence the dimensioning, such as stresses and deformations, in order to obtain a better performance from both the substructure and superstructure as well as vehicle dynamics (Alamaa, 2016; Byun, Hong and Lee, 2015; Giannakos, 2010; Li, Hyslip, Sussmann and Chrismer, 2015; Ministry of Housing and Urban Affairs, 2018; Selig and Waters, 1994).

4.3. An independent contract for signalling and communications systems

Portugal decided to equip its infrastructure with the following signalling and communication systems European Rail Traffic Management System (ERTMS) Level 2 and Global System for Mobile Communications-Railway (GSM-R). The implementation of these systems transpired through an independent PPP contract called PPP6. The scope of this contract was for the whole high-speed railway network. The contractor awarded was responsible for design, supply, installation, finance, and maintenance for 20 years, with a public payment based on availability (Rede Ferroviária de Alta Velocidade, 2004, 2007; Tribunal de Contas, 2014).

An independent contract for signalling and communications systems has the following advantages. Due to the reduced number of ERTMS suppliers, if they were integrated into consortiums with the rest of the infrastructure system companies, the number of bidders would decrease, the high technological risk during operation would be minimized, and a unique contract would increase the competitivity in the sector.

Analysing all the European high-speed railway lines constructed through public-private collaboration, Portugal was the only example involving this type of separate agreement for signalling and communication systems (Rede Ferroviária de Alta Velocidade, 2007; Boletín Oficial del Estado, 2016; ERE Eiffage Rail Express and Réseau Ferré de France, 2013; Geluk, 2007; LISEA and SNCF Réseau, 2017; National Audit Office, 2001; OC'VIA and Réseau Ferré de France , 2012; Tribunal de Contas, 2014; Tweede Kamer, 2008) .

Almost every country in the European Union had its own Automatic Train Protection (ATP) system, which were not compatible with one another in most cases. With the increase in international services, it was therefore necessary for the vehicles to possess all the ATP systems of the countries though which they were going to pass. Because of this, in 1989, the European Union launched the development of a single signalling system for the entire network that would facilitate transit between countries. This system was referred to as ERTMS and, in 2000, the first technical specification was published (European Union, 2021). In parallel to the development of the ERTMS system, it was necessary to implement a communication system between the railways and the trains. Thus, it was decided to adapt the existing communication system to the Global System for Mobile Communications (GSM) for railways, which led to the creation of the GSM-R communication system (UIC, 2021b).

Since the first technical specification of the ERTMS system in 2000, 12 new versions of this document have been published (European Union, 2021). The GSM-R communication system will now be replaced by a new development, known as the Future Railway Mobile Communication System (FRMCS) (UIC, 2021a). It is clear that this technology is constantly evolving, representing a significant investment for technologists, infrastructure managers, and railway companies. For this reason, the European Union, aware of the large outlay involved in implementing a single railway signalling system, supported the roll-out of this technology with a subsidy of 3.9 billion euros between 2007 and 2019. (European Commission, 2020). A peculiar fact about this continuous technological evolution is that in Spain, through a public-private collaboration contract, awarded to the technologist Alstom, the ERTMS signalling and GSM-R communication systems have been implemented in the Albacete-Alicante high-speed section, whereas the substructure and superstructure were implemented through a traditional contract (European Commission, 2014).

5. CONCLUSION

This research analysed RAVE high-speed rail network project. This project enabled Portugal to link to the European high-speed network.

This research has required the application of an exploratory approach and the identification of critical success factors (CSFs). The purpose of this research was to develop a list of recommendations and good practices that can serve as a tool for governments, private investors, and railway stakeholders to help them make the best and most efficient decisions in terms of new high-speed rail line construction.

To that end, we present the following recommendations and good practices. Cross-border cooperation for international sections must be established through an agreement between the countries involved, including stakeholders, to guarantee a common objective and the development of similar benefits for all countries. Single contracts should be awarded for a combination of substructure and superstructure, as the design must be implemented jointly by one group of engineers, since any modifications of the substructure affect the superstructure and vice versa, due to the load transmission relationship between these two elements. An independent contract for signalling and communication systems should also be awarded due to the enormous technological risk involved in implementing the ERTMS signalling and GSM-R communications systems, which are constantly evolving in terms of technical specifications. In addition, greater competitiveness must be allowed in this area due to the reduced number of existing technologists. With this list of recommendations and good practices, it is expected that the implementation efficiency of new high-speed rail infrastructures will improve. In addition, this project could be applied not only to the field of public-private collaborations but also to the railway environment as a whole.

LIST OF ABBREVIATIONS

ADIF: Administrador de Infraestructuras Ferroviarias
ATP: Automatic Train Protection
CSF : Critical Success Factor
ERTMS: European Rail Traffic Management System
FRMCS: Future Railway Mobile Communication System
GSM-R: Global System for Mobile Communications-Railway
HSL-Zuid: Hogesnelheidslijn Zuid
PPP: Public–Private Partnership
RAVE: Rede Ferroviária de Alta Velocidade

REFER: Rede Ferrovíaria Nacional
TTT: Terceira Travessia do Tejo
UIC: Union Internationale de Chemins de Fer

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FROM INNOVATION TO THE LAW: A COMPARATIVE ANALYSIS OF NEW TECHNOLOGIES IN AUTONOMOUS MOBILITY LEGISLATION

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ABSTRACT

Spanish Autonomous Communities have been approving Transport Laws for regional and urban services for more than thirty years. An analysis comparing these rules allows us to see how they have evolved towards greater involvement in sustainable mobility. From simple texts, which are limited to delimiting competences and ordering coordination between Administrations, to rules that assume the drawbacks of the current mobility model. The most recent Laws introduce in its principles and objectives the promotion of sustainable public transport from the socioeconomic and environmental aspects. This means offeríng conditions of universal accessibility and universal design and encourages the introduction of information and communications technology and quality at service. This paper is a review of this evolution, highlighting those Laws that have been milestones and culminating with the last two: that of the Principality of Asturias and that of Castile and León. Even with some shortcomings, this introduction represents a commitment by the legislator to sustainable mobility and quality public transport.

1. INTRODUCTION

Technological innovation is a fundamental aspect of public passenger transport. Autonomous Laws have been introducing the promotion of quality and technology in public service beyond specific rules on vehicle approval, active and passive safety, and universal accessibility. All this has the aim of promoting an alternative for sustainable mobility. But we can ask ourselves: from what point has the law of transport been concerned with incorporating quality? How is innovation introduced into the legal regime of the public transport service?

2. EVOLUTION OF QUALITY AND NEW TECHNOLOGIES IN AUTONOMOUS LAWS

Public transport is regulated in Spain with two legislative levels, apart from European legislation. On the one hand, transport that takes place within an Autonomous Community is considered autonomous competence. On the other hand, transport transiting the territory of two or more Autonomous Communities is the responsibility of the State. These powers affect regulation (primary and secondary) and its management.

The first autonomous legislative rule is the Catalan *Ley 12/1987, de 28 de mayo, sobre regulación del transporte de viajeros por carretera mediante vehículos de motor* (Law 12/1987, of 28 May, on the regulation of the transport of passengers by road by motor vehicles). This rule is contemporaneous with State *Ley 16/1987, de 30 de julio, de ordenación de los transportes terrestres* (Law 16/1987, of July 30, on land transport ordinance).

The Catalan Law lacks any reference in the main text to quality or sustainability. For its part, Law 16/1987 has as general principles the establishment and maintenance of a common system throughout the country, the satisfaction of the needs of society with the maximum degree of efficiency and minimum social cost and the maintenance of the market unit.

The appeal of the Generalitat de Catalunya (Catalan Government) before the Constitutional Court of certain provisions of Law 16/1987 was decided by Judgment 118/1996 of 27 June. That judgment annulled the provisions which supplementally regulated urban transport. The annulment led to a regulatory gap that had to be covered by regional legislation, so in the following years the Autonomous Communities passed laws to regulate urban transport and coordinate it with the regional intercity service.

The first autonomous laws after the Judgment were passed in Galicia and the Foral Community of Navarra. Specifically, they were *Ley 6/1996, de 9 de julio, de coordinación de los transportes urbanos e interurbanos por carretera de Galicia* (Law 6/1996, of July 9, coordination of urban and intercity transport by road of Galicia) and *Ley Foral 7/1998, de 1 de junio, reguladora del transporte público urbano por carretera* (Law 7/1998, of June 1, regulating public urban transport by road), respectively. None of them have references in their articles to sustainability or quality of service.

A first precept is found in *Ley 20/1998, de 27 de noviembre de ordenación y coordinación de los transportes urbanos de la Comunidad de Madrid* (Law 20/1998, of 27 November on the ordinance and coordination of urban transport in the Community of Madrid). This Law contains a brief chapter about environmental conditions. It consists of a single article, the 15th. This article indicates that sustainability will be promoted in the processes of renewal and expansion of fleets and in the setting of the technical conditions of taxis. This would be achieved through technologies that pursue maximum energy efficiency, the use of renewable fuels, the reduction of air and noise pollution and the recycling of materials. This inclusion of environmental or quality issues can be described as exceptional.

Both the *14/1998, de 30 de diciembre, de los Transportes Urbanos de la Comunidad Autónoma de Aragón* (Law, 14/1998, of December 30, of the Urban Transports of the Autonomous Community of Aragon) and the *15/2002, de 28 de noviembre, de transporte urbano y metropolitano de Castilla y León* (15/2002, of November 28, of urban and metropolitan transport of Castile and León), antecedenty the current Law of this Community lack objectives, principles or precepts linked to the quality and innovation in transport.

Ley 2/2003, de 12 de mayo, de Ordenación de los Transportes Urbanos y Metropolitanos de Viajeros de Andalucía (Law 2/2003, of 12 May, on Ordinance of Urban and Metropolitan Transports of Travellers of Andalusia) was a milestone. Its Preamble introduced the recognition of mobility problems in urban areas.

Its article 3, dedicated to the purpose and principles of public action, incorporates objectives linked to mobility. In particular, the Administrations will promote the adequate satisfaction of the transport needs of citizens, under conditions of social equity, territorial solidarity, security and accessibility for persons with reduced mobility.

The same article 3, in its second section, adds that the purpose Law is to promote and improve the quality and safety of the public passenger transport service. This is the first time that the improvement in the quality of transport is reflected in an autonomous law and, of course, it does so with prominence.

Article 4, concerning definitions, defines mobility as a set of displacements that persons and goods must make on the basis of work, training, health, social, culture or leisure, or by any other. Regarding sustainable mobility, the Law defines it as mobility that satisfies at a reasonable time and cost and minimizes the negative effects on the environment and the quality of life of people. It is the first definition of the concept of sustainable mobility in a Spanish law.

According to Moreu (2014), the legal concept of sustainable mobility is profiled by the following elements: holistic and integrated view of public policies: it is cross-cutting in including not only traffic and transport, but urban planning, education, health or the environment; pursues social and territorial cohesion; environmental objective, to reduce negative effects such as polluting emissions; economic outlook through low consumption and lower energy dependence; accessibility, especially for persons with reduced mobility; citizen participation.

This Law 2/2003 represents a qualitative leap. It is not limited to being a rule that seeks to order and coordinate, but takes mobility as a necessity of citizenship, which must be addressed through services. In addition, it is the first Law that introduces the concept of mobility linked to universal accessibility and sustainable development, as well as quality improvement.

A new step forward is found in *Ley 9/2003, de 13 de junio, de la movilidad* (Law 9/2003, of 13 June, on mobility). This Catalan rule is the first to introduce the concept of mobility into its title. Its first principle is based on the characteristics of what it is known as sustainable mobility, with its three facets: social, economic and environmental. It includes the promotion, not only of public transport, but of zero impact modes, such as on foot and bicycle. This Law also introduces sustainable urban development.

The objectives of the mobility policy are a catalogue of measures. Actions linked to public transport include studying fare integration formulas, improving commercial speed and promoting demand-responsive transport. It should be noted that this Law does not regulate public transport, but mobility, in particular, instruments for planning, programming, evaluation and monitoring. Participation and management bodies are also regulated.

Law 4/2004, on the Transport of Road Travellers, of the Basque Country, recognizes in its Preamble the strategic nature of public transport for social, economic and territorial development and cohesion, aimed at meeting the population needs of society, within sustainable development. The safety and quality of this service are described as priority elements.

The article on the principles of the Law reproduces the above paragraph and has the basis of transport policy. In addition, this policy will also comply with other principles: meeting mobility needs effectively and lower social cost and promoting intermodality. Quality and environmental sustainability are each reflected in two principles. The quality of serviceis explained through the rights and obligations of users and through the development of quality transports. With regard to environmental criteria, the promotion of technology is established for this purpose, and more generically, the promotion of sustainable transport.

We move forward in this temporary review with *Ley 8/2005, de 30 de junio, reguladora del Transporte Urbano por Carretera de La Rioja* (Law 8/2005, of June 30, regulator of Urban Transport by Road of La Rioja). In this Community we find the peculiarity of being the only one where one Law regulates urban transport and another, which we will talk about later, establishes the legal regime for intercity transport. Both its Preamble and articles lack references to quality or sustainability.

The next rule is *Ley 14/2005, de 29 de diciembre, de Ordenación del Transporte de Personas por Carretera por Castilla-La Mancha* (Law 14/2005, of December 29, on the Ordinance of the Transport of People by Road in Castilla-La Mancha). This Law acknowledges in its Preamble that is based on the need for a transport system that responds the demand of the inhabitants, taking into account the geographical, demographic and economic peculiarities of the Community. It is based on the right to mobility, giving the importance it deserves to public transport.

The article on principles recognizes public transport as an essential public service to respond the mobility needs of the population. Among other objectives, transport policy will be aimed at meeting the demand for the mobility of the population, in conditions of safety and comfort.

This objective focuses on people with fewer resources, with reduced mobility or special transport needs, as well as in areas with low population density or remoteness.

Another objective is the achievement of optimal quality and safety objectives, through efficient use of resources, to reduce environmental costs. It is also mentioned the promotion of public transport spreading its knowledge and boosting its use.

We return again to La Rioja, because, as stated above, Law 8/2005 regulates only urban transport. Intercity service has its regulation in Law 8/2006 of 18 October. In its Preamble there is not relevant reference to quality or sustainability.

Within the purpose of the Law, in addition to the usual ones, it is intended to promote public transport through measures aimed at modernizing vehicles, a homogeneous corporate image of public services, improving access to persons with reduced mobility and incorporating technological innovations that improve the service.

The next law in this chronological review is the *Ley 13/2007, de 17 de mayo, de ordenación del Transporte por Carretera de Canarias* (Law 13/2007, of May 17, of planning of Transport by Road of the Canary Islands). The summary of the content made in the Preamble highlights the objective of promoting public passenger transport that responds the demand for population mobility by guaranteeing the right to quality and sustainable transport, with particular attention to people under-favoured and disabled. This is, undoubtedly, an object that is repeated in the different laws.

We also find other objectives in this Law: the promotion of public transport versus the private; the rational use of public resources, the achievement of the highest quality and safety in the provision of the service and the reduction of environmental impacts and costs.

Finally, within the Second Chapter, named mobility planning, sector promotion and financing of regular public transport, in title III, road transport services, there is a small section called promotion actions. The corresponding Regional Department may, in collaboration with the Island Councils, carry out development programmes.

Those promotion programmes will seek the modernization of company facilities and systems; the dissemination of the transport sector and any measures to facilitate the competitiveness and efficiency of the sector.

The next Law of this analysis is of the Community of Madrid, *Ley 5/2009, de 20 de octubre, de Ordenación del Transporte y la Movilidad por Carretera* (Law 5/2009, of October 20, on Transport and Road Mobility Ordinance). The brief Preamble to this rule indicates that its enactment responds to the relevance of road transport to the socio-economic development of the Community and at the will to ensure sustainable mobility. In general, it is a law simpler than its contemporaries. The purpose of this Madrid Law is to achieve an efficient and coordinated transport system that meets the mobility needs of citizens.

As regards principles and objectives, the Law aims to facilitate mobility and contribute to territorial articulation, economic development, social cohesion and improve, in short, the quality of life of citizens. The provision of the service, as well as the construction and maintenance of the facilities should minimize the environmental impact, as well as seek the optimal consumption of resources. Finally, operators should ensure accessibility to persons with reduced mobility.

More advanced is *Ley 6/2011, de 6 de abril, de la Generalitat, de Movilidad de la Comunidad Valenciana* (Law 6/2011, of April 6, on Mobility of the Valencian Community). Its Preamble is noteworthy, recognizing the role of mobility in the progress of advanced society. Even more remarkable is the recognition of the limitations and conditions of mobility and development. The text refers to Buchanan's *Traffic in Towns*. The goal is to maintain the level of mobility by making it compatible with an urban space suitable for people and without falling into unacceptable energy dependencies.

The Preamble refers to European legislation for the legal framework for transport and mobility. The aim is to promote non-motorized modes and public transport. It recognizes the advantages of the Mediterranean urban model, which facilitates sustainable mobility by relying on integration of uses, intermediate densities and occupation of adjoining spaces. According to the Preamble, this model must be protected by the regulation. Therefore, it seeks to integrate mobility plans into urban development.

In the light of the main text, it is established that the purpose of the Law is the regulation of the powers of the *Generalitat* (Regional Government) in the field of mobility, i.e. to regulate planning instruments, the land transport of passengers and infrastructure.

The first principle of the Law is that administrations will facilitate the mobility of people, understanding that it is a backbone of their quality of life, by allowing them access to work, training, services and leisure.

The second principle is that administrations will promote the growth of mobility in a way that a number of objectives related to safety, accessibility, reduction of air and noise pollution, efficiency in energy consumption, participation of society in decision-making and the promotion of public transport and intermodality are met simultaneously.

Boix (2014) considers that this rule does not, despite what is stated in the Preamble and the principles, bring anything new in terms of transport to the problem of mobility. Thus, he tells us:

> "All Title II of the Law, referring to the regulation of passenger transport, seems transplanted from a legal rule that had been prepared regardless of what the Law says in its preamble or the regulation and principles of Title I. The idea of sustainability disappears from the purposes and objectives to guide public authorities in setting routes, programmes or contracts, award procedures, exclusivity or subsidy mechanisms (...) but in no case links to mobility considerations these elements, as it was able to, for example, by identifying certain preferences for a certain type of vehicle or performance that guarantee less polluting emissions in the general rules that should be awards which, however, choose to give not a few technical and legal indications as to how these are to be carried out, but say nothing about the issue at hand."

Through various planning instruments, dedicated to territorial areas, but also to mobility-generating locations, the aim is to achieve the objectives of the Law. In particular, planning instruments should seek a modal distribution where the use of non-motorized modes and public transport expands. Also, the public transport must be accessible. These plans affect both the organization of transportation and the configuration of urban space.

The next rule of this study is *Ley 4/2014, de 20 de junio, de transportes terrestres y movilidad sostenible de las Illes Balears* (Law 4/2014, of June 20, on land transport and sustainable mobility of the Balearic Islands). This Law, the first to incorporate the qualifier of *sustainable* in its title, is very broad and regulates road and rail services in detail.

According to its Preamble, public administrations will promote the satisfaction of transport needs and favour the mobility of citizens. All this actions must be in accordance with a series of general principles, such as free access to goods and services, through adequate, accessible and safe mobility, with minimal social and environmental impact. Efficiency and rationalization in the use of media, resources and spaces are part of mobility policy.

One concept that is introduced in this catalogue of principles is that of social profitability. It is qualified as the assumption, according to the means available, of the needs of public service in terms of spatial or temporal availability, of attention to specific groups or the achievement of average levels of quality. Other principles included in this Law are the proper distribution of costs of implementation and management of transport, and the involvement of citizens through social participation.

We have left for the end another interesting principle, that of subsidiarity of the establishment of new transport services. It implies that such establishment will be subject to the existence of a demand commensurate with investment and environmental costs, and will take into account alternative modes of transport according to their price, safety, quality and environmental assessment results. If this principle had been applied in a widespread and rigorous manner, disproportionate investments would have been avoided, not only in public transport, but also in road infrastructure.

As regards the purposes of the Law, it retains a similar structure to the Law of the Valencian Community. Thus, this rule regulates public transport of travellers, urban and intercity; rail service, and mobility management through planning tools. Another purpose is to set the objectives and contents of the Sectoral Mobility Master Plan, island plans for regular road transport and mobility plans.

In addition to the principles and purposes of the Law, the objectives of the public transport service itself are also listed. These must constitute an integrated offer, organized as a network or multimodal infrastructure, to offer citizens the possibility of covering their travels.

A quality, safe, accessible and appropriately priced public transport is the first right of users listed in the Balearic Law. Others include the provision of services adapted for people with disabilities or transporting bicycles in public transport vehicles.

We move forward to reach the *Ley de Cantabria 1/2014, de 17 de noviembre, de Transporte de Viajeros por Carretera* (Law of Cantabria 1/2014, of November 17, on Road Passenger Transport). Its Preamble introduces equality and equity between men and women as a fundamental principle. This principle responds to the role of transport as an element of social and territorial cohesion, as well as the promotion of work-life balance. Also, sustainable mobility is pursued through intermodality and the transfer of travellers to greener ways.

The Preamble highlights several objectives of the Law, such as sustainability, transport modernization, attention to less-favoured sectors, persons with reduced mobility and areas with low population density. It should be noted that this section highlights the importance of public transport in a region with important demographic and orographic conditions. This point coincides with what is analyzed in the Law of Castilla- La Mancha.

The transport policy will also respond to these principles: achieving the optimum degrees of quality and safety in the provision of the service, through the appropriate use of available resources and the reduction of environmental cost; the rational use of resources for promotion and investment in transport, by prioritising projects with greater viability, social and environmental profitability and respect for the environment; combating climate change by promoting collective or non-motorized modes, encouraging the implementation and use of non-polluting technologies.

This last point is noteworthy, since, after the early inclusion in Law 20/1998 of the Community of Madrid, no autonomous law had met the factor of less polluting propulsion technologies.

Similar to the Balearic Islands Law, the Cantabrian one recognizes the right to use vehicles in conditions of comfort, hygiene and safety, with accessibility conditions, a timely and regular service.

Turning to planning regulation, sustainable mobility plans should accommodate novel solutions to reduce environmental impact, at the lowest possible cost and contribute to road safety.

We reached the last rule before entering the Laws of the Principality of Asturias and Castile and León, *Ley 10/2015, de 24 de marzo, por la que se establece el sistema competencial en el transporte urbano e interurbano de la Región de Murcia* (Law 10/2015, of March 24, which establishes the competency system in urban and intercity transport of the Region of Murcia).

The Preamble is more typical of the oldest laws. It should be noted, however, that this introductory statement expressly points out that the regulation of the mobility of persons is not an object of the Law. On the contrary, it merely regulates the competency frameworks for urban and intercity transport within the Community. Some aspects are outside, such as mobility planning and management, the operation of services, and the inspector and sanctioning regime. It should therefore come as no surprise that the objectives of the Act are limited to issues of service coordination and cooperation between operators. All other elements will be regulated by another rule, which has not been approved so far.

3. INNOVATION AND QUALITY IN THE MOBILITY AND TRANSPORT LAWS OF THE PRINCIPALITY OF ASTURIAS AND CASTILE AND LEÓN

The Autonomous Communities of the Principality of Asturias and Castile and León have common factors, such as a low density and areas with scattered, aged population and with complicated orography. This is a real challenge for an adequate sustainable mobility policy, and in particular for the provision of the public transport service. It should be noted that while the Asturian Law is broader, it includes more elements of mobility, as well as rail transport, its Castilian and Lioness counterpart focuses on the transport of passengers by road.

Ley del Principado de Asturias 12/2018, de 23 de noviembre, de Transportes y Movilidad Sostenible (Law of the Principality of Asturias 12/2018, of November 23, on Transport and Sustainable Mobility) seeks, according to its Preamble, a legislative body (since they already have a prior Law regulating their Transport Consortium) that takes into account territorial, population and orographic singularities. Public transport should be part of a mobility model aimed at improving the quality of life of citizens, which is more economically sustainable, ensuring greater territorial and social accessibility, affordable and with care for persons with reduced mobility or disabilities.

The new model should offer alternatives to private transport, such as non-motorized modes, on foot and by bicycle, and public transport. The latter is intended to be empowered by its ability to reduce the environmental and social impact for mobility.

The Asturian Law clearly distinguishes between principles and objectives. The first are enumerated in a list of words or short concepts, without expound on them: safety, minimization of environmental impact, minimization of social costs, intermodality, sustainability and rational use of the territory, cost assessment and management, priority of universal accessibility in the allocation of public resources, coordination between public administrations, citizen participation, and incorporation of the gender perspective into transport planning and management.

The index of objectives stands out for its extension, thirty-three headings. A first transport policy block, with objectives aimed at improving transport accessibility by reducing its negative impacts. At this point, two objectives relating to the drive towards the knowledge economy can be highlighted through the development and application of technological advances to public transport; another is to introduce technological means linked to management and information.

The second goal block concerns urban planning and territorial and environmental impact of transport. More interesting for our study is the third block, related to innovation, security and education.

In that third block of objectives we find the introduction of new technologies in transport and mobility management, especially in user information and payment methods; encourage proposals that reduce accidents; incorporate safety measures into vehicles, and training programmes to promote sustainable ways.

Another section where we find references to innovation and quality in transport is in the planning instruments, something that we have already seen also happens in other studied laws. In this regard, we can underline that the Sustainable Mobility Strategy will have sectoral strategies as development instruments.

Several areas to be developed in Sectoral Strategies: the implementation of the electric vehicle and its infrastructures for public and private transport, with the objective of zero emissions; intermodality for the implementation of new technologies, fare unification, user rights status and physical adaptation of facilities and vehicles, and finally, the development of the bicycle and other active means without emissions. The content of some of these Strategies is developed, as detailed by Blasco (2019 a), in the Additional Provisions of the Law.

Finally we move on to *Ley 9/2018, de 20 de diciembre, de Transporte Público de Viajeros por Carretera de Castilla y León* (Law 9/2018, of December 20, Public Transport of Travelers by Road of Castile and León). Perhaps the most noteworthy facet about its Preamble is that it attaches great importance to the rural area of the Autonomous Community, where it is considered that ensuring mobility is fundamental.

The summary of the objectives highlights the adaptation of management contracts to mobility in a sustainable way, with the highest quality, safety and incorporating new technologies, elements that interest us in this study. The aim is also to improve environmental and economic efficiency. It is clearly stated that the Law is committed to sustainable mobility as a basic principle through a series of measures and instruments.

The Castilian and Lioness Law has only a catalogue of principles, not objectives, making it more succinct at this point than its Asturian counterpart. As we will see below, the accessibility of the rural environment will have great prominence in these principles.

The first principle is the satisfaction of the mobility needs of citizens, with special attention to persons with reduced mobility or disabilities, with guarantee of equal access to transport throughout the territory. Another principle is the development of a coordinated autonomous transport system, which promotes intermodality and promotes socio-economic cohesion and territorial structuring, especially in rural areas. The third principle is the promotion of sustainable mobility as an instrument towards less pollution and more efficient use of energy.

Two particularly relevant principles are the fourth and fifth. The fourth is the guarantee of the highest level of safety, quality and comfort in service, with the use of technological development in intelligent transport systems. The fifth is the promotion of the use of information and communications technology in the management of public transport.

The other principles concern issues of great importance such as universal accessibility and universal design, flexibility of modes of exploitation for better adaptation to social and territorial changes, an adequate fare regime, the promotion and prioritisation of public versus private transport, the integration of the autonomous transport network into the national single market, the guarantee and defence of user rights and the rational and efficient use of public resources in projects with greater social profitability.

The quality in public transport is reflected in a specific Chapter, dedicated to quality, sustainability, intelligent transport systems and automated driving. In his brief analysis of this Law, Blasco (2019) stops in this section, delving into its novel aspects.

As regards the quality of service, on the one hand the Administration will promote the obtaining of quality certifications. On the other hand, the Autonomous Government will establish the certifications required in this matter.

This quality shall be measured by controls by the Administration. The operators shall provide the required information. Several systems are indicated: user surveys, level of complaint response and contingency protocols. Vehicle technical requirements and employee working conditions will also be monitored.

Information and communication technologies also have a presence in the new Law of Castile and León. The transport network must have intelligent transport systems according to the characteristics of the service. This channel will serve citizens and operators. The Administration will promote the use of social networking services.

The Transport Department also assumes the role of collecting, systematizing and disseminating essential information on public transport. The Law establishes minimum data: critical qualitative and quantitative objectives of the service, impact on ecological footprint, supply and demand, costs, and, finally, occupational safety and health issues.

Another function of the Administration will be the impulse of marketing elements. The objective is the dissemination and promotion of public transport. In particular, a homogeneous corporate identity is mentioned.

An information tool would be a web portal, which would be launched within a year. This website would include data from all public transport services in the Community. The minimum information would be itineraries, schedules, universal accessibility, the possibility of traveling with bicycles and links to the purchase of tickets.

The Law includes the implementation of automated mobility systems. The goal is to improve efficiency, safety and environmental impact. The role of the Administration will be to facilitate testing for these systems.

In summary, the precepts collected focus on quality certifications, promotion of alternative propulsions, intermodality with the bicycle, quality control, information and promotion and automated systems. In the case of this Law, we see a remarkable emphasis on innovation and transport quality, something novel in regional transport legislation.

4. INNOVATION AND QUALITY IN LAWS

The presence of innovation refers to two main aspects. The first, in information and communication technologies, oriented both to the management of the service itself, mainly through navigation and geolocation systems, and to the user, through websites that, among other things, collect the information of others Systems. As for vehicles, the most noteworthy is the technology oriented to the reduction of pollution through more efficient propulsions or with reduced emissions. At this point, the most notable is the electric vehicle, both for private and public use.

Rojo (2011) developed an analysis method on the quality of the urban transport service. Its peculiarity was the introduction of variables in addition to those of frequency and fares, such as newer vehicles, large-class vehicles, fast-track traffic, fewer intermediate stops or the use of air conditioning, variables that affected demand and satisfaction. It is true that more advanced elements such as Wi-Fi connection, USB connectors and, on long journeys, individual screens are currently valued.

Therefore, we have two models to regulate quality and innovation in the two most recent laws. On the one hand, a Law contains a specific chapter, albeit with somewhat open promotion measures. On the other hand, mobility and transport planning instruments includes determinations about innovation and quality.

5. IN CONCLUSION. FROM LAWS TO THE ROAD

Sectoral legislation on passenger transport has been leading an evolutionary trajectory towards greater involvement in sustainable mobility. It has moved from rules aimed at regulating the delimitation of competences and coordination between administrative bodies to others that seek to increase quality and innovation in public service.

The inclusion of quality and innovation in the Laws are a sign of the involvement of autonomous legislatures in the improvement of public transport. It is recognition of the need to provide accessibility to citizens and to have alternatives for sustainable mobility.

The incorporation of these elements into the Laws, which have a vocation of permanence, has the risk of being too advanced or, on the contrary, being outdated by technological evolution. That is why, while positively reflected in the Laws, this carries certain risks.

On the other hand, these legislative developments generally lack of putting in place, as they refer to planning instruments or are not reflected in the conditions of management contracts. This limits the possibility of all these improvements reaching the road.

Moreover, there is no doubt that developments in the rules would become just theory if the Administrations do not support through appropriate compensation for the transport deficit to facilitate the incorporation of innovations.

Therefore, and with the limitations indicated, the incorporation of quality, safety and environmental sustainability implies the clear will of the regional legislator to enhance public transport as a quality tool for sustainable mobility.

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IDENTIFICACIÓN DE RESPONSABILIDAD DE LOS CONDUCTORES. APLICACIÓN AL MÉTODO DE EXPOSICIÓN CUASI-INDUCIDA

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RESUMEN

Determinar las tasas de accidentalidad y mortalidad de diferentes colectivos de conductores es un objetivo importante de la investigación científica de accidentes de tráfico. Para ello, es necesario contar con información acerca de los niveles de exposición de los conductores de manera desagregada.

Sin embargo, el nivel de exposición de diferentes colectivos de conductores no es conocido al nivel requerido y, esta carencia, puede salvarse mediante el método de exposición cuasi-inducida, que permite determinarlo de forma relativa a partir de los datos contenidos en las bases de accidentes de tráfico. La hipótesis principal es que entre los conductores implicados en un accidente entre dos vehículos, se puede distinguir al responsable y no responsable de su ocurrencia y que, éstos últimos, constituyen una muestra aleatoria de la población de conductores. Por lo tanto, determinar correctamente la responsabilidad del conductor, es un objetivo secundario, pero de gran importancia en la investigación.

Hasta el momento, la asignación de responsabilidad se hace, fundamentalmente, en base a dos tipos de infracciones: del conductor y de velocidad, dejando de lado otros registros que sí que podrían incrementar la probabilidad de que un conductor sea responsable.

En este trabajo se presenta la exploración del conjunto de registros de infracciones y condiciones desfavorables de los conductores, que pueden influir en la responsabilidad de los conductores con la metodología Self-Organizing Maps (SOM).

Los resultados obtenidos indican que la clasificación de conductores mejora en comparación con la clasificación tradicional: más conductores clasificados, mayor número de variables consideradas y mayor calidad esperada en el proceso de asignación de responsabilidad.

1. INTRODUCCIÓN

Determinar las tasas de accidentalidad o el riesgo de colisión de diferentes colectivos de conductores es muy importante en seguridad vial con el objetivo de establecer medidas preventivas que traten de evitar el accidente o minimicen sus impactos, tal y como han señalado investigadores como Stamatiadis y Deacon (1997); Redondo et al. (2000); Hing et al. (2003); Jiang y Lyles (2007, 2010); Lenguerrand et al. (2008); Chandraratna y Stamatiadis (2009); Lardelli et al. (2011); Jiang et al. (2012, 2014); Haque et al. (2013); Huggins (2013); Martínez et al. (2013); Pulido et al. (2016).

Las tasas de accidentalidad de un colectivo de conductores se definen como el cociente entre el número de accidentes de este colectivo y la exposición del mismo (Chandraratna y Stamatiadis, 2009; Gómez y Aparicio, 2010; Huggins, 2013). Por lo tanto, para determinarlas es necesario contar con alguna medida de los niveles de exposición del colectivo en cuestión, lo que supone un importante desafío entre los investigadores de seguridad vial (Redondo, 2000; Chandraratna y Stamatiadis, 2009; Gómez y Aparicio, 2010; Lardelli et al., 2011; Haque et al., 2013; Pulido et al., 2016).

Por ello, se recurre al método de exposición cuasi-inducida, que es una modificación del trabajo de Thorpe (1967), realizada por Carr (1969), Hall (1970), Carlson (1970) y Haight (1970) y que permite la estimación relativa de la exposición de un grupo de conductores a partir de la información contenida en la base de datos de accidentes (Stamatiadis y Deacon, 1997; Lardelli et al., 2005; Redondo et al., 2000; Lenguerrand et al., 2008; Chandraratna y Stamatiadis, 2009; Cooper et al., 2010; Lardelli et al., 2011; Huggins, 2013; Jiang et al., 2012, 2014; Pulido et al., 2016).

La hipótesis principal de este método es que los conductores no responsables en accidentes entre dos turismos constituyen una muestra aleatoria de la población general de conductores (Stamatiadis y Deacon, 1997; Hing et al., 2003; Lardelli et al., 2005, 2011; Yan et al., 2005; Yan y Radwan, 2006; Jiang y Lyles, 2007, 2010, 2011; Lenguerrand et al., 2008; Chandraratna y Stamatiadis, 2009; Gómez y Aparicio, 2010; Cooper et al., 2010; Mohaymany et al., 2010; Jiang et al., 2012, 2014; Haque et al., 2013; Martínez Ruíz et al., 2013). Por tanto, la correcta asignación de responsabilidad a partir de la información de la base de datos de accidentes constituye una importante tarea para la estimación posterior de la exposición relativa.

El registro de accidentes de tráfico con víctimas de España no contiene información específica sobre la responsabilidad de cada conductor implicado en un accidente, aunque sí registra las infracciones cometidas por los mismos, así como el estado de dichos conductores (Martínez et al., 2013; Pulido et al., 2016). Sin embargo, no existe un consenso claro acerca de cuáles son las variables que se deberían utilizar para realizar tal asignación de responsabilidad, dado que algunos autores como DeYoung et al. (1997), Jiang y Lyles (2007, 2010), Jiang et al. (2012, 2014) pusieron de manifiesto que asignar la responsabilidad en base a comportamientos no relacionados con la conducción podrían sesgar los resultados. Por ello, fundamentalmente en los últimos años, los investigadores se han inclinado más a asignar la responsabilidad del conductor en base a acciones de conducción peligrosas (Jiang y Lyles, 2010, 2011; Jiang et al., 2012, 2014), principalmente englobadas en las variables infracción del conductor e infracción de velocidad.

En esta investigación se lleva a cabo el análisis de un conjunto más amplio de variables que podrían influir sobre la responsabilidad de los conductores, pero no suelen ser tenidas en cuenta. Para ello, se propone el uso de la metodología de clúster Self-Organizang Maps (SOM) al conjunto de datos de los conductores con dos objetivos fundamentales: (a) Establecer cuáles podrían ser las variables más relevantes en la asignación de responsabilidad y (b) Realizar una propuesta de asignación de responsabilidad que será comparada con la asignación tradicionalmente realizada.

2. MATERIAL Y MÉTODOS

La base de datos utilizada para llevar a cabo esta investigación fue proporcionada por la Dirección General de Tráfico (DGT) y contiene información de los conductores implicados en accidentes de tráfico ocurridos en España entre 2004 y 2013.

Inicialmente la base de datos fue sometida a un proceso de filtrado para únicamente mantener los accidentes en vía interurbana de tipo frontal, frontolateral, lateral y de alcance, entre dos turismos. Además, se realizó un importante trabajo de depuración de la base de datos filtrada, dado que se detectaron errores que podrían sesgar los resultados de la posterior investigación. Por tanto, la base de datos de partida contaba con un total de 836.598 conductores y tras el filtrado y la depuración de la misma esta quedó finalmente reducida a 145.904 conductores.

La base de datos cuenta con la información relacionada con el conductor (edad, género, infracciones, etc.), con el accidente (día, lugar, etc.) y con el vehículo (tipo, defectos, etc.). Por tanto, a partir de estas variables se seleccionaron todas aquellas que se consideraron que podrían afectar, en mayor o menor medida, a la asignación de responsabilidad del conductor. Por este motivo, las variables seleccionadas para la construcción posterior de los mapas Self-Organizing Maps (SOM) son: infracción del conductor, infracción de velocidad, infracción administrativa, consumo de alcohol y/o drogas, enfermedad súbita, sueño, cansancio y/o preocupación (englobada bajo la variable sueño), defecto físico previo del conductor y estado del vehículo.

Por otro lado, para poder trabajar con estas variables aplicando la metodología SOM, ha sido necesario llevar a cabo un proceso de transformación de los valores de las mismas de forma que estas pasasen de ser categóricas a numéricas. Por convenio, se adoptó el valor de 0 para indicar que dicha infracción o condición no estaba presente, mientras que el valor 2 indicaba justo lo contrario. Además, se ha utilizado el valor intermedio de 0,25 para indicar que se ignora si está presente o no dicha infracción. Para tomar este valor, se ha partido de dos hipótesis: (a) el mismo tendría que estar comprendido entre 0 ó 2, dado que su categoría es intermedia a las otras dos y (b) si este valor está indicado como “Se ignora” es más probable que sea porque no estuviese presente, por lo que debe asignarse un valor más cercano al 0. Para validar esta cuestión se realizó un análisis de sensibilidad de los mapas SOM para distintos valores (comprendidos entre 0,25 y 1) para los casos en los que el valor de una o más variables era desconocido. Los resultados obtenidos, que no son mostrados aquí por no ser objeto de esta publicación, demostraron que no era significativa la elección de este valor de entre todos los valores probados. Por tanto, basándonos en las hipótesis planteadas, se escogió el valor de 0,25 para los casos en los que se desconocía el valor de la variable. Más información puede encontrarse en Sanjurjo-de-No et al. (2021).

La metodología empleada para llevar a cabo esta investigación es el método clúster conocido como Self-Organizing Maps (SOM).

Self-Organizing map es una técnica de aprendizaje no supervisado que fue desarrollado por Kohonen (1990) y forma parte de las técnicas de Machine Learning. El propósito de SOM es representar datos que, originalmente están en un espacio multidimensional, en un espacio de dimensión más reducida, pero manteniendo la topología original de los datos. Así, conductores que por sus características estuviesen cercanos en el espacio original, deberían seguir estando cercanos en el espacio proyectado. Como señalan algunos autores como Liu, P. (2009), Kohonen, T. (2013), Kohonen, T. (1998) o Lagus, K. (2002), esto supone una importante ventaja del SOM con respecto otros métodos de clúster, dado que permite la visualización de las nubes de puntos generadas por la proyección de los datos, ya que estas suele realizarse en 2 ó 3 dimensiones.

En la presente investigación, la metodología SOM permite realizar un análisis conjunto de las 8 variables anteriormente seleccionadas. De esta forma, se realiza un análisis conjunto de los conductores en el espacio original de 8 dimensiones el cual es proyectado sobre el espacio de 2 dimensiones, pero manteniendo la topología original de los datos de los conductores. Esto tiene por objetivo ayudar a identificar patrones de comportamiento entre los conductores en función de las infracciones que estos pueden o no haber cometido, lo que permitirá arrojar mayor nitidez sobre la responsabilidad de los mismos. Además, al apoyar la asignación de responsabilidad con esta metodología se está proporcionando más información acerca de cómo son los datos de manera multivariante, dado que se tiene en cuenta la distancia conjunta de todas las variables. Esto hace que el proceso de asignación de responsabilidad sea menos radical, esperando con esto que la asignación sea más precisa.

3. RESULTADOS

El mapa SOM de infracciones sobre el que se reparten los 145.904 conductores de la base de datos es el que se muestra en la Figura 1. Este mapa está dividido en 25 clústers o nodos y cada uno de los cuales alberga el número de conductores que se indica en negro en la parte superior de cada clúster. En rojo, se indica el número del clúster en cuestión. Así, por ejemplo, el clúster 15 contiene un total de 30.729 conductores, mientras que en el clúster 23 no hay ningún conductor. Un análisis más detallado puede encontrarse en Sanjurjo-de-No et al. (2021).

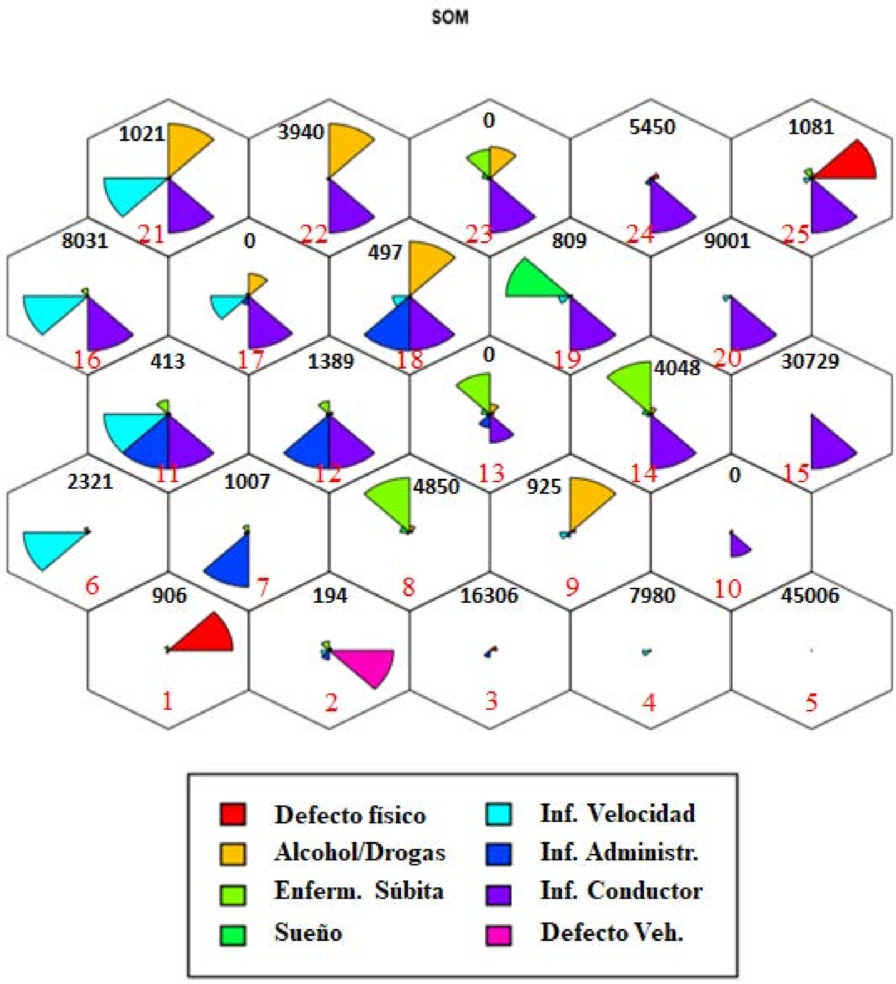

Fig. 1 – Mapa SOM de infracciones

En cada clúster es posible visualizar las características de los conductores en el espacio proyectado de 2 dimensiones, cuando originalmente estaban en el espacio de 8 dimensiones (una dimensión por cada variable contemplada en el SOM). Cada uno de los vectores de colores que se muestran en cada clúster indica el valor promedio de la variable que representan para todos los datos (conductores) que han sido asignados a ese clúster. En la Tabla 1 se indica numéricamente dicho valor promedio para cada una de las variables en cada uno de los clústers en los que hay algún conductor asignado.

	Defecto físico	Alcohol/Drogas	Enfermedad súbita	Sueño/Cansancio	Inf. Velocidad	Infr. Administrativa	Inf. Conductor	Defecto del vehículo
Cluster 1	2	0.02	0.02	0.02	0	0.09	0	0
Cluster 2	0.10	0.10	0.05	0.06	0.25	0.33	0	2
Cluster 3	0.22	0	0	0	0	0.25	0	0
Cluster 4	0	0	0	0	0.25	0.03	0	0
Cluster 5	0	0	0	0	0	0	0	0
Cluster 6	0.09	0.02	0.02	0.02	2	0.07	0	0
Cluster 7	0.02	0.03	0.03	0.07	0	2	0	0
Cluster 8	0.10	0.24	0.27	0.29	0	0.03	0	0
Cluster 9	0.17	2	0	0	0.32	0.18	0	0
Cluster 11	0.07	0.07	0.07	0.08	2	2	2	0.07
Cluster 12	0.13	0.05	0.06	0.08	0	2	2	0.05
Cluster 14	0.09	0.25	0.26	0.25	0	0.04	2	0
Cluster 15	0	0	0	0	0	0	2	0
Cluster 16	0.02	0.04	0.04	0.04	2	0.03	2	0.03
Cluster 18	0.05	2	0	0	0.52	2	2	0.04
Cluster 19	0.07	0	0	2	0.36	0.02	2	0.02
Cluster 20	0	0	0	0	0.25	0.02	2	0
Cluster 21	0.09	2	0	0	2	0.03	2	0.02
Cluster 22	0.03	2	0	0	0	0.04	2	0.03
Cluster 24	0.25	0	0	0	0	0.24	2	0.12
Cluster 25	2	0.17	0.04	0.02	0.25	0.02	2	0

Tabla 1 – Valor promedio de cada variable en cada clúster

3.1 Variables importantes en la asignación de responsabilidad

En este apartado se realiza un análisis de las variables introducidas en el SOM con el objetivo de determinar cuáles son aquellas que mejor identifican a los grupos o clústers de conductores del SOM. Se debe llegar a una solución de compromiso entre usar un número excesivo de variables para realizar la asignación de responsabilidad y tener en cuenta el suficiente número de variables para la identificación de los grupos de conductores responsables y no responsables de forma que se pierda la menor cantidad posible de información.

En la Tabla 1 y Figura 1 puede observarse que la variable que mejor divide a los conductores en dos grupos es la infracción del conductor, dado que, entre todos los clústers con conductores asignados, esta variable siempre adopta valor 0 ó 2 y no un valor intermedio entre estos. Por lo que se trata de la variable que mejor define la responsabilidad de los conductores. Por otro lado, se observa que la infracción de velocidad es una variable también relevante en la agrupación de los conductores en diferentes clústers y mide comportamientos de conducción peligrosos. Por tanto, esta variable también debería ser considerada en el proceso de asignación de responsabilidad.

La variable defecto físico previo aparece sólo en los clústers 1 y 25 del mapa, lo que hace pensar que no es significativa en la responsabilidad de los conductores. Los defectos físicos de los conductores son principalmente defectos de visión y audición y estos defectos están relacionados con la edad de los conductores (Sanjurjo-de-No et al., 2020) y hay investigaciones, como la realizada por Sagar et al. (2020), que indican que los conductores más mayores tienen más probabilidad de ser responsables en un accidente que los conductores pertenecientes a otras franjas de edad. Esta variable debería, por tanto, ser sometida a análisis futuros que evalúen más profundamente su grado de influencia sobre la responsabilidad del conductor.

Por otro lado, se observa que las variables denominadas “Estado del vehículo” y “Sueño” aparecen de manera aislada en muy pocos casos o aparecen combinadas con otras variables, como la infracción del conductor, que ya por sí sola permitía clasificar a los conductores. Por lo que, se considera que estas variables podrían no ser tenidas en cuenta en el proceso de asignación de responsabilidad.

En relación con las infracciones administrativas, se considera que la única infracción de este tipo que podría ser relevante sobre la responsabilidad es no haber efectuado la Inspección Técnica Reglamentaria del Vehículo (ITV) cuando esta va unida a un mal estado de dicho vehículo. Sin embargo, no se ha identificado ningún clúster en los que ambas variables de infracción aparezcan en un estado desfavorable de manera conjunta. Por lo tanto, se considera poco relevante el uso de esta variable a la hora de realizar la asignación de responsabilidad.

Finalmente, en relación a la variable “Enfermedad súbita”, es importante señalar que en la base de datos de accidentes no se especifica el tipo de enfermedad súbita sufrida por el conductor que la padece. Realmente esta variable no aparece por sí sola en muchos de los clústers, por lo que podríamos no considerarla en el modelo. Sin embargo, teniendo en cuenta la definición de enfermedad súbita como aquellas que aparecen sin ser esperadas y normalmente hacen perder las facultades normales que presenta la persona que las padece (desmayo, ataque de ansiedad, infarto, etc), podríamos considerar que puede afectar a la probabilidad de que un conductor que la padezca pueda ser responsable de un accidente de tráfico. Por esta razón, análisis adicionales también deberían llevarse a cabo en relación a esta variable para determinar el grado de influencia de la misma sobre la responsabilidad de los conductores.

En la Tabla 2 se muestran finalmente las variables consideradas más importantes para realizar la asignación de responsabilidad.

Variables más influyentes en la asignación de responsabilidad	Variables menos influyentes en la asignación de responsabilidad	Relevancia desconocida en el proceso de asignación de responsabilidad
Infracción del conductor	Infracción administrativa	Defecto físico previo
Infracción de velocidad	Sueño	Enfermedad súbita
Consumo de alcohol/drogas	Estado del vehículo	

Tabla 2 – Variables más relevantes para la asignación de responsabilidad con mapas SOM

3.2 Propuesta de asignación de responsabilidad en base al SOM

En este apartado se realiza el análisis del mapa SOM anteriormente creado desde el punto de vista de la responsabilidad de los conductores. Para ello, se tratará de identificar el perfil de cada uno de los conductores en función del clúster al que estos pertenezcan.

Como puede observarse en la Figura 2, es posible establecer una frontera en el mapa, por criterio experto, en función de la combinación de variables que aparece en cada uno de los clústers.

Así, a través de la agrupación de los conductores en diferentes clústers gracias a la proyección de los mismos en el espacio de 2 dimensiones, es posible distinguir dos regiones: potencialmente responsables y potencialmente no responsables.

En la región superior (Potencialmente responsables) se localizan todos aquellos conductores que han cometido una o múltiples infracciones o presentan condiciones desfavorables para la conducción. Se considera que estos conductores son responsables, dado que el perfil de infracciones presentes en esta zona del mapa.

Por otro lado, en la región inferior del mapa (Potencialmente no responsables) se encuentran los conductores que con seguridad no han sido responsables (en el clúster 5) y aquellos conductores que habría que analizar en profundidad junto con el otro conductor del accidente, con el objetivo de determinar si es posible la clasificación de los mismos.

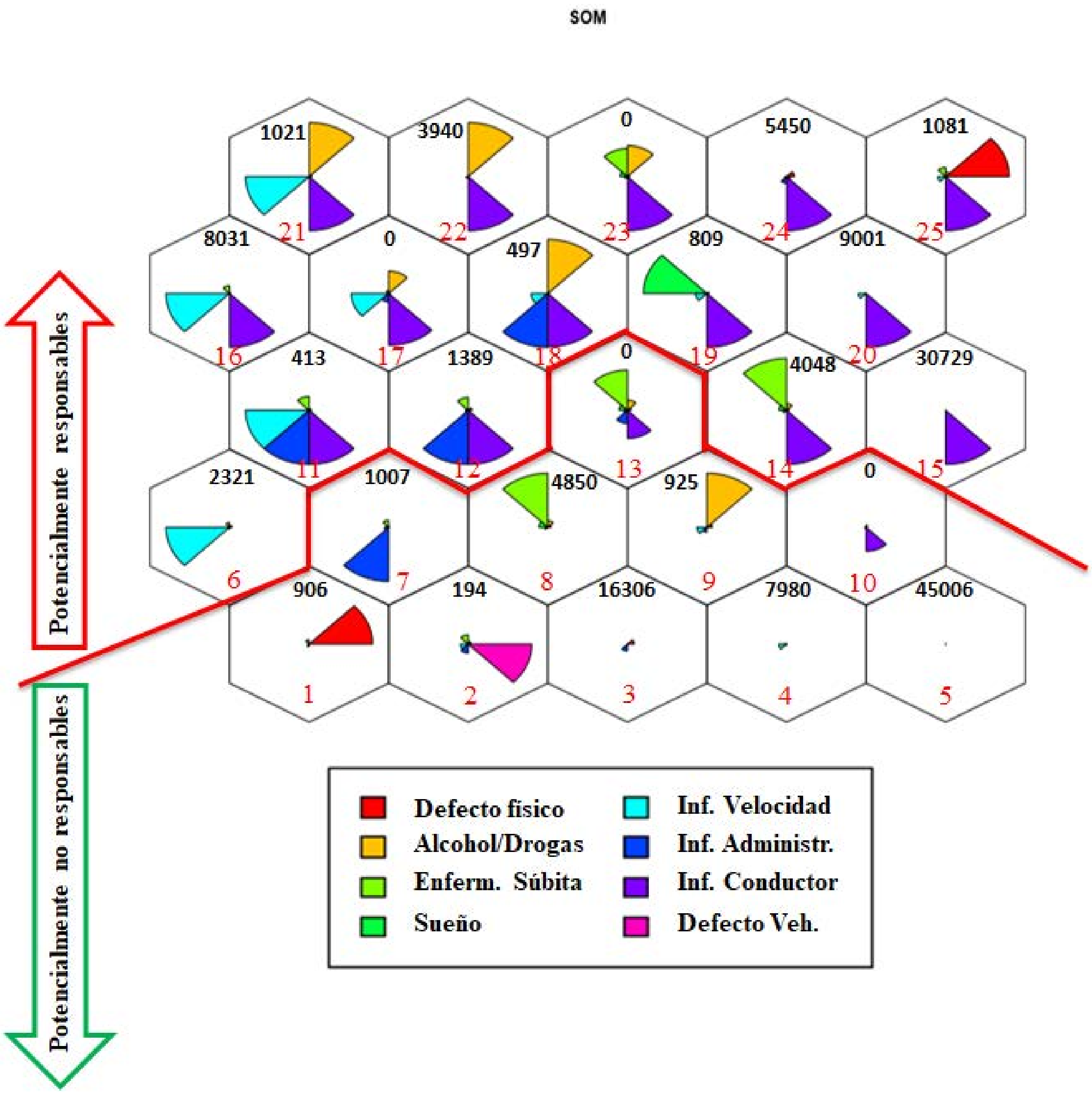

Fig. 2 – Mapa SOM de infracciones con la frontera de separación de regiones

El análisis conjunto de las parejas de conductores implicados en un mismo accidente dio lugar a la identificación de varias casuísticas posibles: (I) Responsable / No Responsable: Si un conductor está situado en la parte superior del mapa y el otro conductor con el que tuvo el accidente está situado en la parte inferior del mapa (establecido por la frontera), entonces el primer conductor podría considerarse responsable del accidente, mientras que el segundo sería considerado como no responsable; (II) Responsable / Responsable: Si ambos conductores están situados en la parte superior del mapa de acuerdo con la frontera establecida, entonces ambos podrían considerarse responsables y, por lo tanto, no se tendrían en cuenta en el análisis; (III) No responsable / No responsable: Si ambos conductores implicados en un mismo accidente están en el clúster 5, entonces los dos podrían ser considerados no responsables y, por lo tanto, podrían no ser tenidos en cuenta en el posterior análisis; Y (IV) Casos de Análisis: Si ambos conductores están en la parte inferior del mapa de acuerdo con la frontera establecida y, al menos uno de ellos en un clúster diferente al 5, entonces habría que realizar análisis adicionales para determinar si es posible saber cuál de ellos podría haber sido el responsable del accidente.

En la Tabla 3, se muestra el reparto de conductores en cada una de estas categorías y, puede observarse como, a partir de la interpretación del mapa SOM, podrían llegarse a clasificar un total de 83,76% de los conductores en Responsable / No responsable.

	Número de conductores	%
Responsable / No responsable	122.208	83,76%
Responsable / Responsable	7.626	5,23%
No responsable / No responsable	2.014	1,38%
Casos de Análisis	14.056	9,63%
TOTAL	145.904	100%

Tabla 3 – Clasificación de los conductores con mapas SOM

Los resultados obtenidos usando los mapas SOM para realizar la asignación de responsabilidad fueron comparados con los resultados obtenidos cuando dicha asignación se hace teniendo en cuenta únicamente la infracción del conductor y la de velocidad, que son las variables más comúnmente utilizadas para realizar esta asignación. En este caso, se considera que un conductor es responsable si ha cometido infracción del conductor y/o de velocidad y no será responsable en caso contrario.

Los resultados son los que se muestran en la Tabla 4, donde se observa que se logra clasificar al 72,47% de los conductores.

Por tanto, realizando la asignación de responsabilidad utilizando la metodología SOM logramos rescatar a un mayor número de conductores para el análisis posterior. Además, tiene en cuenta una mayor cantidad de variables a la hora de realizar dicha asignación. Por lo que se espera que la calidad de la misma sea mayor.

	Número de conductores	%
Responsable / No responsable	105.736	72,47%
Responsable / Responsable	7.706	5,28%
No responsable / No responsable	13.098	8,98%
Casos de Análisis	19.364	13,27%
TOTAL	145.904	100%

Tabla 4 – Clasificación de los conductores en función sólo de las infracciones del conductor y de velocidad (método tradicional)

4. CONCLUSIONES

En esta investigación se propone el uso de la metodología Self-Organizing Maps (SOM) de cluster como herramienta alternativa de ayuda para la asignación de responsabilidad. Con el SOM es posible identificar diferentes patrones en los conductores en relación a las infracciones que estos han cometido. Esto permite, en primer lugar, identificar las variables más y menos relevantes para llevar a cabo la asignación de responsabilidad y, en segundo lugar, estos patrones nos servirán como herramienta de ayuda para llevar a cabo el proceso de asignación de responsabilidad.

Así, se ha observado que las variables más relevantes a la hora de asignar la responsabilidad son: infracción del conductor, infracción de velocidad y consumo de alcohol y/o drogas.

Finalmente, la distribución de los conductores en el mapa SOM permite ayudar en la identificación de la responsabilidad de los conductores, clasificando un total del 83,76% de los conductores frente a los 72,47% de los conductores clasificados mediante la asignación tradicional que, fundamentalmente, tiene en cuenta sólo las infracciones del conductor y las de velocidad. Por tanto, además de conseguir una mayor clasificación de los conductores aplicando la metodología SOM, se tienen en cuenta de manera multivariante un mayor número de variables, por lo que se espera que la calidad de los conductores clasificados sea mayor.

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DOES SIZE REALLY MATTER? DUAL DISTRIBUTION CHANNEL WITH VANS AND AUTONOMOUS DELIVERY DEVICES

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ABSTRACT

E-commerce sales worldwide are expected to skyrocket in future years, increasing freight traffic in cities. In this context, sidewalk autonomous delivery devices (ADDs) show great potentialities to decrease carriers' last-mile operation costs. Nevertheless, the implementation of these autonomous robots requires some adjustments in the supply chain because of their particular characteristics. To avoid severe accidents with pedestrians, their speed and size will be limited and, as a consequence, ADDs seem more adapted to the delivery of small items. The objective of this paper is to estimate the carrier's total operation costs in a dual delivery channel. If its size is lower than a given threshold, the parcel is delivered to the customer through a supply chain compound of a logistics micro-hub and ADDs. Otherwise, if the parcel is bigger than the given threshold, it is delivered through a business-as-usual supply chain with delivery vans. The carrier's total operation costs is the sum of the costs induced by the two distribution channels. Assuming that the parcel size follows a known probability distribution function, the carrier's total operation costs are estimated using the continuous approximation methodology. Different probability distribution functions modelling the size of the parcels are studied in the paper. Finally, the dual distribution channel is optimized considering the size threshold as a decision variable of the system.

1. INTRODUCTION

Freight vehicles represent around 20% of traffic in cities (Russo and Comi, 2012). Last-mile operations in dense urban environments is a major concern for carriers and logistics service providers. The rise of e-commerce is likely to worsen this situation if no measures are taken. To address these challenges and decrease last-mile operation costs, autonomous delivery devices (ADDs) could be used in future years (Figliozzi and Jennings, 2020). Nevertheless, because ADDs are medium-size vehicles that are only able to deliver small items, a dual supply chain (SC) that depends on the parcel size has to be implemented. The main objective of this paper is to quantify the carrier's total operation costs in this dual SC and compare them with the business-as-usual (BAU) deliveries.

2. OPERATION COSTS MODELLING

The continuous approximation methodology (Daganzo, 1984) will be used. The carrier's job is to deliver the parcels that are in its distribution center (DC) to final customers (see Fig. 1). The distance between the carrier's DC and the center of the service region is ρ_{DC} (see Fig. 1). In this process, the total operation costs have to be minimized. This is a particular instance of the vehicle routing problem.

2.1 Model description

A uniform demand density δ (expressed in receivers/km^2/day) is served in a service region of area A. The parcel volume stochastic variable y follows a probability distribution function (PDF) $f(y)$ (see Fig. 1). If its volume is superior to a given threshold y_{lim}, the parcel passes through a supply chain (SC) with conventional light commercial vehicles (LCVs). This is the first supply chain SC1 (see Fig. 1). On the contrary, if its volume is inferior to y_{lim}, the parcel is taken from the carrier's distribution center (DC) to a micro-hub located within the service region. Then, some ADDs perform the delivery to the final receiver. This is the second supply chain SC2 (see Fig. 1).

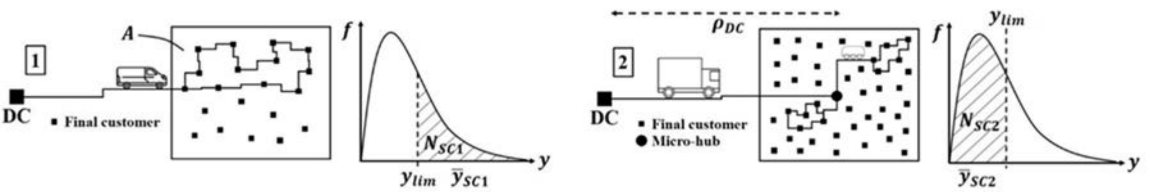


Fig. 1 – Dual SC with HDVs, LCVs and ADDs

We consider that N_{SC1} parcels with an expected volume $\bar{y}_{SC1}$ are delivered through SC1. Similar variables are denoted for the SC2 Scenario. In SC2, we assume that the parcels are carried from the carrier's DC to the micro-hub with heavy-duty vehicles (HDVs) to maximize the economies of scale. The expressions of N_{SC1}, N_{SC2}, $\bar{y}_{SC1}$ and $\bar{y}_{SC2}$ are given in Equations (1) and (2).

$$N_{SC1} = \left[\int_{y_{lim}}^{+\infty} f(y)dy\right]\delta A \; ; \; \bar{y}_{SC1} = \left(\int_{y_{lim}}^{+\infty} yf(y)dy\right) / \left(\int_{y_{lim}}^{+\infty} f(y)dy\right) \quad (1)$$

$$N_{SC2} = \left[\int_{0}^{y_{lim}} f(y)dy\right]\delta A \; ; \; \bar{y}_{SC2} = \left(\int_{0}^{y_{lim}} yf(y)dy\right)/\left(\int_{0}^{y_{lim}} f(y)dy\right) \quad (2)$$

2.2 SC1

The expected time spent per delivery in SC1 t_{SC1}^{d} is estimated by Equation (3) considering the work of Daganzo (1984).

$$t_{SC1}^{d} = \frac{1}{v_L^{LCV}} \frac{2}{\sqrt{3}} \sqrt{\frac{A}{N_{SC1}}} + \tau_s^{LCV} \tag{3}$$

Where v_L^{LCV} is the speed of LCVs in the local road grid and τ_s^{LCV} the LCV unit stop time, including parking and customer delivery process.
Then, the number of parcels delivered along one LCV route Ψ_{SC1}^{LCV} can be computed as

$$\Psi_{SC1}^{LCV} = min\left\{\frac{C^{LCV}}{\bar{y}_{SC1}}; \frac{H_{SC1} - \frac{2\rho_{DC}}{v_{LH}^{LCV}}}{t_{SC1}^{d}}\right\} \tag{4}$$

Where C^{LCV} is the LCV volume capacity, ρ_{DC} the distance between the carrier's DC and the center of the service region (see Fig. 1), H_{SC1} the operation time window of SC1, and v_{LH}^{LCV} the speed of LCVs on metropolitan highways.

To estimate Ψ_{SC1}^{LCV}, two restrictions are considered: the number of parcels loaded in a LCV is limited and the LCV route duration cannot be longer than H_{SC1}.

Then, the total distance travelled on metropolitan highways D_{SC1}^{LH} (respectively in the local road grid D_{SC1}^{L}) and the total time worked by the LCV fleet T_{SC1} are computed.

$$D_{SC1}^{LH} = 2\rho_{DC} \left[\frac{N_{SC1}}{\Psi_{SC1}^{LCV}}\right]^{+} ;\ D_{SC1}^{L} = \frac{2}{\sqrt{3}} \sqrt{AN_{SC1}} ;\ T_{SC1} = \frac{D_{SC1}^{LH}}{v_{LH}^{LCV}} + \frac{D_{SC1}^{L}}{v_L^{LCV}} + \tau_s^{LCV} N_{SC1} \tag{5}$$

Finally, the LCV operation costs in SC1 are estimated in Equation (6), where c_t^{LCV} and c_d^{LCV} are the LCV unit time and distance operation costs.

$$Z_{SC1} = c_t^{LCV} T_{SC1} + c_d^{LCV} (D_{SC1}^{LH} + D_{SC1}^{L}) \tag{6}$$

2.3 SC2

Once the operation costs of SC1 have been modelled, let us focus on SC2 (parcels whose volume is inferior to the threshold y_{lim}).

2.3.1 From the carrier's DC to the micro-hub

The parcels are first taken from the carrier's DC to the micro-hub with HDVs (see Fig. 1). As previously, the first step is to compute the HDV capacity Ψ_{SC2}^{HDV} in Equation (7), where C^{HDV} is the HDV volume capacity and $\bar{y}_{SC2}$ the expected parcel volume in this SC2.

$$\Psi_{SC2}^{HDV} = \frac{C^{HDV}}{\bar{y}_{SC2}} \quad (7)$$

The term Ψ_{SC2}^{HDV} corresponds to the maximum number of parcels that can be loaded in the HDV at the carrier's DC. Then, the total distance travelled D_{SC2}^{HDV} and total time worked T_{SC2}^{HDV} by the HDV fleet are determined in Equation (8), where v_{LH}^{HDV} is the speed of HDVs on metropolitan highways and τ_{LU}^{HDV} the expected time needed to load and unload one HDV at the carrier's DC and micro-hub.

$$D_{SC2}^{HDV} = 2\rho_{DC}\left[\frac{N_{SC2}}{\Psi_{SC2}^{HDV}}\right]^{+} \; ; \; T_{SC2}^{HDV} = \frac{D_{SC2}^{HDV}}{v_{LH}^{HDV}} + 2\tau_{LU}^{HDV}\left[\frac{N_{SC2}}{\Psi_{SC2}^{HDV}}\right]^{+} \quad (8)$$

Finally, the HDV total operation costs in SC2 Z_{SC2}^{HDV} are presented in Equation (9), as the sum of the time-based and distance-based operation costs. The parameters c_t^{HDV} and c_d^{HDV} are the HDV unit time and distance operation costs.

$$Z_{SC2}^{HDV} = c_t^{HDV} T_{SC2}^{HDV} + c_d^{HDV} D_{SC2}^{HDV} \quad (9)$$

2.3.2 From the micro-hub to the final receiver

This is the second stage of SC2. The parcels are taken from the micro-hub to the final receivers with ADDs. The methodology presented by Daganzo (1984) will be used.

The expected distance between the micro-hub and the locations of the visited points ρ_h is assumed to be $\rho_h = \frac{\sqrt{A}}{2}$, where A is the total area of the service region. We assume that the logistic micro-hub is located in the center of the service region, and we define an expected distance d_{SC2}^{d} and expected time t_{SC2}^{d} per parcel delivery (see Equation 10).

$$d_{SC2}^{d} = \frac{2}{\sqrt{3}}\sqrt{\frac{A}{N_{SC2}}} \; ; \; t_{SC2}^{d} = \frac{1}{v^{ADD}}\frac{2}{\sqrt{3}}\sqrt{\frac{A}{N_{SC2}}} + \tau_s^{ADD} \quad (10)$$

Where v^{ADD} is the ADD speed and τ_s^{ADD} the ADD expected unit stop time per parcel delivery to give the parcel to the final customer. We can now estimate the expected number of parcels delivered along one ADD route Ψ_{SC2}^{ADD} by Equation (11)

$$\Psi_{SC2}^{ADD} = min\left\{\frac{C^{ADD}}{\bar{y}_{SC2}}; \frac{H_{SC2} - \frac{2\rho_{DC}}{v_{LH}^{HDV}} - \tau_{LU}^{HDV} - \frac{2\rho_h}{v^{ADD}}}{t_{SC2}^{d}}; \frac{L_b^{ADD} - 2\rho_h}{d_{SC2}^{d}}\right\} \quad (11)$$

Where C^{ADD} is the ADD volume capacity, H_{SC2} the SC2 operation time window, v_{LH}^{HDV} the speed of HDVs on metropolitan highways, τ_{LU}^{HDV} the HDV loading/unloading time at the micro-hub and L_b^{ADD} the maximum distance that an ADD can travel considering its limited battery capacity restriction.

In addition to the volume and time horizon restrictions, we also need to consider the ADD limited range (because of the robot limited battery capacity) in this SC2. Thanks to the expression of Ψ_{SC2}^{ADD}, we are able to define the total distance D_{SC2}^{ADD} and total time worked T_{SC2}^{ADD} by the ADD fleet in Equation (12). This Equation is valid only if the following consition is met (Robusté et al., 1990): $7 < \Psi_{SC2}^{ADD} < 1.5\left(\frac{N_{SC2}}{\Psi_{SC2}^{ADD}}\right)$.

$$D_{SC2}^{ADD} = 2\rho_h \left[\frac{N_{SC2}}{\Psi_{SC2}^{ADD}}\right]^+ + \frac{2}{\sqrt{3}}\sqrt{AN_{SC2}}\ ;\ T_{SC2}^{ADD} = \frac{D_{SC2}^{ADD}}{v^{ADD}} + \tau_s^{ADD} N_{SC2} \tag{12}$$

We now compute the operation costs induced by the ADD fleet in SC2 Z_{SC2}^{ADD}, by Equaiton (13), where c_t^{ADD} and c_d^{ADD} are the ADD unit time and distance operation costs.

$$Z_{SC2}^{ADD} = c_t^{ADD} T_{SC2}^{ADD} + c_d^{ADD} D_{SC2}^{ADD} \tag{13}$$

2.3.3 SC2 total operation costs

We obtain the SC2 total operation costs Z_{SC2} aggregating the HDV, ADD and micro-hub operation costs, by Equation (14), where Ω_h is the micro-hub daily operation costs.

$$Z_{SC2} = Z_{SC2}^{HDV} + Z_{SC2}^{ADD} + \Omega_h \tag{14}$$

3. NUMERICAL USE CASE

3.1 Input parameters

Different parcel volume PDFs will be considered in this paper (see Fig. 2).

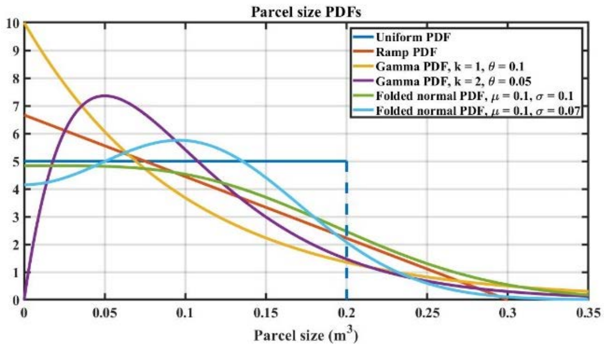


Fig. 2 – Parcel volume PDFs

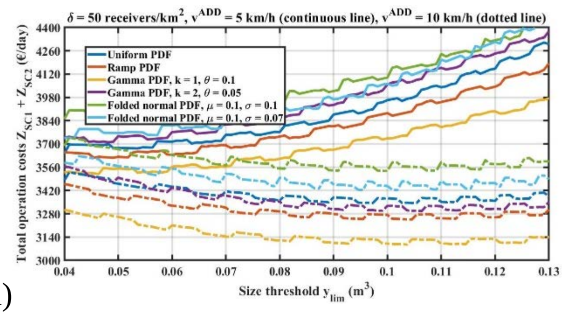
We built the PDFs presented in Fig. 2 considering the standard boxes available in-store at FedEx Office (FedEx, 2021) and assuming small parcels represent the biggest trade volume. For comparison purposes, the PDFs have the same expected parcel volume $\bar{y}$ = 0.1 m^3. The other input parameters are A = 50 km^2, ρ_{DC} = 20 km, $H_{SC1} = H_{SC2}$ = 8 h, Ω_h = 68 EUR/day, v_{LH}^{LCV} = 70 km/h, v_L^{LCV} = 20 km/h, τ_s^{LCV} = 2 min, C^{LCV} = 5 m^3, c_t^{LCV}= € 24/veh-h, c_d^{LCV}= € 0.2/veh-km, v_{LH}^{HDV} = 60 km/h, τ_{LU}^{HDV} = 30 min, C^{HDV} = 10 m^3, c_t^{HDV} = € 25/veh-h, c_d^{HDV}= €

0.3/veh-km, v^{ADD} = 5-10 km/h, τ_s^{ADD} = 1 min, C^{ADD} = 0.5 m^3, L_b^{ADD} = 50 km, c_t^{ADD} = € 5/veh-h and c_d^{ADD} = c€ 0.8/veh-km.

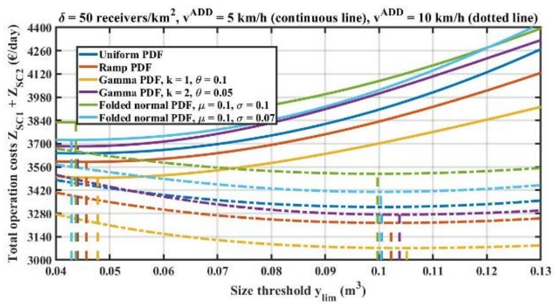
A service region of area A = 50 km^2 approximately corresponds to the city of Barcelona. We estimated the micro-hub daily operation costs Ω_h based on the work done by Estrada & Roca-Riu (2017). The ADD unit stop time τ_s^{ADD} is twice lower as τ_s^{LCV} because ADDs do not have to look for a parking spot and park. Then can access final customers more easily. We estimated the LCV (respectively HDV) unit time and distance operation costs c_t^{LCV} and c_d^{LCV} (respectively c_t^{HDV} and c_d^{HDV}) using data from the Observatory of Road Freight Transport in Catalonia (2019). To compute the ADD unit distance operation cost c_d^{ADD}, we estimate that the robot energy consumption is around 30 Wh/km (at 5 km/h) and that 1 kWh of electricity costs € 0.25 in Spain. As for the ADD unit time operation cost c_t^{ADD}, we assume that a robot costs around € 6,000 and is linearly depreciated over 4 years (2,500 working hours per year). We estimate the ADD maintenance costs to be around 20% of the capital costs on a yearly basis, i.e. 0.2 x € 6,000 = € 1,200/year-veh = € 0.5/veh-h (still with 2,500 working hours per year). One operator is in charge of 10 ADDs, i.e. € 20/10 = € 2/ADD-h. The ADD insurance costs are assumed to be around € 2,000/ADD-year as well as the carrier's structural costs.

3.2 Results

Fig. 3 presents the total operation costs Z_{SC1} + Z_{SC2} of the dual SC as a function of the volume threshold y_{lim}. We consider the different PDFs depicted in Fig. 2 and two ADD speed: 5 km/h (continuous lines in Fig. 3) and 10 km/h (dotted lines in Fig. 3). Fig. 3a shows the outputs of the equations presented in Section 3. Some discontinuities appear in the graphs because we considered the upper integer to compute the number of LCV, HDV and ADD routes. Fig. 3b depicts the same results considering that the number of vehicle route is directly N/C, where N refers to the total number of parcels that are to be delivered and C the capacity of the vehicle. In Fig. 3, a total demand density of 50 receivers/km^2 is considered.



a)

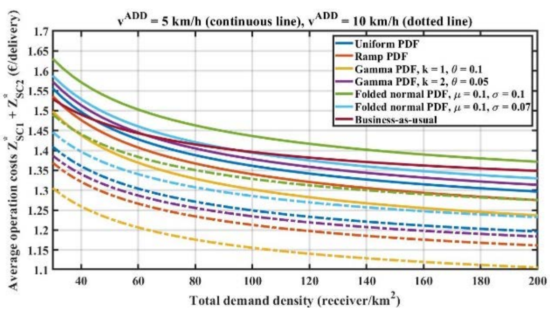


b)

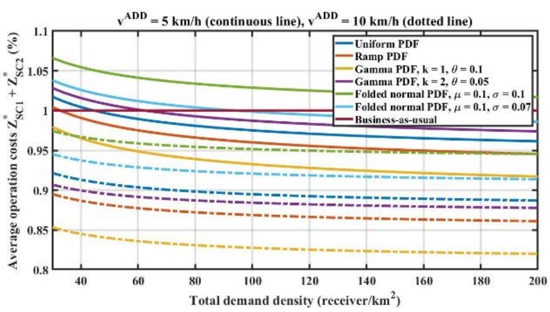
Fig. 3 – Total operation costs as a function of the volume threshold y_{lim}

Two main results can be drawn from Fig. 3. First, the parcel volume PDF has an impact on the carrier's total operation costs. The PDF that generates less operation costs is the gamma PDF with k = 1 and θ = 0.1. This result makes sense because this is the PDF for which the parcel volumes are the most "concentrated" around 0 m^3 (see Fig. 2). More parcels are delivered through SC2 and the economies of scale generated by the ADDs are increased. On the contrary, the carrier's total operation costs are the highest when a folded normal PDF is considered. In this case, less parcels are delivered through SC2 because their volume is more uniformly distributed. There are fewer small parcels and more big parcels than in the gamma PDF. For y_{lim} = 0.1 m^3 and v^{ADD} = 10 km/h, the difference between the gamma and folded normal PDFs is around 15% (€ 3,500/day approximately for the normal folded PDF and € 3,050/day approximately for the gamma PDF, see Fig. 3b).

The second main result is that the volume threshold y_{lim} is an important decision variable of the problem and that the carrier can optimize its total operation costs. This is especially the case when v^{ADD} = 5 km/h. For a gamma PDF (μ = 0.1, σ = 0.1) and v^{ADD} = 5 km/h, when y_{lim} passes from 0.04 m^3 to 0.13 m^3, the carrier's total operation costs are increased by 14% (from € 3,840/day to € 4,400/day). The optimal threshold y^*_{lim} for which the carrier's total operation costs are minimum depends on the ADD speed. For v^{ADD} = 5 km/h, y^*_{lim} is around 0.045 m^3 whereas it is around 0.1 m^3 for v^{ADD} = 10 km/h (see Fig. 3b). At a higher speed, ADDs are more competitive and the carrier should deliver more parcels through SC2 to minimize its costs. At a lower speed, ADDs are not so competitive when compared to the LCVs of SC1 and the robots are only dedicated to the smallest parcels. In the rest of the section, we consider that the number of vehicle routes is a continuous function (see Fig. 3b). Fig. 4 presents the carrier's optimized average operation costs $(z_{SC1} + z_{SC2})^*$ per parcel delivery as a function of the total demand density δ. The average operation costs correspond to the total operation costs (see Fig. 3) divided by the total number of parcels δA. Fig. 4a shows these optimized average operation costs in absolute value (as in Fig. 3). On the contrary, they are expressed as a percentage of the business-as-usual (BAU) average operation costs in Fig. 4b. The BAU scenario corresponds to the delivery of all the parcels through SC1, without using the micro-hub or the ADDs. The micro-hub daily operation costs are not considered in this BAU situation.



a)



b)

Fig. 4 – Optimized average operation costs as a function of the total demand density δ

The dual SC presents economies of scale because the average operation costs per parcel delivery decreases when the demand density increases. This is a common result is logistics operation analysis. As we observed previously, the parcel volume PDF and the ADD speed are important variables that condition the carrier's operation costs. At a demand density of 30 receivers per km^2, if the robot speed is 5 km/h, the operation costs induced by the dual SC are equal or higher (except in the case of the negative exponential PDF) than the BAU operation costs. On the contrary, if v^{ADD} = 10 km/h, the carrier's operation costs are reduced between 2% (with the worst PDF) and 15% (with the best PDF). At a higher density of 200 parcels/km^2, almost all configurations are more favorable to the dual SC. Only the combination of a normal folded PDF and a robot speed of 5 km/h generates more operation costs than the BAU delivery pattern. For v^{ADD} = 10 km/h, the cost reduction ranges from 5% to 17% depending on the considered PDF.

Finally, the optimal volume threshold y^*_{lim} as a function of the demand density δ is presented in Fig. 5.

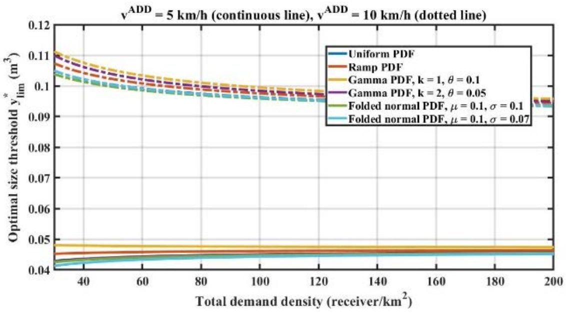


Fig. 5 – Optimized volume threshold y^*_{lim} as a function of the total demand density δ

When the robot speed is defined, y^*_{lim} is quite robust and does not depend on the demand density. For v^{ADD} = 5 km/h, the optimal threshold is around 0.045 m^3 whereas it is 0.1 m^3 when v^{ADD} = 10 km/h.

4. CONCLUSION AND FURTHER RESEARCH

In the numerical use case presented in this paper, the dual SC using ADDs could decrease the carrier's total last-mile operation costs up to 15% in the best configuration. Nevertheless, this cost reduction highly depends on the parcel volume PDF and the robot speed. If the parcel volumes are more uniformly distributed, the cost reduction is lower because less items are distributed by the ADDs. If we increase the speed of the robots, the operation cost reduction is higher because ADD operations take less time. It will be important to describe some realistic operative scenarios for ADDs in future years (circulation on secondary roads, bike lanes, sidewalks) to more precisely quantify the potential of these autonomous technologies. However, since the boom of e-commerce is expected to generate smaller parcels with higher delivery frequencies, the use of ADDs could be even more justified.

To conclude, some limitations to the developed model appear. First, the unit time and distance operation costs of ADDs are highly uncertain, which limits the representativeness of the results. Secondly, we considered that only one logistic micro-hub was implemented for a service region whose size is equivalent to the city of Barcelona. Creating a network of micro-hubs, adequately located, would certainly increase the efficiency of operations. This is left for further research.

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CASE OF STUDY OF A MIXED CARSHARING SYSTEM DESIGN

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ABSTRACT

One of the most significant issues when designing a carsharing system is the decision of implementing a free-floating or stations-based system. The advantages and drawbacks of each system are well known. Free-floating systems provide more accessibility to users. But they are more sensible to demand imbalance and can be limited if public space availability is restricted by municipalities. Station-based don't need public space occupation, but the station infrastructure requires more investment. The authors have developed a macroscopic design model that considers the case of a mixed carsharing system, which includes both free-floating and station-based options working together. This model not only allows to compare which option will perform better on any given scenario, but also to provide solutions that combine the accessibility and cheapness of free-floating with the lack of public space limitations of station-based systems. This document describes that model and shows its application to a case of study.

1. INTRODUCTION

Carsharing is the evolution of car rentals. The idea behind them is the same: to provide a flexible on-demand transportation alternative with less costs than acquiring a private car or vehicles for hire (e.g. taxis). And from this idea, the system has been improved using new technologies in order to increase its flexibility. Membership systems, geolocations, and mobile apps have eased a lot the process of search, reservation, and payment for the use. Allowing users, for example, to spend less time in the renting process, making only one-way trips, or paying per minutes instead of an hourly or daily basis.

These new features have produced a positive effect on the market size. As of October 2016, carsharing was operating in 2095 cities in 46 countries with approximately 15 million members sharing over 157.000 vehicles. The second carsharing market is Europe with 19% of worldwide members and 37% of the fleet. (Shaheen and Cohen, 2020)

However, those features have also added a completely new dimension on the complexity of the design and management of these systems. One of the most significant issues is the decision of implementing a free-floating or station-based carsharing configuration.

	2006	2008	2010	2012	2014	2016
Members	346,610	670,822	1,163,645	1,788,027	4,842,616	15,050,192
Compound Annual Member Growth Rate (2 yr)	0%	39%	32%	24%	65%	76%
Vehicles	11,501	19,403	31,967	43,554	104,125	157,416
Compound Annual Fleet Growth Rate (2 yr)	0%	30%	28%	17%	55%	23%
Member-Vehicle Ratio	30.1	34.6	36.4	41.1	46.5	95.6

Fig. 1 – Global carsharing market (Source: Shaheen and Cohen, 2020)

On free-floating carsharing (FF), the fleet of cars is placed on the city streets. Users can check the location of nearby available cars through a mobile app and reserve the desired vehicle to make their trips. Once the ride has been complete, users can return the car by parking it on any available place inside a designed service region (typically the whole municipality area).

On station-based carsharing (SB), the fleet is distributed through certain specific parking lots or stations. Users can also check the availability of cars via mobile app, and make a reservation. But, at the end, they must return the car on any of those designated parking locations. So, in practice, all trips are station-to-station.

Each carsharing type has some advantages and drawbacks, Soriguera and Jiménez (2017), Tournier (2017) and Ciari et al. (2014) mentioned a few of them:

- Firstly, from the operator point of view, FF requires less infrastructure costs since there is no need to pay any fee to the local parking provider in order to reserve parking spots. The cars can be parked at any free parking slot in the street, so there is no cost of renting the parking.
- Following this line, it is also important to emphasize in the fact that a FF service is easier to implement than a SB since it is not dependent of the construction times of parking slots.
- However, note that municipalities and local administrations could be reluctant to concede the free usage of public space, and therefore, they could limit the number of FF cars in service.
- From a customer perspective, accessibility is key. In the case of SB carsharing, there might not be stations near the trip origin or destination point. Hence, customers will lose

more time by accessing to the system, or even discard the trip if the access or egress distance is too big.

- However, on SB systems it is easier to ensure a good distribution and availability of cars, since the stations distribution and capacity limits demand imbalance. FF services are usually perceived as less reliable. Users don't take for granted to find a car. Either for that current trip, or on the way back home after the activity on destination is finished. So, service usage is discouraged when there's no a viable alternative.

Since both the SB and FF systems have different pros and cons, during the design phase it's crucial to compare the expected performance of both configurations in order to decide which one would be better in our case. Or, moreover, it could be interesting to design mixed configurations that combine the advantages of both. For example, SB systems with a limited number of stations can improve their coverage by including a number of FF cars. Or otherwise, if the public space occupation is very limited by the municipalities, FF systems could operate with a bigger fleet by including cars on stations.

With that purpose, the authors developed a macroscopic design model defined for a mixed carsharing system, which includes a FF and a SB part working simultaneously (Jiménez-Meroño and Soriguera, 2021). The model is based on the continuous approximations methodology. The main advantage of those models is their simplicity. They can be run with easily obtainable parameters. And its insights are depicted more clearly than more complex models without losing much accuracy or robustness in their results. Therefore, this methodology is adequate to evaluate the performance and take strategic decisions in the design phase.

In the following section of the document, an overview of the model is provided. Section 2 corresponds to the state of art and the review of academic literature. On Section 3, the main characteristics of the model are presented. That includes the tradeoff and decision variables characterization, the demand modelling, the cost equations, and the possible restrictions to apply. On Section 4, the model is applied to a case study based on the city of Barcelona, in order to provide an example of how it works and how it can be used in practice. Finally, the document ends with the conclusions section, acknowledgments and reference list.

2. CARSHARING STATE OF ART

2.1 Current picture of carsharing

Carsharing companies can be classified into two groups. The first one are agencies that were founded as rent-a-car companies, but they have been gradually introducing new features that change their business model. That's the case of Communauto, Enterprise, Flinkster, or Zipcar. Since those companies do not implement the same features on all cities or regions at once, many of them still rely on round-trip rentals.

The second group are companies that were founded with the carsharing business model in mind. Most of them, later than 2010. ShareNow, Enjoy, or Yandex.Drive belong to this group. They all operate offering one-way trips, either on SB or FF mode.

The authors consider that this trend shows that one-way services will be the prevailing option on future implementations. And, under a design point of view, it would be more useful to focus on that option. It could be argued that round-trip services are a remainder of the former rent-a-car structure due to the difficulty to adapt an existing business model. So, for the purpose of this work, only the one-way case is studied.

Name	Location	Service Type	Fleet size	Members	Vehicle Type	Fare
Cambio Carsharing	Belgium, Germany	Station-based round-trip	+1.700	63.500	Car/e-car	From 0.23 €/min
Communauto	France, Canada	Free-floating one-way Station-based round-trip	+2.000	+40.000	Car/e-car	From 0.28 €/h
Delimobil	Russia	Free-floating one-way	+12.000	+1.000.000	Car	
Enjoy	Italy	Free-floating one-way	2.670		Car	From 0.25 €/min
Enterprise Car Club	UK	Station-based round-trip	+500	20.000	Car/e-car	From 3.53 €/h
Flinkster	Austria, Germany, Netherlands	Free-floating one-way & round-trip	+6.500	+300.000	Car/e-car	From 1.50 €/h
ShareNow	Many European cities (see Table 4) and USA*	Free-floating one-way	+20.000		Car/e-car	From 0.19 €/min
Stadtmobil	Germany	Station-based round-trip	+2.600	+40.000	Car	From 0.26 €/km
Ubeeqo	Belgium, France, Germany, Italy, Spain, UK	Station-based one-way			Car/e-car	From 3.50 €/h
Yandex Drive	Russia	Free-floating one-way	+21.000		Car	
Zipcar	UK, USA, Canada, Costa Rica, Iceland, Turkey, Taiwan	Station-based round-trip and one-way trip	12.000	+1.000.000	Car/e-car	From 4.05 €/h

*On February, 29th 2020, ShareNow stopped its activity in North America, London, Brussels and Florence.

Table 1 – Main car-sharing operators in operation in Europe.

City	GDP [€/capita]	Fleet size [vehicles]	Service area [km^2]	Average price [€/min]	Average demand [trips/day]	Average trip
Berlin	41.967	2.975	165	0.25	-	
Madrid	35.041	2.400	80	0.27	-	31.9 min
Milan	49.500	3.021	120	0.26	3.500	
Moscow	19.696	30.000	850	0.079	150.000	13.34 km

Table 2 – Aggregated car-sharing services offered for different European cities.

2.2 Literature review

Many scientific papers have provided a good overview of the key factors for the success of carsharing programs. For instance, Alzahrani et al. (2019) and Münzel et al. (2018) analyze market studies and the factors that influence the selection of the best carsharing alternative of Portland and Germany, respectively. Schmöller et al. (2015), or Le Vine and Polak (2019) focused on different impacts that carsharing systems have had in different aspects of Munich and Berlin and London, respectively. From a more environmental point of view, Martin and Shaheen (2011) provide an overview on the green-house emission impacts of carsharing in North America. Another interesting work was carried out by Vosooghi et al. (2017) where different existing methods of demand estimation for one-way carsharing systems are analyzed. The main conclusion is that there are research gaps to be addressed regarding carsharing systems. For example, the integration of carsharing with the more traditional transportation modes or the general benefits of using autonomous vehicles in carsharing systems.

Regarding the carsharing system design, research can be classified into two different levels: strategical level, basically the planning of the system layout and the vehicle fleet; and operative level, mainly the optimization of the repositioning operations basically in one-way systems. Significant literature is reviewed next, following this classification.

Strategical planning addresses all the decisions that need to be taken when dealing with the implementation/expansion of a carsharing system. These decisions will be valid for the medium to long term. They include the study and optimization of the number and location of stations in the station-based system or the sub-zones in the free-floating system, the required number of parking spots, the dimensioning of the vehicle fleet and the definition of the repositioning period.

Kortum et al. (2016) provide an overall overview on free-floating carsharing. They evaluate empirical data on use of free-floating carsharing in different cities of Europe and North America. They make evident that carsharing is becoming a more integral part of the mobility of city, although different growth patterns can be observed for the different analysed cities. It is remarkable that the data included in this study is until 2015 and some cities appeared saturated at that time.

Recently, Ampudia-Renuncio et al. (2020) provide a spatial evaluation of the FFCS trip profile, obtaining the main flows throughout the whole service area. This spatial analysis is the first one carried out in Spain that uses real rental data collected from the different operators. Their results show that for short distance, users prefer carsharing system than the available public transport since carsharing is faster and public transport is highly correlated with parking availability at origin and destination.

The station-based one-way carsharing problem was assessed by Huang et al. (2018). They included to the problem relocations and non-linear demand. For relocations, they presented a Mixed-integer Non-linear Programming model to solve the carsharing station location and capacity problem. Then, for flexible demand, they construct a logit model to represent the non-linear demand rate by using the utility of carsharing and private cars. They draw the conclusion that pricing and parking space rental costs are key factors that influence the profitability of carsharing operators.

The operational level includes daily decisions. They mainly assess the rebalancing operations, which take place mainly in one-way carsharing systems. Different strategies are proposed to solve the system imbalance across the whole service area. Some of the most influential literature regarding this topic is herein presented.

An overall literature review of the vehicle relocation problem in one-way carsharing was carried out by Illgen and Höck (2019), who revised the relevant literature regarding one-way trips and relocations from 2012 to 2019 with several case studies in order to give a more thorough overview on different methodologies proposed by different authors.

Boyaci et al. (2017) carried out a simulation for a station-based carsharing system where, iteratively, optimize the decision variables related to vehicle and relocation personnel. In their work, the results show the importance of efficient algorithms when dealing with relocation operations. They proved the importance of forecasting the demand to optimize the initial locations of vehicles for an efficient use of the resources.

A relocation algorithm for free-floating carsharing with conventional and electric vehicles is proposed by Weikl and Bogenberger (2015). In their work, they carried out three real world field tests for different stages of development of the model. In the final result they achieve promising results in reducing the idle time of the vehicles and a high efficiency of relocations. It is interesting since the model was applied to the carsharing system in Munich (Germany). So, it provides a realistic scenario that can be easily applied to other free-floating carsharing systems.

3. MODEL DEFINITION

In this section, the main characteristics of the model are summarized. The complete formulation and details of the model are described in Jiménez-Meroño & Soriguera (2021).

3.1 Model overview and decision variables

Model is defined over a continuous service region, where the free-floating (FF) and station-based (SB) systems act simultaneously. Users will behave as it follows:

- The FF service is preferred on origin due to accessibility reasons. Users will check first for vehicles on street inside their virtual station. If there's any available vehicle, users will reserve and rent that vehicle.
- If the virtual station is empty, users will try to use the SB system. If users are inside the coverage of the SB system, they will opt for the SB system. Otherwise, the trip is lost.
- When opting for the SB system, users will check the nearest station. If there is any available vehicle, users will reserve and rent that vehicle. Otherwise, the trip is lost.

In order to control the tradeoff between demand losses and agency costs, operators have five options that correspond to the five degrees of freedom of the system. Each one is associated to a single decision variable:

- Change the on-street FF fleet size ($\boldsymbol{m_{FF}}$) or the SB fleet size ($\boldsymbol{m_{SB}}$).
- Change the number of employees carrying repositioning operations. The variable that characterizes repositioning operations is the repositioning period. It defines the average time until a station (or virtual station) is rebalanced. That variable can be different for FF and SB and their values are $\boldsymbol{h_{FF}}$, $\boldsymbol{h_{SB}}$.
- Change the number of stations in order to modify the coverage and accessibility of the SB system. This coverage is determined by the density of stations per km^2 is defined as $\boldsymbol{\Delta_{SB}}$. And, therefore, the total number of stations is $\Delta_{SB} \cdot R$.

Name	Description		Symbol	Units
Station density	Number of parking stations per area unit		$\boldsymbol{\Delta_{SB}}$	[stations/km2]
Available fleet size	Number of available vehicles in the system	Total	$\boldsymbol{m}$	[cars]
		Free-floating	$\boldsymbol{m_{FF}}$	
		Station-based	$\boldsymbol{m_{SB}}$	
Repositioning period	Avg. time between complete rebalancing	Free-floating	$\boldsymbol{h_{FF}}$	[hours]
		Station-based	$\boldsymbol{h_{SB}}$	

Table 3 – Decision variables summary.

There are two additional degrees of freedom not considered in this model: changing the available parking, and changing the battery recharging system.

The model considers that parking availability only affects demand on long term decisions. Not finding parking on the desired destination can discourage users from using the service more times in the future. But the current trip will be made eventually, either parking on street or on a station. For that reason, the number of parking places is considered an output here. And it is restricted to be at least as big as the fleet size.

Finally, battery recharging is a complex process by itself with several decision variables. The number of electric cars, the number and type of chargers, or battery autonomy can be changed and result in more or less demand losses. Including all of them would overcomplicate the model and shadow the main design insights. Therefore, battery recharging is considered here a constraint.

3.2 Demand modelling

The amount of served trips (λ_{FF} and λ_{SB} in trips/km^2·h) depends on two factors. First, if there is enough demand of trips in the system (i.e. potential demand density, input of the model). And second, if there is enough fleet capacity to serve those trips. Served trips will be the minimum of both.

However, note that potential demand and fleet are variable in time and space. This phenomenon is accounted by the definition of three correction factors defined stochastically:

- Temporal fluctuations. On off-peak hours, potential demand will be lower than the average. So, there’s a probability of having more available vehicles than potential demand. Therefore, demand served is reduced.
- Demand spatial imbalance. There are regions that are usually attraction poles. Cars tend to accumulate on those zones. If the accumulation of cars exceeds the potential demand, some of the cars will remain unused. Therefore, demand served is reduced.
- Demand spatial decentralization. This phenomenon is equivalent to the previous one but on a station level. In this case, one station can randomly exceed the potential demand at any moment, no matter if it’s located near of an attraction pole or not.

According to those criteria and stochastic phenomena, demand served is estimated.

3.3 System cost equations

Once demand is estimated, it is possible to calculate all costs of the system. Costs are depicted in monetary units per time unit (€/h in our case). So, consequently, all results will be also divided per time units (i.e. trips per hour, penalties per hour, or even hours of repositioning work per hour).

Both agency and user costs are considered in order to define two possible objective functions: the total generalized cost and the agency revenue.

- Infrastructure costs ($\boldsymbol{Z_I}$). It accounts for all the investments made to acquire and renew the vehicle fleet and parkings.
- Operative costs excluding repositioning ($\boldsymbol{Z_O}$). This term includes all charges that can be imputed to vehicle usage, such as maintenance, cleaning, and fuel consumption.
- Repositioning cost ($\boldsymbol{Z_R}$). It's the cost that summarizes all relocation operations. Those operations are meant to compensate system demand imbalance or move electric vehicles to recharging points.
- User access cost ($\boldsymbol{Z_{AC}}$). It accounts the walking time of users at origin or destination.
- User no service penalties ($\boldsymbol{Z_{NSP}}$). This cost applies to all lost demand in order to account the losses and annoyance perceived by the users after a failed trip attempt.

With those costs, two objective functions are defined. The first one is the total generalized cost per time unit. It includes all user and agency costs. The second one is the agency profit per time unit. It consists in the revenue generated by the served demand minus the agency costs.

$$Z_{GCF} = Z_I + Z_O + Z_R + Z_A + Z_{NSP} \tag{1}$$

$$Z_{PRF} = fare \cdot (\lambda_{FF} + \lambda_{SB}) \cdot R - (Z_I + Z_O + Z_R) \tag{2}$$

Note that, in case of agency revenue maximization, the fare must be an input of the model.

3.4 Battery consumption and charging restrictions

The design model could be applied for any type of fleet, including partially or totally electric vehicles. In that case, the model includes solutions to ensure that the average recharging ratio is enough to compensate the battery consumption ratio. To do so, two different charging systems are defined: distributed and centralized charging.

Distributed charging uses the SB parking facilities to install domestic recharging points. Recharging with these devices is slow, but installation is cheaper and easier than other faster alternatives. If this option is considered, the solution must ensure that vehicles on stations and relocating operations are enough to reach the minimum recharging rate.

Alternatively, centralized charging considers a central hub, inaccessible to users, where all recharging operations take place. This infrastructure is equipped with superchargers, which allow to recharge vehicles quicker. However, they require a more expensive installation and additional repositioning operations in order to move the cars to the hub and redistribute them again once the battery is charged.

4. CASE OF STUDY: BARCELONA

4.1 Description of the scenarios

The base for this case study will be a mixed carsharing system placed in a region of 39.19 km^2 in central Barcelona. Six different optimization scenarios are compared. In three of them the sum of users' and agency costs will be minimized. And in the other three, the agency profit will be maximized. For each objective function, three different vehicle and recharging configurations will be addressed: 100% of electric vehicles with decentralized recharge on stations, 100% of electric vehicles with hub recharging, and 0% of electric vehicles (all ICE vehicles).

Scenario	Objective function	% of electric vehicles	Battery charging configuration
#1	Max. profit	100 %	Distributed
#2	Max. profit	100 %	Centralized
#3	Max. profit	0 %	-
#4	Min. GCF	100 %	Distributed
#5	Min. GCF	100 %	Centralized
#6	Min. GCF	0 %	-

Table 4 – Optimization scenarios summary.

Since the number of parking places and recharging parameters are not decision variables, and therefore, are not subject to optimization, further considerations must be taken into account:

- By default, the number of parking places is set to the minimum feasible.
- In case of decentralized recharging, if the fleet constraint is not fulfilled, the number of SB vehicles will be increased until reaching the minimum. Note that reducing the FF fleet size is another possible solution. But it is considered that, in general, that case would result in less demand served and a worse performance.
- The number of charging devices on parkings is also set to the minimum feasible.

Tables 5 and 6 summarize the parameter estimation for the city of Barcelona.

	Parameter description	Units	Value	Source
Demand inputs	Area of the service region	[km²]	39.19	The area selected was a region of central Barcelona. Demand data was provided by Inlab UPC as a O/D matrix of 228 zones. Only trips longer than 1.5km were considered, and a carsharing market penetration of 0.5%. (InLab, 2019)
	Request subregion	[-]	0.53	
	Return subregion	[-]	0.47	
	Average potential demand density	[trips/h·km²]	9.77	
	Standard temporal deviation	[trips/h·km²]	0.977	
	Request imbalance	[-]	0.215	
	Return imbalance	[-]	0.241	
	Fraction of station returns	[-]	0.43	Estimation from EMEF 2019 (Autoritat del Transport Metropolità, 2020).
User behavior inputs	Maximum access distance	[km]	0.4	Transportation Research Board (2013)
	Average walking speed	[km/h]	3	Generalitat de Catalunya (2017)
	Users' average value of time	[€/h]	11.4	Official value used for transport investment appraisal in Barcelona (Autoritat del Transport Metropolità, personal communication, July 2017).
	Users' no service penalty (FF)	[€/trip]	7.93	Considered as the average taxi fare in central Barcelona (Autoritat Catalana de la Competencia, 2018; Institut Metropolità del Taxi, 2020)
	Users' no service penalty (SB)	[€/trip]	2.50	Estimation according to the works of Herrmann et al. (2014) and Ampudia-Renuncio et al. (2018). 80% avg. public transportation fare (Transport Metropolità de Barcelona, 2020) + 20% Avg. taxi fare in Barcelona (see above).

Table 5 – Input estimation (Part 1).

	Parameter description	Units	Value	Source
City inputs	Average circulating time	[min]	11.1	Result of dividing the average trip distance by the average car speed.
	Average parking time	[min]	6.6	Survey conducted in nineteen major European cities (Conduent, 2016)
	Average service time	[min]	27.7	Result of $\tau_c + \tau_p + \tau_r/2$.
	Average car speed in the city	[km/h]	15.3	This is 2/3 of the average measured speed in Barcelona. The 1/3 reduction considers delays at intersections. (Ajuntament de Barcelona, 2018)
	Average repositioning speed (in electric scooter)	[km/h]	8.8	Liu et al. (2019)
Agency costs and policies	Acquisition cost per vehicle	[€/car·h]	0.33 (electric car)	Seat Mii market cost (SEAT, 2020a), considering a useful life of 5 years, a residual value of 50%, an unavailability ratio of %5 due to maintenance and repairs (Bösch et al., 2018), and average insurance costs.
			0.23 (ICE car)	
	Average cost per parking (SB)	[€/parking·h]	0.25 (no charger)	Long-term renting cost of a parking slot in Barcelona (B:SM, 2020; SABA, 2020) plus the installation of charging infrastructure (Wallbox, 2020; Schroeder and Traber, 2012; Zhang et al., 2018).
			0.30 (Wallbox)	
			1.18 (fast charger)	
	Average cost per parking (FF)	[€/parking·h]	0	Subsidized on-street parking
	Average operative cost per trip	[€/trip]	1.37 (electric car)	Energy and fuel consumption is estimated according to trip distance, the SEAT Mii technical specifications (SEAT, 2020b), and the price index in Catalonia (IDESCAT, 2017). Cost of administrative control and manteinance are adapted from Bösch et al. (2018) to the currency and power purchase in Spain.
			1.45 (ICE car)	
	Average cost per repositioning worker	[€/worker·h]	21.54	Labor cost of 14.32 €/h according to IDESCAT (2017). 33% of the working time is considered lost or ineffective for repositioning. The prorated acquisition cost of scooters is included but it is residual (0.04 €/h).
	Average time spent on fixed repositioning operations	[min]	6	(SEAT, personal communication, March 2020)
	Average autonomy of electric vehicles	[h]	13.07	SEAT Mii technical specifications (SEAT 2020b).
	Average recharging time of electric vehicles	[h]	4	
			1	
	Hub location	[km]	0	The hub is considered near the city centre.
	Maximum reservation time	[min]	20	Similar to Car2Go policies in Madrid. (Car2Go, 2020).
	Average fare	[€/min]	0.27	

Table 6 – Input estimation (Part 2).

4.1.2 Limitation of the number of stations

Before examining other results, it should be noted that the optimum station density, Δ_{SB}, resulted in a huge value for all studied scenarios.

When the generalized cost is minimized, user access cost is much larger than all the other agency costs and user penalties. So, the model keeps adding stations in order to minimize access distance even after reaching the full SB coverage.

In case of maximizing profit, where user costs are not considered, the effect is attenuated, but still the optimal Δ_{SB} results unrealistically large. This is because sometimes the number of repositioning operations is determined by the battery recharging operations or the compensation between the FF and SB modes (i.e. returning cars to station). In those cases, the station density, Δ_{SB}, has no effect on increasing the number of operations. In fact, it decreases its cost because it reduces the average repositioning distance. That effect exceeds any other cost increase associated to the number of stations.

The conclusion is that in those cases, the number of parking stations to be used should be as large as possible, because this will reduce both, user and agency cost. This conclusion could change if the infrastructure cost includes some kind of penalty for being able to park on several different stations.

Taking the previous conclusion into account, for the purpose of this study, the number of parking stations has been set to a more realistic fixed number of 48 stations. This corresponds to $\Delta_{SB} = 1.22$ stations/km2 and represents a SB coverage of roughly 20% of the service region ($c \cdot \Delta_{SB} = 0.195$).

4.2 Optimization results

Tables 7, 8 and 9 summarize the main optimization results for all scenarios. In the following subchapters, the main findings and comparisons are explained with more detail.

Parameter		Units	Max. Agency Profit			Min. Generalized Cost		
			Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn. 6
Density of stations		[stations/km^2]	1,22	1,22	1,22	1,22	1,22	1,22
Fleet size	FF	[cars]	314	166	370	91	99	121
	SB	[cars]	31	27	26	47	8	9
	Total	[cars]	367	214	421	149	120	136
Parking slots in stations		[parking slots]	33	27	27	47	8	9
Repositioning period	**FF**	[hours]	113,0	351,1	115,7	82,1	38759,4	19308,1
	SB	[hours]	46,6	6,7	11,6	13,5	1066,9	244,5

Table 7 – Optimization results. Decision variables.

Parameter			Units	Max. Agency Profit			Min. Generalized Cost		
				Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn. 6
Fleet size	FF	In use	[cars]	123	109	125	91	85	90
		Idle vehicles	[cars]	191	57	245	0	14	31
		Total	[cars]	314	166	370	91	99	121
	SB	In use	[cars]	8	13	10	17	8	9
		Idle vehicles	[cars]	23	14	16	30	0	0
		Total	[cars]	31	27	26	47	8	9
	Spare	Hub operations	[cars]	-	9	-	-	7	-
		Repositioning	[cars]	5	2	4	4	0	1
		Reparation	[cars]	17	10	20	7	6	6
		Total	[cars]	22	21	24	11	13	7
	Total system fleet		[trips/vehicle]	367	214	420	149	120	137
Daily trips per vehicle			[trips/vehicle]	10,75	17,96	9,62	22,01	24,61	21,62
Total number of stations			[stations]	48	48	48	48	48	48
Parking in stations			[parking slots]	33	27	27	47	8	9
Charging points at hub			[parking slots]	-	6	-	-	5	-
Repositioning rate	Free-floating		[operations/h]	10,21	8,41	13,26	16,59	0,23	0,55
	Station-based		[operations/h]	6,03	0,00	2,91	0,00	0,00	0,00
	Maintain FF restriction		[operations/h]	0,00	6,07	0,00	16,59	0,23	0,55
	Maintain EVs battery		[operations/h]	6,03	0,00	0,00	4,46	0,00	0,00
	Total		[operations/h]	16,25	8,41	16,16	16,59	0,23	0,55
Average repositioning time			[h/operation]	0,26	0,35	0,25	0,24	0,50	0,24
Total repositioning time			[hours/h]	4,15	5,09	4,01	4,01	2,39	0,13
Total time lost			[hours/h]	2,07	2,54	2,01	2,01	1,19	0,07
Number of repositioning teams			[workers]	6,2	7,6	6,0	6,0	3,6	0,2
Average team performance			[ops/worker·h]	2,61	1,89	2,69	2,76	1,34	2,76
Average access distance			[meters]	200,0	200,0	199,9	200,0	200,0	200,0
Total demand	Served		[trips/h·km^2]	7,28	6,79	7,49	5,97	5,18	5,49
			[%]	74,55	69,48	76,62	61,10	53,00	56,19
			[trips/day]	3711	3458	3814	3041,	2638	2797
	Lost		[%]	25,45	30,52	23,38	38,90	47,00	43,81
			[trips/day]	1267	1519	1164	1936	2340	2181
	SB fraction		[%]	93,69	89,29	92,56	84,48	91,46	91,32
	FF fraction		[%]	6,31	10,71	7,44	15,52	8,54	8,68

Table 8 – Optimization results. KPIs.

Parameter		Units	Max. Agency Profit			Min. Generalized Cost		
			Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn. 6
Infrastructure costs	Fleet	[€/h]	115,32	67,19	92,15	46,92	37,68	29,78
	FF parking	[€/h]	0,00	0,00	0,00	0,00	0,00	0,00
	SB parking	[€/h]	9,48	6,71	6,77	12,83	1,99	2,16
	HUB parking	[€/h]	0,00	7,08	0,00	0,00	5,40	0,00
Operation costs (without repositioning)		[€/h]	391,08	364,45	425,40	320,49	278,00	311,93
Repositioning costs		[€/h]	89,29	109,63	86,41	86,38	51,40	2,84
Access costs		[€/h]	433,90	404,35	445,71	355,58	308,44	326,99
Demand lost	FF penalties	[€/h]	232,06	292,16	223,77	372,38	396,57	374,74
	SB penalties	[€/h]	36,51	0,00	0,00	0,00	169,20	141,64
Total agency costs		[€/h]	605,17	555,06	610,73	466,61	374,47	346,70
		[M€/year]	5,30	4,86	5,35	4,09	3,28	3,04
Total users' costs		[€/h]	702,47	696,51	669,48	727,96	874,21	843,38
Total costs		[€/h]	1307,63	1251,58	1280,20	1194,58	1248,68	1190,08
Gen. cost per trip		[€/trip]	4,58	4,70	4,36	5,11	6,15	5,53
Fare		[€/trip]	4,78	4,78	4,78	4,78	4,78	4,78
Revenue neutral fare		[€/trip]	2,12	2,09	2,08	1,99	1,85	1,61
Profit	per trip	[€/trip]	2,66	2,69	2,70	2,78	2,93	3,17
	per day	[€/day]	9865,56	9309,48	10285,20	8465,92	7737,42	8856,59

Table 9 – Optimization results. Costs.

4.2.1 Optimum demand served

In all scenarios, SB served demand is a small fraction of total served demand. This is due to three reasons. The FF preference and lesser coverage makes that only a fraction of users is a potential candidate to access the SB system. SB cars are more expensive than the FF cars because of the associated cost of renting the parking place on a station. And, since only a fraction of users returns the car to stations, serving more SB demand means additional repositioning costs to compensate that imbalance. For those reasons, the optimal system for all scenarios in this case is almost a pure FF system.

Also, in all scenarios only a fraction of the demand is served. This allows increasing the vehicle utilization rates and reducing artificial rebalancing needs, which is translated into reduced agency costs and higher profit.

Difference between both objective functions lays in which is that percentage of served demand (70-75% in case of agency profit maximization and 53-60% in case of minimizing users and agency costs). The reason for that is that no-service penalties are less expensive than the revenue lost when maximizing profit. Therefore, when profit is maximized, more vehicles are necessary. Because of this higher vehicle availability in the max. profit scenario, the average usage of each vehicle (trips/day) decays. This yields a lower profit per trip, but is compensated by the larger demand served.

4.2.2 Electric vehicles and recharging

With respect to the difference between the electric vehicles or ICE, in general, the system seems to perform a bit better when composed only of ICE vehicles (Scenarios 3 and 6). In any case, differences are slight, and different effects compensate each other. For instance, the additional vehicles due to battery recharging tend to be compensated by the lower cost of gasoline vehicles, pushing toward a higher fleet. Also, the operative costs of gasoline vehicles are higher, implying a somehow lower optimal demand to serve.

When comparing the recharging options for electric vehicles, overall, the difference is slightly in favor of decentralized charging. This is because the additional repositioning costs force the system to reduce the fleet of cars, resulting in less demand served than the decentralized recharging at stations.

However, that not diminish the positive effect of installing superchargers. The cost increase is compensated by the quicker recharge. It’s their distribution on a central hub what makes them costlier. In case of splitting the superchargers in different installations, their performance gets very close to the domestic recharging at stations.

Parameter		**Units**	**Decentralized (Scn. 1)**	**ONE HUB (Scn. 3)**	**SIX HUBS**
Fleet size	FF	[cars]	314	166	226,03
	SB	[cars]	31	27	36,31
	Total	[cars]	367	214	286,26
Charging points at hub		[parking slots]	-	6	6
Number of repositioning teams		[workers]	6,2	7,6	6,1
Profit	per trip	[€/trip]	2,66	2,69	2,70
	per day	[€/day]	9865,56	9309,48	9635,01

Table 10 – Optimization results. Costs.

4.2.3 Robustness of optimal results

Robustness is a desirable property in optimization frameworks. A robust optimal solution means that small deviations in the selection of the optimal decision variables imply equally small deviations in the result of the objective function. Errors in the analytical definition of the model, or in the estimated parameters, are unavoidable; but the objective should be that these errors do not affect significantly the final objectives (i.e. the design of the system and the results in costs).

This subsection shows that the optimal results obtained, are robust, in the sense that the effects in costs and profit of the system due to sub-optimal selection of decision variables are small, so that the system may be feasible even when its design is suboptimal. Figure 2 shows the variations on the profit and agency cost as a function of variation of decision variables. See, for instance, that variations of 50% with respect to the optimal FF fleet size, m_{FF}, imply variations in agency costs of 10% or less. Also, the effects on the profit of the system are even less, because larger fleets allow to serve more demand, while for smaller fleets the utilization rate of vehicles might increase.

For the other decision variables, especially for the repositioning period, the result is even more robust. The reason is that, after all, the repositioning period is a convenience variable related to the number of repositioning employees. Note that this latter variable results to be small (6-7 employees working simultaneously). Hiring an additional one would imply a small difference on the overall performance, but relatively a bigger increase on the variable.

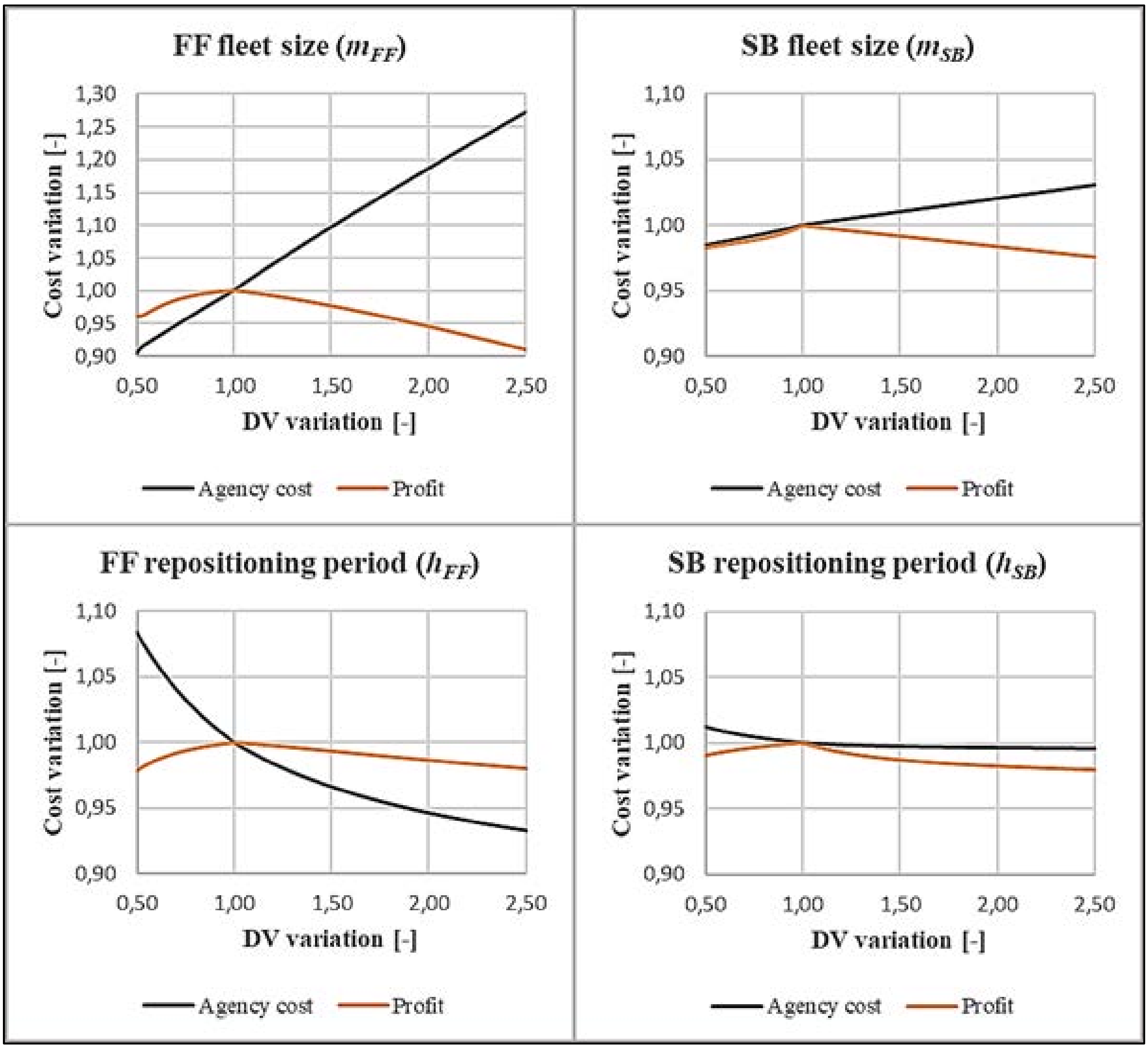

Fig. 2 – Robustness of DVs around the optimum value

5. CONCLUSIONS

An analytical planning model for a one-way mixed FF and SB car-sharing system has been developed. This is based on the modeling of the strategical variables of the system and their relevant trade-offs, using continuous approximations. This analytical approach requires a simplification of the reality (e.g. assumption of spatially uniform demand level) and to obviate some details of operation. However, results provide clear insights, valid in a wide range of contexts and which should be the foundations for further research.

This concluding section summarizes the main findings when the model was applied to a case of study for the city of Barcelona with different scenarios considered. Note that, despite input parameters have been estimated especifically for this case of study, many of them would be very similar for any city of similar size and socio-economical context. So, the insights and considerations to be taken into account would be still valid in many cases if the model is applied in the future in the context of planning a one-way carsharing system.

Take the following bullet points as general conclusions of this document:

- The model gives preference for the FF system. The SB system becomes auxiliary when the difference between SB and FF parking cost is big. A sensitivity analysis of the on-street parking cost would be an interesting point for future research.
- In all scenarios, model shows that it is advisable to leave part of the potential demand not-served (30-35% in case of agency profit maximization and 40-50% in case of minimizing users and agency costs). This allows increasing the vehicle utilization rates and reducing artificial rebalancing. However, the model assumes that potential demand is constant even if a fraction of users is experiencing no-service situations. Further research must be made in order to estimate which is the minimum level of service that must be achieved to maintain that potential demand.
- With respect to the recharging infrastructure, it seems a better option to decentralize the charging points. Superchargers can be as profitable as domestic chargers. Their higher cost gets compensated by their efficiency, which reduces the duration of repositioning tasks.
- The sensitivity of system costs and profit to suboptimal designs is small. This means that the proposed designs are robust, and deviations could be accepted without implying severe penalties. However, it should be noted that this sensitivity is larger when the deployed resources are below the optimal values. This means that special care should be devoted to avoid being excessively conservative in the fleet size deployment, knowing that over-sized fleets almost do not penalize profit.

ACKNOWLEDGEMENTS

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SOFTWARE TOOL FOR ANALYSIS AND VISUALIZATION OF GPS TRACKS IN URBAN ENVIRONMENTS

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ABSTRACT

Traffic in urban environments vary significantly depending on the areas of the city and the time of day. Nowadays, thanks to the large number of GPS devices that are integrated in all kinds of devices, it is possible to make a quantitative analysis of traffic. This contribution presents an application developed to analyse this information in a simple way and with a visual representation. One of its main advantages is that it is adaptable to any city in the world, as its internal algorithms adapt to the available data are presenting and adjusting it to the traffic through the city. This is done by extracting information directly from the data provided by GPS devices moving around the city. In addition, an analysis of the execution times of all application processes is presented to determine which parts involve a higher execution cost and determine the overall scalability of the application.

1. INTRODUCTION

Nowadays, the general availability of devices capable of tracking the movements of a subject or vehicle makes movement data collection easier than ever. However, once the data is collected, a more difficult task must be completed to extract relevant information about this monitoring: the data must be cleaned (Chen *et al.*, 2016), organized (de Almeida *et al.*, 2020), aggregated, etc. (Zheng, 2015). This problem grows exponentially when it is necessary to analyse massive amounts of vehicles or people movements at the same time.

This work presents a web application prototype that facilitates the completion of the aforementioned analysis tasks. The tool takes individual regular GPS tracking files and performs operations to filter track errors, detect traffic clusters and nodes, calculate traffic summary indicators between nodes, and display all this information on a dashboard. In addition, it includes an interactive map and additional analytical charts allowing the user to perform exploratory analyses. Additionally, it allows the processed files and their results to be exported in standard format, so they can be used in other software solutions.

The software has been tested with real data obtained from mobility activities in some worldwide cities, obtaining interesting analytical results that will be included in the contribution as examples. These examples are drawn from two datasets. The first one, with a temporal scope of up to one year, including data on up to 442 vehicles and 1,674,141 trips. The second one with a temporal scope of just over one and a half months and 12,695 routes. The geographical scope of the application can be extended to wider areas, not just urban areas, provided the user has the necessary data.

The main capabilities of the presented tool allow us to represent a set of individual GPS files in a graphical environment. It makes possible a global exploratory analysis of the complete dataset. Furthermore, it is possible combine the tool with other analytical software. Finally, the flexibility of its design that makes it easy to extend its functionality with additional data analysis algorithms.

2. STATE OF THE ART

There are three types of commercial solutions on the market. Some are completely focused on the end user and do not allow a general traffic analysis but offer concrete solutions to individual movements (Google Maps, WAZE). The second type of applications are those that allow experienced users to analyse the data in a general way and visualise the results (CARTO, QGIS ArcGIS, and Elastic Maps). The third type are those that allow us to analyse traffic congestion or traffic events with a high level of detail (TomTom Road analytics).

In the literature, there are different techniques to analyse and visualise traffic. One of the most common and simplest method of visualization is the heat maps (Wang, Lu and Li, 2020). It is very common to use groups to classify the regions through which routes pass to analyse the traffic density. The most widespread techniques in this case are grouping by using some characteristic of the location of the data such as neighbourhoods or districts (Ibrahim and Shafiq, 2019). Another option is using clustering techniques that perform an automatic classification of the routes (Bian *et al.*, 2018). These two methods seek to analyse the relationships between the different clusters (Yuan and Raubal, 2014).

There are other analyses with the same type of data that can help us understand traffic and propose improvements. Such as the detection of anomalies and events that allow us to detect anomalous changes in traffic (Donovan and Work, 2017)(Zhong *et al.*, 2020). This also is useful for analysing the resilience of transport systems. And the detection of patterns between routes, which is used to detect which routes are the same or have a high degree of similarity (Barann, Beverungen and Müller, 2017). These techniques are widely used in car sharing services.

Unlike these methods, in this contribution we perform a classification of the route's points. The objective is that the extracted clusters adapt to the distribution of streets and traffic in the city, getting a visual representation of the traffic status through a bidirectional network that is easily understandable.

3. METHODOLOGY

This prototype is based on the methodology described below (and represented on Figure 1), firstly explaining the data structure. Then the application processes are detailed until the graphical representation of the information is obtained.

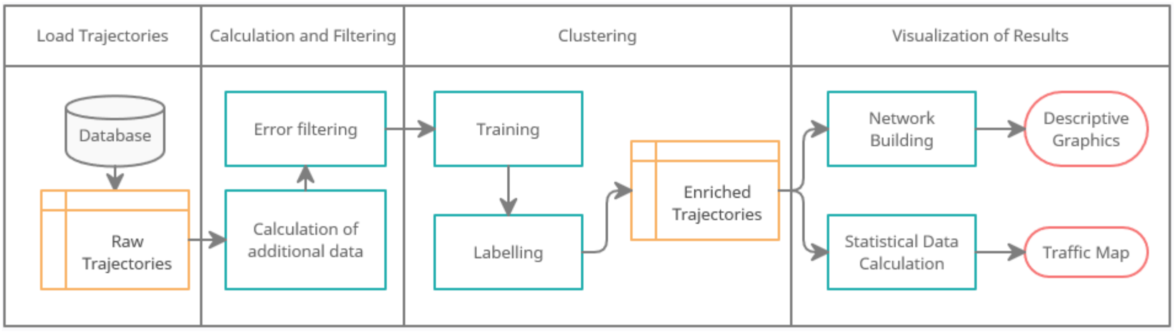

Figure 1 Pipeline of the operations performed by the application

Figure 1 shows the different phases through which the data passes until it is displayed to the user. In the first phase, the data is loaded into the application's memory. In the second phase, data such as distance, speed and time of the registered movements are calculated. This phase includes the elimination of the measurement's errors and outliers. In the third phase, a classifier is trained using this data and the data is grouped according to the geographical distribution. In the last phase, with the data applied and classified, a complex network representing the displacements is generated and the statistics are calculated. Both, the complex network and the statistics are displayed graphically to the user. In the following sections, each step is explained in more detail.

3.1. Trajectories

The basic data used by the application are GPS trajectories or routes. Which are used throughout the execution cycle of the application to perform the analysis.

The trajectories or routes consist of a series of geospatial points ordered chronologically that describe the route of an element. A trajectory T_i is formed by n points P_i that are composed of longitude$x$, latitude y and instant of time$t$.

It is important that the difference between t_n and t_{n-1} has a value small enough to make the path sufficiently descriptive and large enough so that the trajectory is not too bulky. In first data set used, the difference is 15 seconds.

From these simple paths that are stored in a database, it is necessary to calculate other data for processing. First the time intervals and the distance between the points are calculated. This also allows us to calculate the speed at which the movement between these occurs which is crucial for error filtering, as it is described next.

3.2. Error filtering

For (Yan *et al.*, 2013) the trajectories have two types of errors, the first is due to the precession of the GPS itself. These errors produce a loss of accuracy of approximately ± 15 meters. We ignore these types of errors, as they are not very relevant for the analysis. The second type is due to GPS synchronisation failures. This type of error produces failures in the real location of the device recording its location in previous locations or with displacements of kilometres. This causes the speed of an element to be calculated at an unrealistic speed.

To solve these errors, we use the speed, which is the variable that produces the failures. This error detection is context dependent. Since in the experiments we use data from motor vehicles movements in urban environments, to detect if a route contains errors, we filter those that in some intervals exceed 200 km/h. If the context is different, the speed must be adapted to a higher speed than the maximum expected.

3.3. Clustering

Clustering is a data mining technique that is used to separate data into natural groups. For (Mussardo, 2019) this technique has two functions: Summarizing the data allows us to work with a smaller volume of data, which improves processing performance and simplifies visualization. Segmentation of the data allows us to analyse the behaviour of each group. Clustering can be seen as an optimisation problem where the aim is to maximise or minimise a certain variable.

In this study, we compare two widespread algorithms for this task:

- K-means: It tries to minimize the sum of the quadratic distances with the centre of the cluster. It is necessary that we indicate the number of clusters to this algorithm.
- HDBSCAN: It is a variant of DBSCAN, this algorithm reduces the distance that can exist between children until all the points are independent building a hierarchical tree. Then it keeps those branches of the tree that have a greater stability discarding their children. The stability is the number of iterations that a branch maintains the minimum number of points or without dividing. Not all data are classified.

With these techniques, we group each point of a trajectory according to its geographical location. In this way, we can summarize a trajectory as the movement between the areas into which the map is divided, which coincide with the determined clusters. This segmentation of the trajectories allows us to analyse the relationships that exist between the different clusters.

3.4. Visualization of Results

The processing of the information concludes with the creation of an interactive map and additional analytical graphics that allow the user to perform exploratory analyses. Additionally, the application also enables the export of the already processed data.

3.4.1. Map

A complex network is built from the clustering of points, using the centroid of each group as the node of the network. To do this, the number of edges between nodes and the speed at which the movement between nodes takes place are counted. Once the network is built, it is represented graphically on a map. This is represented in a bidirectional way, with a line thickness proportional to the traffic and with a colour that varies between green and red depending on the speed.

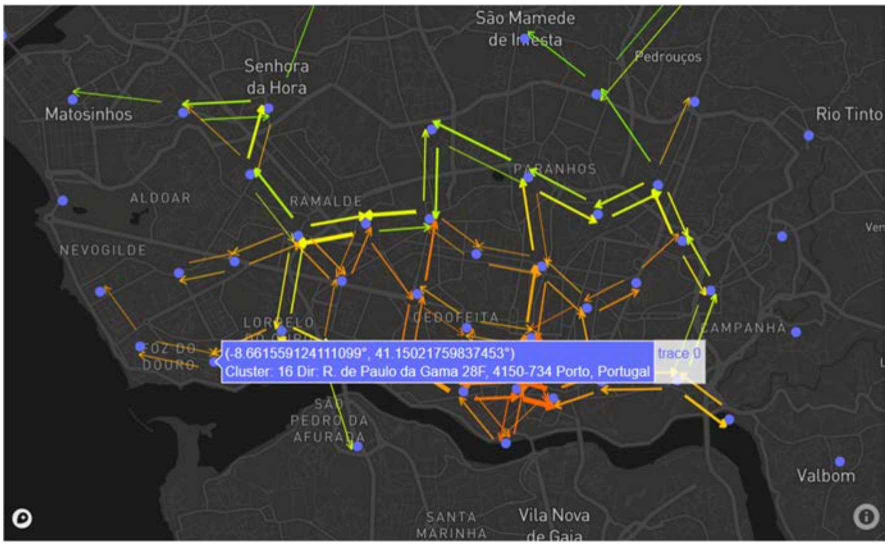

Figure 2 Map with graphical representation of traffic

All the clusters are represented on the map, but only those relationships that have a minimum support are represented. This is done so that the map is as clean and legible as possible, omitting those relationships that have little information. For this reason, there are clusters, especially those on the periphery, which do not have relations represented. As example, we show the traffic flow over the map of Porto (Portugal) can be seen on Figure 2.

3.4.2. Descriptive statistics

A series of statistics and graphs are provided to complement the information on the map. This allows to understand the data used and to analyse other factors not directly related to mobility. It also allows us to analyse the characteristics of the selected data set. As an example, Figure 3 shows a chart representing the frequency of routes completed on each hour of the day, on different days of the week.

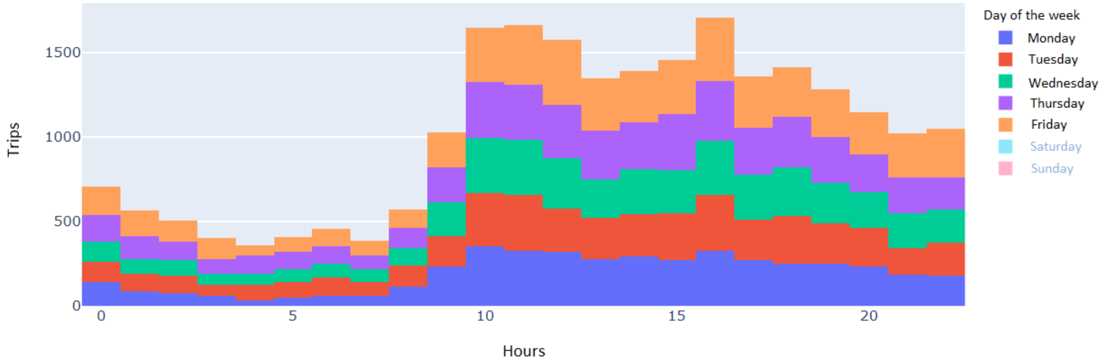

Figure 3 Example of an interactive graphic showing the frequency of routes on each hour of the day

4. EXPERIMENTS

The aim of the experiments is to evaluate the efficiency of the algorithms and them behaviour on different types of datasets. For this purpose, two different datasets are used, the first one is a dataset of taxis from Porto (*Taxi Trajectory Data | Kaggle*, 2018) and the second one is a dataset of taxis from Mexico (*Taxi Routes of Mexico City, Quito and more | Kaggle*, 2017). The difference is that the first one consists of complete routes and has 1,674,141 trips, while the second one only consists of the start and end point of the route and has only 12,695 trips. In the experiments, data loading times, clustering, calculation of the associated data and filtering, network creation and calculation of the statistical data of the routes are measured. These calculations are performed with datasets of different sizes, which allows seeing the growth of the different times. The number of points used for the calculations measures the size. The routes are randomly selected, and the data is split in such a way that there are only the set number of points for each experiment.

For the experiments, we have used a computer with 16 GB RAM, a 2-core 4-threaded processor and an SSD hard disk.

Table 1 and Table 2 show the results for each part of the execution in seconds and are the data used for the graphs in Figure 4.

	5,000	10,000	15,000	20,000	25,000
Data Loading	0.18	0.31	0.53	0.62	0.77
Clustering	0.90	1.78	2.65	3.02	3.91
Calculation and Filtering	0.65	1.33	1.93	2.79	3.13
Network Building	1.36	2.75	4.04	5.64	6.61
Statistical Data Calculation	3.36	6.70	10.21	13.41	16.22
Total	6.45	12.88	19.35	25.49	30.65

Table 1 Mexico taxi execution results. Execution times measured in seconds.

	250,000	500,000	750,000	1,000,000
Data Loading	9.63	16.44	24.08	31.58
Clustering	30.23	59.67	87.91	119.16
Calculation and Filtering	36.00	72.86	106.92	145.59
Network Building	69.88	140.52	207.71	279.83
Statistical Data Calculation	222.34	443.53	653.45	885.08
Total	368.08	733.02	1080.06	1461.24

Table 2 Porto taxi execution results. Execution times measured in seconds.

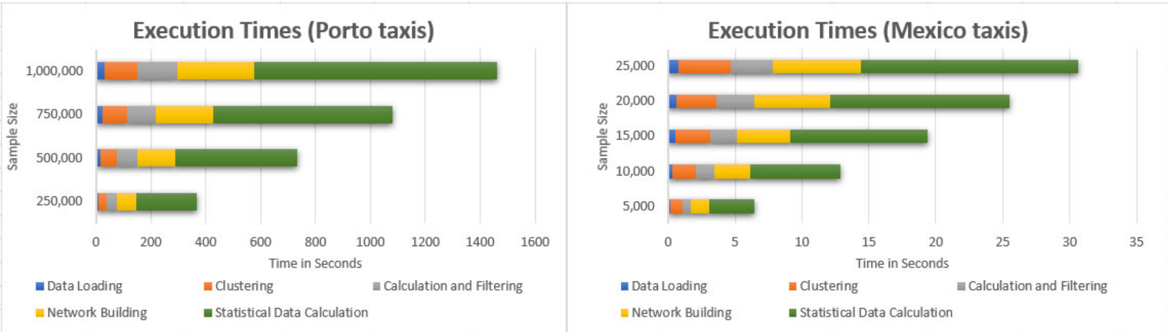

Figure 4 Graphs with the execution times of each experiment differentiating each part of the execution.

5. EXPERIMENT DISCUSSION AND LIMITATIONS

The graphs in Figure 4 show the results of the experiments, indicating the time measured in seconds, for each run and each part of the analysis. The overall time of the runs is linear, which makes it scalable. It can also be seen that all parts of the run maintain their proportionality within the same data set but vary slightly between the two sets. Finally, the runtimes for the network construction and the computation of the statistical data highlight significantly. Unlike the data loading and statistics calculation, which were optimised during the development of the program, these have not been yet optimised. These could probably be optimised or performed concurrently in the future to reduce the waiting time for the user.

The experiments are conducted with two datasets, which are limited to the mobility of two cities. This implies that only the behaviour at the urban level has been analysed. Therefore, we do not yet know the behaviour in other environments.

The application focuses only on data exploration tasks, which allows us to see the behaviour of the data over the time in which they were taken. This allows us to analyse changes in mobility in a simple way. This leads us to think that in specific contexts such as the data set used, it would allow us to make a short-term forecast of mobility.

6. CONCLUSIONS AND FUTURE WORK

The contribution has presented an application for urban traffic analysis. It is oriented towards raw route analysis and exploratory analysis. It is functional and can be used without programming skills.

The performance of the application with small to medium data sets is good using average hardware resources for computing. In the case of large datasets, the use of computing servers should be considered. In addition, the algorithms used show good scalability with linear growth.

The application has proven to be able to adapt to the data and does not need specific information from the environment in which the data was taken. Simply with low-level trajectory data the application can adapt itself to the contour of the city and to show a clear visualisation of the traffic.

The data displayed to the user on the map is clear, based on real traffic information and easily interpretable by any user. In addition, graphs and statistical tables help the user to put into context what is being visualised, giving an analysis of the characteristics of the dataset.

The complex network created from the clustering results is only used for the visual representation of the data. Moreover, it remains as a future line of work to exploit it to obtain information about traffic behaviour.

A future line of work is to improve the performance of those parts of the application that are no optimized yet, such as the calculation of statistical data. This part of the application could even be parallelised to be able to visualise the traffic status, even if this part has not yet finished executing.

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ESTUDIO DE LA CAPACIDAD EN ESTACIONES FERROVIARIAS: METODOLOGÍA PARA EL CÁLCULO TEÓRICO

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RESUMEN

Desde su aparición, el ferrocarril se ha caracterizado por ser el medio más eficiente para transportar tanto viajeros como mercancías a medias – largas distancias. Una de sus principales características, ser un transporte guiado que debe discurrir por una plataforma propia y especifica, hace que sean las estaciones, los nodos de transporte, los puntos donde se presentan fenómenos de congestión que van afectando con el tiempo al conjunto de la red. Actualmente los principales nodos de la red ferroviaria española, particularmente las estaciones de mayor afluencia de tráficos, muestran síntomas de saturación. Debido a esta situación, resulta de especial interés disponer de una herramienta que permita cuantificar la capacidad de estos nodos, entendida como el número de circulaciones que pueden ser atendidas en un periodo de tiempo, bajo unas condiciones de calidad y estabilidad, para dimensionar las insuficiencias de capacidad y proponer las soluciones más adecuadas para cada caso. Este estudio presenta un modelo de cálculo que permite determinar la capacidad de los nodos ferroviarios congestionados, particularmente de las estaciones ferroviarias con gran afluencia de tráficos.

Habitualmente, los estudios enfocados al cálculo de la capacidad de las estaciones han estado centrados en el análisis de las incompatibilidades entre circulaciones y la formación y propagación de retrasos. Sin embargo, en contraposición a estas aproximaciones, el modelo desarrollado se basa en las características de la infraestructura, de los servicios prestados y la experiencia de explotación, obteniendo con ello una aproximación flexible y aplicable a las diferentes configuraciones que presentan las distintas estaciones.

En una situación de congestión en las estaciones se hace necesario realizar actuaciones que permitan devolver a la normalidad la explotación de éstas. En este sentido, el modelo presentado provee de una herramienta de decisión que permite estudiar y optimizar la capacidad para las composiciones de tráfico existentes en las estaciones.. Esto se debe a que el modelo puede ser reconfigurado para cada caso en función de las características de las distintas actuaciones previstas.

1. INTRODUCCIÓN

El ferrocarril es un modo de transporte caracterizado por el seguimiento de un itinerario fijo, guiado y controlado, por lo cual es capaz de aportar una elevada capacidad de transporte, alcanzando elevadas velocidades de explotación sin que ello suponga un elevado consumo energético. Esta amplia capacidad de transporte hace que dicho modo sea propicio para un amplio espectro de aplicaciones, cubriendo desde el transporte a medias y largas distancias de mercancías y pasajeros hasta el transporte de pasajeros en las crecientemente congestionadas urbes. El ferrocarril juega, por tanto, un papel clave en el conjunto del sistema de transporte, por lo que es fundamental prever la saturación de los principales nodos de la red ferroviaria y hacer un análisis de la capacidad que estos son capaces de aportar.

Para comprender la situación actual del sistema ferroviario es necesario analizar su irregular evolución a lo largo del tiempo ya que, desde la puesta en servicio de la línea entre Liverpool y Manchester en 1830 y su consecuente rápida expansión a nivel mundial, la popularización del motor a combustión con el nacimiento del automóvil y la concatenación de guerras durante la primera mitad del siglo XX relegarían al ferrocarril a un segundo plano con gran parte de la infraestructura europea devastada. El inicio de la recuperación de la popularidad del ferrocarril vendría asociado al éxito inmediato de la alta velocidad en Japón. Este hecho derivaría en el inicio de distintos proyectos de alta velocidad a lo largo del mundo, y que en España se traduciría en la línea de Madrid - Sevilla en 1992.

El desarrollo de la alta velocidad ferroviaria española supuso un desafío tanto técnico como tecnológico. Para afrontarlo se hizo necesario mejorar las características de los elementos que condicionan la operación de los ferrocarriles: diseñar nuevos materiales móviles adaptados a las elevadas velocidades, establecer nuevas infraestructuras capaces de proveer de condiciones de circulación seguras y confortables (condicionadas por los mayores esfuerzos impuestos por el aumento de la velocidad), y desarrollar sistemas de protección que permitiesen asegurar la recepción e interpretación de las señales por parte de los maquinistas.

En España supuso la integración de una red ferroviaria de distinto ancho a la previamente establecida, por lo que su establecimiento ha requerido de infraestructuras específicas que han sido el resultado de la adaptación de las existentes o la nueva construcción en casos necesarios. Debido a la diferencia entre anchos de vía la red de alta velocidad tiene una permeabilidad muy limitada con la ya existente, que sólo se da en puntos específicos equipados con cambiadores de ancho de vía o vías de triple hilo adaptadas para la circulación de tráficos de ambos anchos. Dichos equipamientos se encuentran ubicados en el entorno de las principales estaciones de la red, donde conviven tráficos de ambos anchos de vía y se hace necesaria esta permeabilidad para favorecer la accesibilidad a la red de alta velocidad de tráficos que conectan núcleos de población en los que dicha red aún no ha sido desarrollada.

Con la adición de los cambiadores de ancho se produce la reafirmación de la importancia de las estaciones como nodos de la red ferroviaria. Sin embargo, el papel de las estaciones no se limita a este entorno, ya que componen el enlace necesario entre la realidad urbana y la red ferroviaria. Su impacto en el sistema de transporte de las ciudades en las que se enmarcan suele ser considerable: salvo en casos de nueva construcción, las estaciones se ubican en los sectores centrales de las ciudades, requiriendo una amplia reserva de terreno para su establecimiento y ampliación. Estas ubicaciones son privilegiadas, debido a que permiten atraer grandes volúmenes de pasajeros, lo cual hace necesaria una coordinación con el transporte público local que se suele traducir en el establecimiento de grandes nodos intermodales, indispensables para la movilidad diaria en las urbes.

La expansión de la intermodalidad con el modo ferroviario es una de las principales consecuencias de las políticas de transporte impulsadas desde la Unión Europea, encaminadas al impulso de dicho modo en un afán de promover la eficiencia de las redes de transporte de los Estados miembros. Entre estas políticas cabe destacar dos en el plano ferroviario: el establecimiento de una red ferroviaria interoperable y la liberalización de los servicios comerciales de viajeros y mercancías.

En España estas medidas se han adoptado mediante la creación de la red de Alta Velocidad con estándares interoperables y la segregación de Renfe (organismo público que ejercía las veces de operador y administrador de infraestructuras de forma simultánea), en Adif (como empresa administradora de infraestructura ferroviaria) y Renfe Operadora permitiendo con ello el concurso de diferentes operadores por los servicios comerciales.

Debido a la apertura del mercado de servicios comerciales de viajeros se hace necesario armonizar los tráficos a ofertar a los distintos operadores, por lo que la capacidad ferroviaria se debe cuantificar y adjudicar en función de los trayectos a realizar. Tradicionalmente esta capacidad ofertada se limitaba a la reserva del trayecto en las líneas ocupadas, sin embargo, una posible congestión de los principales nodos ferroviarios hace necesario coordinar dichas reservas con el estudio y la adjudicación de la capacidad disponible en aquellas estaciones consideradas como susceptibles de encontrarse saturadas.

Por tanto, el estudio de la capacidad de las estaciones ferroviarias se alza como una consecuencia del aumento de la demanda inducida por la liberalización de los servicios comerciales que introduce nuevos operadores en infraestructuras con una elevada exigencia de puntualidad. Este aumento de la demanda junto con el grado de saturación ya existente puede inducir fallos o errores que desemboquen en retrasos, los cuales a su vez son capaces de transmitirse de tren a tren. Este efecto produce la amplificación de los retrasos, provocando la saturación del nodo y, dependiendo de la importancia del nodo dentro de la red ferroviaria, la totalidad de líneas puede llegarse a ver afectada.

El presente documento es el resultado de una colaboración en forma de prácticas de empresa con Adif, en el contexto de la redacción de un trabajo de fin de máster en ingeniería de caminos, canales y puertos, por lo que los datos empleados para la calibración del modelo son resultado de la operación real y los resultados obtenidos han sido cotejados con la experiencia de explotación.

2. ESTADO DEL ARTE

El funcionamiento de las redes de ferrocarril requiere de una planificación exhaustiva y eficaz, necesaria para asegurar que los servicios prestados tengan unos altos estándares de calidad, medida en puntualidad y seguridad. En escenarios de elevada demanda la necesidad de planificación se intensifica, surgiendo la necesidad de estudiar la capacidad de los elementos de la red más afectados, estableciendo un techo operacional a la oferta planteada a los operadores de la red.

2.1 Concepto de capacidad

Pese a ser una variable clave en la administración de las redes ferroviarias, la capacidad no es un concepto fijo, variando entre los distintos actores del sistema ferroviario (planificadores de infraestructura, planificadores del servicio y operadores). Es por esta situación que, a fin de unificar el concepto, la UIC propone una definición basada en la contabilización del número de circulaciones que pasan por un tramo de red en un periodo establecido, bajo unas condiciones de circulación establecidas (International Union of Railways 2004). De esta forma se reconoce que la capacidad de la red ferroviaria es un ente de cuatro dimensiones, oscilando entre el número de trenes, la velocidad de circulación, la heterogeneidad de servicios y la estabilidad de la red.

Sin embargo, la definición realizada en dicho informe resulta ser insuficiente para la comprensión de la capacidad aportada por la infraestructura, resultando en la necesidad de categorizar la capacidad en función de las condiciones respecto de las que se calcula. En este sentido Abril, Barber, Ingolotti, Salido, Tormos y Lova (2008) definen las siguientes categorías de capacidad:

- Capacidad teórica: representa el máximo número de trenes que podrían utilizar la infraestructura en unas condiciones matemáticamente perfectas, realizando suposiciones como que el tráfico es homogéneo. Por lo general suele constituir el límite superior de la capacidad, pues ignora las ineficiencias que surgen durante la operación real.
- Capacidad práctica: representa el número máximo de trenes que pueden utilizar la infraestructura en unas condiciones aproximadas a las de operación. Para ello se realizan unas suposiciones más realistas a las que emplea la capacidad teórica. En ciertas líneas adquiere una magnitud del 60 – 75 % de la teórica.

- Capacidad usada: representa el número de trenes que circulan realmente por la infraestructura. Es inferior o igual a la práctica.
- Capacidad disponible: diferencia entre la capacidad práctica y la usada.

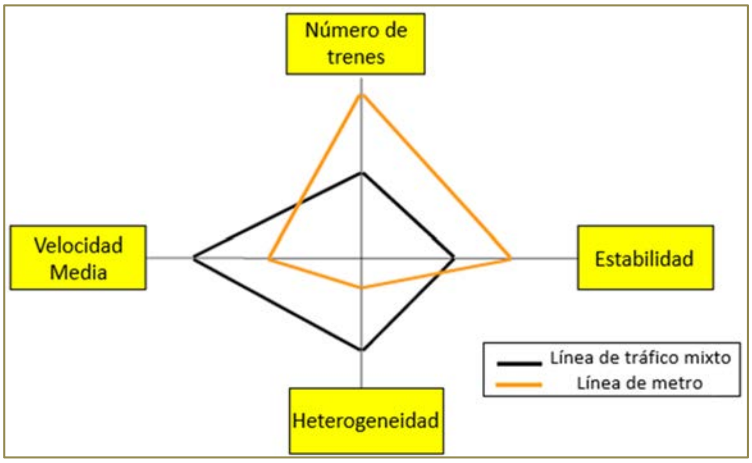

Fig. 1 - Factores que afectan a la capacidad (International Union of Railways 2004)

Estas definiciones se establecen para el estudio de la capacidad de las líneas, que ha sido el objeto tradicional de los estudios de la capacidad ferroviaria, por lo que Liu, Han y Li, (2012) definen la capacidad pasante. Dicha capacidad queda establecida como el número de trenes que se reciben y parten de una estación en un periodo de 24 horas, limitados por las condiciones de operación y de la infraestructura. De esta forma la capacidad aportada por una estación queda limitada por las restricciones impuestas, no sólo por la capacidad inherente a la infraestructura que compone la estación, sino también por la operación a la que se encuentra supeditada y la cual se ha de coordinar con el resto de la red.

2.2 Modelos de capacidad

La determinación de la capacidad y la planificación de su ampliación, son puntos clave en la gestión de las redes ferroviarias, adquiriendo mayor relevancia conforme aumenta la complejidad y la demanda en el sistema ferroviario (Burdett, 2015). El estudio de la capacidad de la red ferroviaria se ha orientado tradicionalmente al estudio de la capacidad de aquellos corredores ferroviarios en los que se detecta una dificultad a la hora de programar circulaciones. Junto con estas líneas de la red, las estaciones han sido tradicionalmente consideradas como generadoras de cuellos de botella (Yuan y Hansen, 2007; Carey y Carville, 2003), pero el estudio de su capacidad ha sido abordado en menor medida. La determinación de la capacidad se aborda mediante la modelización de esta, siendo el modelo más comúnmente empleado en el entorno europeo el establecido por la International Union of Railways (International Union of Railways, 2004; International Union of Railways, 2013). Cabe destacar que, tal como establecen Malavasi, Molková, Ricci y Rotoli (2014), los modelos empleados en la determinación de la capacidad se pueden clasificar a grandes rasgos en dos categorías:

- Analíticos: emplean fórmulas matemáticas generalistas para obtener información y resultados aproximados que puedan ser usados como referencia.
- Simulaciones: permiten obtener una aproximación más precisa de la realidad, replicando las condiciones de la vía. Sin embargo, pese a dar una información más precisa, requieren de definiciones detalladas de los equipos de vía.

Los métodos basados en simulaciones se pueden diferenciar en función del ámbito de aplicación: los modelos microscópicos permiten simular la operación de la estación (Han, Yue, y Zhou, 2014), pudiendo llegar a incluir el impacto de los retrasos y su propagación a lo largo del horario de servicio, cuyo impacto en la determinación de la capacidad ha sido estudiado por Zieger, Weik, y Niessen (2018). Por otra parte, los modelos macroscópicos y mesoscópicos permiten emular y validar las condiciones de funcionamiento de una red; permitiendo los mesoscópicos modelizar puntos clave, como pueden ser los cuellos de botella, con características propias de los microscópicos (Shi, Zhao, Yang, Guo, Zhang, y Feng, 2020) a mayor coste computacional.

La principal ventaja que poseen los modelos analíticos reside en su capacidad de aportar resultados significativos sin tener que recurrir a la simulación, incurriendo, por tanto, en menores costes (Hansen y Pachl, 2008). Los modelos analíticos han evolucionado con el paso del tiempo, pasando de considerar únicamente las incompatibilidades entre movimientos en un nodo, a integrar la teoría de colas y modelos probabilísticos, aumentando su potencia conforme los medios computacionales se han desarrollado (Malavasi et al 2014). En este sentido los modelos analíticos, al permitir realizar una aproximación teórica y puramente matemática, son más adecuados para aplicarse en fases de planificación de infraestructuras. Estos estudios se fundamentan en la optimización de distintas variables de la operación de la estación, como pueden ser las secuencias de tráficos que pasan por la estación (Jovanović, Pavlović, Belošević y Milinković 2020). Así mismo, estos modelos se pueden complementar con métodos de simulación que permitan su validación (Altazin, Dauzère-Pérès, Ramond, y Tréfond, 2020) o su inclusión en una red de mayor entidad. Debido a su naturaleza matemática, el análisis de la sensibilidad de las variables de las que parten estos modelos aporta una herramienta para la toma de decisiones en la expansión de la capacidad (Bevrani, Burdett, y Yarlagadda, 2017).

Como se ha expuesto, la capacidad ferroviaria es un concepto esquivo que varía en función del entorno en el que se considere y de la metodología empleada para su determinación, pero no sólo puede verse afectada por estas variables: El contexto de administración y operación de la infraestructura también resulta determinante. Tal como exponen Pouryousef y White, (2013), las condiciones de contorno del sistema ferroviario varían de una forma muy significativa en los entornos estudiados (Europa y Estados Unidos), resultando en concepciones y metodologías diferenciadas para la determinación de la capacidad. Estas caracterísitcas, reflejadas en la Fig. 2, han propiciado que en estos dos entornos característicos exista una diferenciación clara entre los métodos de determinación de capacidad: En Europa, los estudios de capacidad realizados dependen ampliamente de simulaciones tanto de tráficos como de horarios gracias a la disponibilidad de software como RailSys y OpenTrack, pudiendo combinarse estas simulaciones con métodos analíticos; mientras que en Estados Unidos, debido a su operación no dependiente de horarios, las modelizaciones realizadas dependen de la simulación de los tráficos y, en mayor medida, de métodos analíticos (Pouryousef, Lautala y White, 2015).

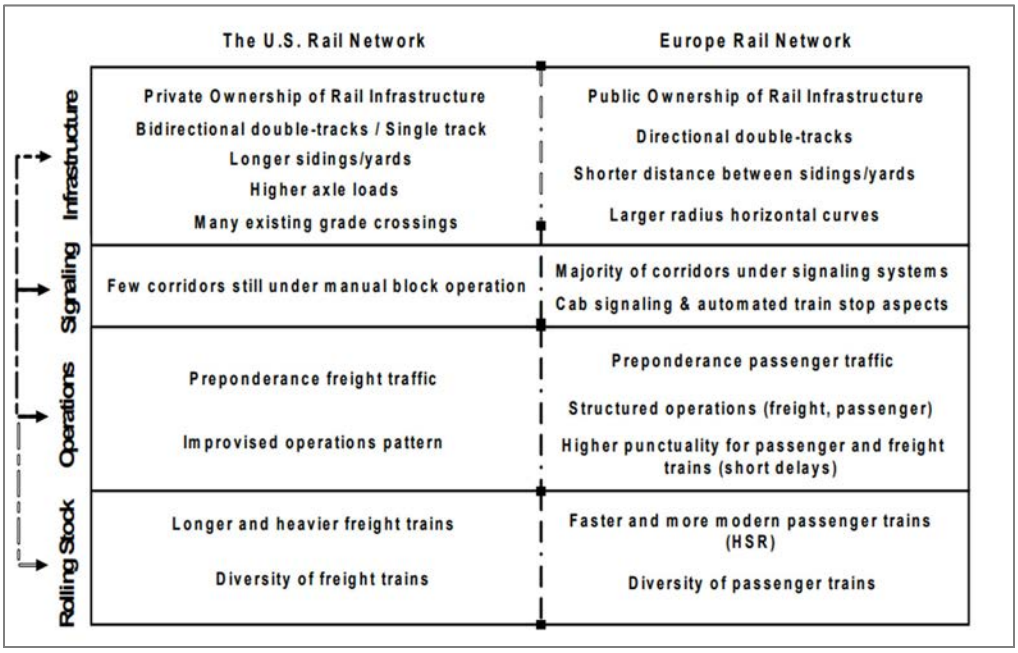

Fig. 2 – Principales diferencias entre los sistemas ferroviarios europeos y de Estados Unidos (Pouryousef y White, 2013).

3. METODOLOGÍA PROPUESTA

Ante la reconocida situación de saturación de los nodos más importantes de la red ferroviaria española se hace necesario estudiar la situación actual y los posibles escenarios derivados de ésta. El estudio de la capacidad asociada a una estación ferroviaria conlleva el estudio de su contexto, su operación y sus características físicas, por lo que resulta necesario desarrollar una metodología que permita establecer dicha capacidad de forma uniforme para los casos presentados, a la vez que conserve una flexibilidad suficiente para reconocer y adaptar sus particularidades.

3.1 Definición de capacidad

Como base la metodología empleada para la determinación de la capacidad de las estaciones ferroviarias se ha establecido el concepto de capacidad definido en las Fichas UIC 406: el número total de trenes que pasan por un tramo de vía en un periodo de tiempo determinado, con una calidad de servicio adecuada y considerando tanto el trayecto empleado como las condiciones establecidas por el administrador de infraestructuras (International Union of Railways 2004).

La definición establecida se hace extensiva tanto para los tramos de vía individuales como para los nodos que formen parte de una red ferroviaria, sin embargo, para su aplicación a las estaciones ferroviarias se va a considerar una puntualización a dicha definición, contabilizando el número de circulaciones comerciales capaces de ser operadas en un periodo de tiempo en las vías de estacionamiento. Esta modificación se sustenta en el hecho de que el complejo de una estación puede poseer vías pasantes por las cuales circulen trenes que no se vean condicionados por el funcionamiento de la misma, no realizando parada y siendo de paso prioritario, por lo que es poco común que sean cizallados (cruces al mismo nivel) por tráficos procedentes de la estación.

La adopción de esta definición conlleva una serie de consideraciones, ya que como se reconoce en la ficha UIC 406 (International Union of Railways 2004), la capacidad ferroviaria es un ente de cuatro dimensiones, interviniendo no sólo el número de trenes, sino la velocidad, la estabilidad y la heterogeneidad. Debido a que tres de estas dimensiones quedan fuera de la cuantificación de la capacidad, se hace necesario integrarlas en el modelo, con el objetivo de que éste sea lo más fidedigno con la realidad presentada en la operación normal.

3.2 Caracterización del tráfico

El tráfico ferroviario que solicita una estación es una pieza clave de la concepción de la metodología al ser el objeto del estudio para la determinación de la capacidad. La modelización del mismo ha de reflejar la heterogeneidad operativa que puede introducir en la estación de estudio, pudiendo variar tanto cuestiones ligadas al propio material móvil, como la longitud, la electrificación o el ancho de vía para el que se encuentran dispuestos (o la capacidad de cambiarlo); como características ligadas a la explotación: el número de circulaciones comerciales que son prestados por una composición a su paso por una estación, si pueden acoplarse/desacoplarse con otros materiales, o si la parada que realizan se produce por cuestiones comerciales o técnicas.

La definición de capacidad adoptada permite homologar los criterios de capacidad contabilizada en líneas a estaciones, pues si bien la definición clásica indica el número de trenes que pasan por una sección de vía, estos trenes a su paso por dicha sección, se encuentran prestando un servicio comercial con un origen y un destino definidos, por lo que se pueden identificar como circulaciones comerciales. La modificación se sustenta en que, si bien una estación puede ser origen o destino de circulaciones, ello no conlleva que sean el origen o el destino final del tren (entendido como el material móvil que presta servicios comerciales), ya que éstos pueden realizar operaciones de rotación, prestando con ello servicios comerciales distintos respecto del prestado al ingresar a una estación. En este sentido, en el presente documento, se referirá un material móvil de distinta forma en función de sus acciones.

- Movimiento: se refiere a la acción de desplazamiento de un material móvil, pudiendo relacionar vías de estacionamiento con vías de apartado, el acceso de la estación u otras vías de estacionamiento. Forman parte de una circulación.
- Circulación: se refiere a la marcha de un tren entre un origen y un destino determinados, prestando un único servicio. Aquellas circulaciones que presten un servicio comercial serán las que permitan definir la capacidad de la estación.
- Tren: se refiere al material móvil, puede prestar múltiples servicios comerciales dependiendo de la ventana temporal observada.

Debido a que la capacidad pasa de ser cuantificada como el número de trenes que pasan por un tramo de la infraestructura en un periodo de tiempo establecido, a la cantidad de circulaciones comerciales que pueden ser prestados en la estación (o la cantidad de trenes que pueden ser operados) en un periodo de tiempo establecido, se hace necesario analizar el tiempo de ocupación de las vías de la estación que es requerido por el tráfico. Debido a que el conjunto del tráfico es heterogéneo respecto a las necesidades de parada de cada circulación planteada, la modelización del mismo requerirá la caracterización de las circulaciones en función de la ocupación de las vías del conjunto de la estación y de la proporción en que se dan.

Así mismo debe de acotarse el periodo temporal en el cual se van a producir los tráficos que van a ser contabilizados. Este período temporal se corresponde con el horario de circulación de los trenes, que contempla dos horas adicionales al horario de servicio contemplado en la Declaración de la Red, de 6:00 a 22:00, de forma que se permita finalizar las circulaciones planteadas al final del mismo y que finalicen su recorrido antes de las 24:00.

Cabe destacar que la consideración de la definición de capacidad adoptada excluye una tipología de movimientos: aquellos que son necesarios para la correcta operación de los tráficos en las estaciones, pero que no forman parte de una circulación comercial. Estos movimientos relacionan la estación con vías de apartado o instalaciones designadas para el estacionamiento y/o mantenimiento de los materiales móviles, donde se realizan de forma parcial o total las operaciones requeridas para la puesta en servicio del material móvil. Estos movimientos se contemplan de forma indirecta, asociándolos a la circulación comercial anterior o posterior que realiza el material móvil.

3.3 Caracterización de la infraestructura

Las estaciones ferroviarias, al igual que en el caso del tráfico, distan de ser homogéneas para cada caso de estudio. En este sentido, las diferencias principales vendrán inducidas por la disposición de las vías, las cuales se pueden diferenciar en tres categorías similares a las establecidas en la ficha UIC 406 (International Union of Railways 2004):

- Vías de acceso: permiten, mediante aparatos de vía, distribuir los trenes entre las distintas vías que conforman el nodo. Un nodo puede tener una o dos zonas de cambio, pudiendo distinguirse con ello dos disposiciones de nodo, el fondo de saco y el pasante.
- Vías de estacionamiento: en las que los trenes pueden realizar las operaciones que requieran, pudiendo variar desde la marcha normal al estacionamiento por razones de limpieza, catering o embarque/desembarque de viajeros.
- Vías de apartado: vías en las cuales un tren puede estacionar pero que no se encuentran conectadas a la terminal de viajeros de la estación. Dependiendo de las características del equipamiento que posean, se podrá dar determinados servicios a los trenes que en ellas se encuentren estacionados. Estas vías no se encuentran diferenciadas como tal en la ficha UIC, pero de encontrarse en el complejo de la estación, permiten acortar el estacionamiento de determinados tráficos en las vías de estacionamiento.

La ocupación de las vías contabilizada para cada circulación será la total, siendo necesario realizar una simulación de marcha desde la señal de entrada de la estación. La caracterización del tiempo de ocupación para cada circulación considerada será el resultado de añadir el tiempo resultante de la marcha a la ocupación de las vías realizada en función de los servicios requeridos en cada caso.

Las características del conjunto de las vías de la estación pueden no ser homogéneas, pudiendo variar su longitud de estacionamiento, la longitud de andén, la electrificación, el ancho con el que se encuentran dispuestas o pudiendo prestar servicio a una composición de circulaciones distinta al resto de vías. Por estas razones será necesario segregar las vías en conjuntos de características similares. La capacidad del conjunto de la estación será el resultado de agregar la capacidad aportada por las distintas agrupaciones de vías que hayan sido consideradas.

En la operación de las propias estaciones se pueden encontrar aparatos de vía que permiten dinamizar la gestión de los tráficos, permitiendo dar servicio a un mayor número de circulaciones de forma simultánea. Los aparatos de vía que se pueden encontrar en las estaciones y que se emplean para este fin son los bretelles, que conectan dos vías paralelas mediante cuatro desvíos simples; y los escapes, que se componen por dos desvíos sencillos y conectan dos vías paralelas en forma de cruz de San Andrés, conformando un escape doble que enlaza dos vías paralelas en ambos sentidos. Se compone por dos diagonales de carriles diferentes superpuestos, contando con una zona singular en la parte central donde tiene lugar la intersección de las dos vías desviadas.

El principal beneficio de los aparatos de vía es que permiten dotar a la infraestructura de una gran flexibilidad de operación, permitiendo cambiar de una vía a la adyacente en los cuatro sentidos de la circulación, todo ello minimizando el espacio ocupado. Su implementación en las vías de estacionamiento de una estación permite dividir dos vías paralelas en cuatro sectores de operación, en los cuales se puede dar servicio de forma individualizada a distintos servicios. Si las vías se disponen en fondo de saco (sólo poseen un acceso) de los cuatro sectores sólo podrán emplearse tres de forma simultánea (dos orientados a las toperas y uno orientado al acceso), dejando el cuarto libre para permitir la salida de todas las circulaciones una vez éstas hayan terminado de realizar las operaciones requeridas. En caso de que las vías de estacionamiento se encuentren dispuestas de forma pasante (pudiendo acceder a ellas desde cualquier sentido de la circulación), se podrían operar hasta cuatro circulaciones de forma simultánea (una por cada sector de vía disponible), sin embargo se trata de un régimen de funcionamiento inestable que no se puede prolongar demasiado en el tiempo (debido a los tráficos pasantes a la estación deben ser acomodados en otras vías en la mayoría de los casos), por lo que lo normal es establecer su funcionamiento dejando un sector libre. La principal ventaja de los bretelles frente a los escapes es que permiten alternar el sector libre, mientras que en los escapes, este sector es fijo.

3.4 Determinación de la capacidad

De manera análoga a lo establecido por Abril et al. (2008), la capacidad teórica puede definirse como el máximo número circulaciones a las que se pueden dar servicio en las vías de estacionamiento de la estación en unas condiciones matemáticamente perfectas. Para su cálculo se requiere caracterizar la estación, estableciendo las vías de estacionamiento y los aparatos de vía que permitan ampliar la capacidad de las vías en las que se encuentren; así como el estudio del tráfico y la ocupación que requiere.

Una vez caracterizado el tráfico que soporta la estación, pormenorizado para cada vía, se procede a agrupar dichas vías en función de sus características, tanto físicas como de demanda. En función de dichas características, se establece la capacidad aportada por cada vía tipo, partiendo de la ocupación requerida por cada servicio planteado y en la proporción determinada que caracterice su tráfico distintivo. Cabe destacar que entre las distintas tipologías de tráfico planteadas pueden encontrarse aquellas que realicen dos servicios independientes entre sí, pudiendo llegar a ser predominantes en las estaciones dispuestas en fondo de saco o que sean el origen o el destino final de los servicios comerciales. Para estos casos la capacidad consumida por cada circulación será la mitad de la consumida por la estancia total del tren.

Una vez obtenida la composición del consumo del tiempo del periodo considerado, establecido en una hora, a su vez determinada por la composición del tráfico considerado para cada vía tipo considerada, se puede determinar la capacidad teórica aportada agregando las distintas capacidades establecidas por cada tráfico y cada conjunto de vías considerado.

Debido a que la capacidad calculada no refleja la capacidad que puede ser operada en la estación, es necesario realizar consideraciones adicionales. El cálculo de la capacidad teórica asume que los tráficos prescritos para cada vía podrán sucederse sin interferir entre sí, por lo cual, la primera consideración debe reflejar el impacto sobre la capacidad que tienen las condiciones de acceso a cada conjunto de vías considerado. Aplicando esta restricción se obtendrían el número máximo de trenes que se podrían operar en la estación, sin embargo, debido a que las estaciones se encuentran sujetas a unas condiciones de funcionamiento garantes de estabilidad, la capacidad que se puede ofertar a las empresas ferroviarias y operadores que en ellas planteen servicios comerciales debe ser estrictamente menor a la resultante del cálculo.

4. MODELO EMPLEADO

La aplicación de la metodología propuesta a un caso práctico se ha realizado mediante el modelo a continuación presentado y resumido en la figura 3. Este modelo, presentado de forma teórica, se ha usado para determinar la capacidad de varios casos de estudio en la red ferroviaria española.

4.1 Cálculo de la capacidad teórica

Como paso previo para determinar la capacidad teórica de la estación se deben definir tanto la infraestructura que la conforma como los tráficos que la solicitan. La caracterización de la infraestructura se puede realizar mediante un esquema de vías, al cual se agregará la información pertinente (datos que permitan la descripción de las vías, tales como el ancho de vía, la longitud de vía, la longitud de andén, la tensión de electrificación…), en función de la cual se agrupan en conjuntos de vía. Para cada conjunto de vía se establece un tiempo de acceso medio, que puede determinarse mediante una simulación de marcha, debiendo realizar un estudio del cizallamiento para aquellos trayectos que puedan verse afectados.

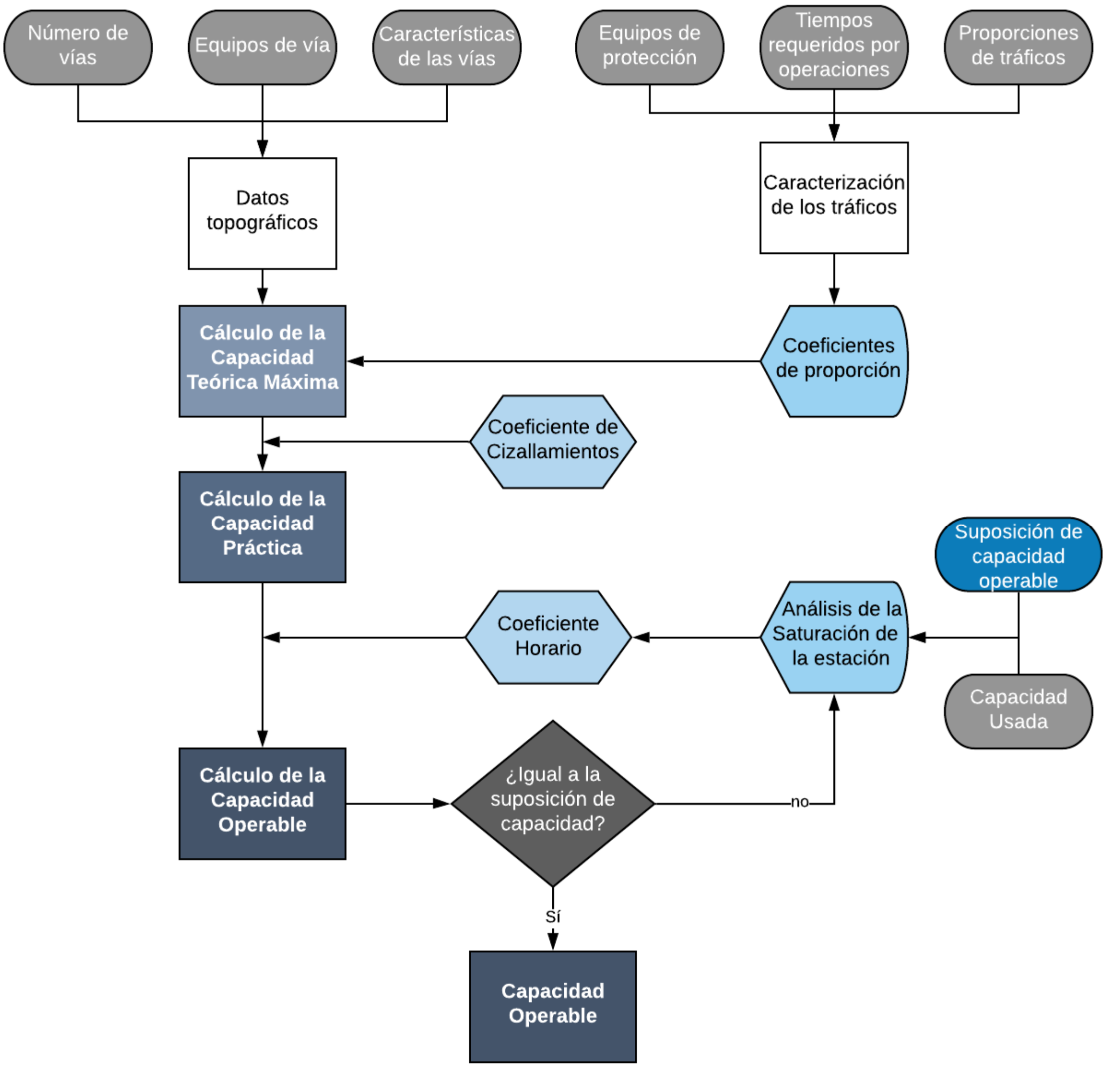

Fig. 3 – Diagrama de flujo del modelo propuesto. (Elaboración Propia)

La caracterización de los tráficos se realiza mediante la observación de las circulaciones que utilizan la estación, en una semana que se considere representativa del funcionamiento normal de ésta. Debido a que el registro de las paradas que realizan las circulaciones refleja aquellas asociadas a las que se realizan por motivos comerciales o técnicos, dicho registro puede resultar insuficiente al no representar el total de las paradas que puede realizar un tren en una estación. La parada no representada es aquella que se realiza al iniciar o finalizar un servicio, pudiendo relacionar dos servicios comerciales o un servicio comercial y un movimiento no comercial a vías de apartado o bases de mantenimiento cercanas. Para el correcto estudio de la ocupación de las vías se debe recurrir a los denominados como Gráficos de Ocupación de Vías (GOV), que permiten visualizar la ocupación de las vías de la estación producida por los trenes. Así mismo, combinando estos documentos con el esquema de vías de la estación se pueden comprender las operaciones de coordinación de tráficos que lleva a cabo el administrador de infraestructuras.

El tiempo de ocupación que requiere cada tren, las circulaciones y los movimientos comerciales serán las variables principales que permitan determinar la composición de tipologías de trenes que utilizan la estación. Una vez determinadas estas tipologías los GOV permiten adicionalmente realizar una segunda fase del agrupamiento de las vías de estacionamiento, estableciendo con ello aquellas que poseen tanto unas características físicas como una composición de circulaciones similares. Este segundo agrupamiento puede realizarse con los propios registros de circulaciones de la estación si a éstas se les ha agregado la vía de estacionamiento real. Con esta información podemos clasificar de forma general los trenes en las siguientes categorías:

- Rotaciones: Son trenes que llegan a la estación prestando un servicio comercial, realizan una parada destinada a la puesta en servicio del tren, realizando operaciones de limpieza, catering…, tras las cuales se procede al embarque de viajeros y parten de la estación prestando un servicio comercial independiente del inicial. Debido a ello, un tren produce dos circulaciones comerciales, que a su vez implican dos movimientos, también comerciales.
- Pasantes: Son trenes que llegan a la estación prestando un servicio comercial y que, tras una parada por razones técnicas o comerciales, parten de la misma prestando el mismo servicio. Por ello, un tren produce una circulación comercial que se traduce en dos movimientos, también comerciales.
- Materiales vacíos: Son trenes que llegan o parten de la estación prestando un servicio comercial, realizando un movimiento complementario (de acceso o salida de las vías de estacionamiento) no comercial, conectando la estación con talleres o vías de apartado. Estos trenes producirán, una circulación comercial y dos movimientos, de los cuales uno de ellos es comercial.
- Acoplados: Son trenes que se encuentran compuestos por dos circulaciones que al llegar a la estación se unen o separan, de forma que una de las circulaciones tiene origen o destino la estación mientras que la otra se comporta como un tren pasante. Por ello, un tren producirá dos circulaciones, ambas comerciales y tres movimientos, también comerciales.

Una vez determinados los conjuntos de vía a analizar y las tipologías de trenes que van a caracterizar el tráfico que las ocupa, se calcula su frecuencia de paso y un coeficiente de ajuste de proporción. Este coeficiente tiene como objetivo establecer el porcentaje real observado de cada tráfico para cada conjunto de vía, permitiendo obtener con ello, los tiempos que de media se consumen por cada circulación en una hora y para cada grupo de vía analizado. Estos tiempos permiten caracterizar la ocupación media que realizaría cada tipología de tráfico en una hora y con ello, las circulaciones que dicha tipología aportaría a la capacidad máxima de las vías estudiadas. La capacidad máxima, por tanto, se calcula en dos fases: en primer lugar, se agrega la capacidad aportada por cada tráfico a la vía tipo de cada conjunto de vías, lo cual permite obtener fácilmente la capacidad aportada por cada grupo de vías. Una vez se ha obtenido la capacidad aportada por cada conjunto de vías, estas capacidades se agregan dando como resultado la capacidad teórica, la máxima a la cual la estación podría dar servicio en unas condiciones ideales.

4.2 Capacidad Práctica y Capacidad Operable

Como se ha establecido el cálculo de la capacidad teórica no resulta representativo de la capacidad que se puede o podría operar en unas condiciones de funcionamiento normales de la estación. Esto se debe a que el cálculo realizado se basa en la suposición de que una vez la vía queda libre otro tren entra para ocuparla, lo cual, pese a poder establecer un margen de tiempo por razones de seguridad, no resulta representativo al no contemplar las posibles incompatibilidades en los trayectos generados por los distintos movimientos requeridos por el conjunto de vías consideradas. Estas incompatibilidades derivan principalmente de la disposición de la playa de vías, que establece las condiciones de acceso a los sectores considerados y particularmente, los tráficos que quedan cizallados entre sí.

A fin de reflejar el impacto que la disposición de las vías de acceso tiene sobre la capacidad se determina el coeficiente de cizallamiento. Dicho coeficiente representa el número de trenes retrasados, cuyo tiempo de ocupación de vía es mayor al estrictamente necesario para realizar las operaciones por cuestiones de indisponibilidad de itinerario. De forma similar a lo establecido por Abril et al. (2008), dicho coeficiente reductor adquiere valores comprendidos entre 0,6 y 0,8 dependiendo de la topología y de las condiciones de explotación de la estación, pudiendo llegar a discriminar el uso de determinadas vías para evitar interferencias entre tráficos. La aplicación de dicho coeficiente a la capacidad máxima teórica permite obtener la capacidad práctica de la estación, representando la capacidad que se podría operar en condiciones máximas, bajo la operación y coordinación de tráficos del día medio.

Tal como se ha establecido, las condiciones de operación de una estación se encuentran sujetas a unas condiciones que han de ser garantes de la estabilidad del servicio, por lo que establecer la capacidad máxima de la estación como la capacidad práctica puede resultar poco representativo de cara al cálculo del estado de saturación de la estación. Debido a ello se introduce el concepto de capacidad operable.

La capacidad operable permite reflejar el funcionamiento de la estación sometida a las condiciones de operación medias. Para ello se estima la ocupación media, que se define como la media de la tasa de ocupación horaria de las vías en un día medio. Se debe a la necesidad de reflejar en el modelo que no todas las horas estarán sujetas a la misma demanda por parte de los operadores. Esta diferencia de demanda permite clasificar las horas de operación en horas valle y horas punta, adaptando como máximo de capacidad horaria la capacidad operable de la estación y la capacidad punta extraordinaria, respectivamente.

La capacidad punta extraordinaria se estima partiendo de los datos de operación de la estación. Mediante un análisis del número de trenes que la estación es capaz de operar en una hora se puede extrapolar o estimar, para un determinado intervalo de confianza la capacidad máxima en la estación. Con el objetivo de que la ley de capacidad sea continua, se establece un modelo de capacidad lineal, permitiendo reflejar cómo varía la saturación de la estación.

El grado de saturación se calculará en función de la clasificación de la hora en hora punta o valle. Para determinar dicha clasificación se comparará el número de trenes que circulan con el número máximo que puede circular por hora, si dicho cociente supera el umbral del 75% (utilizado en el Manual de Capacidad editado por Adif para establecer un tramo como congestionado) la hora se clasificará como punta, en caso contrario, como valle. Aplicando el grado de saturación obtenido a la capacidad práctica se obtiene la capacidad operable, la cual ha de coincidir con la capacidad tomada como base para el cálculo de la saturación. En caso de que no coincida, se debe iterar el proceso hasta llegar a la convergencia de ambos valores. Con el objeto de acelerar este proceso de convergencia, se adopta un factor de iteración igual a la media del valor supuesto inicialmente y el valor obtenido del proceso, llegando a la convergencia en el entorno de la sexta-octava iteración. Tal como se puede apreciar en la figura 4, emplear el valor obtenido puede llegar a suponer la necesidad de llegar a realizar del entorno de 40 iteraciones del proceso.

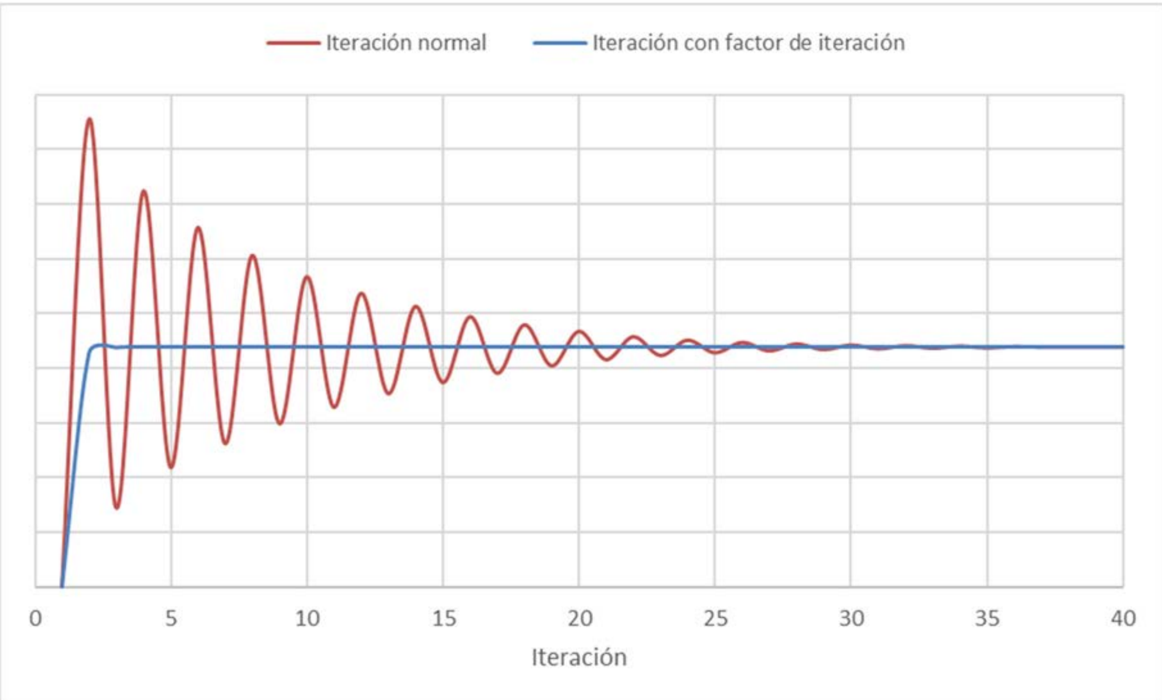

Fig. 4 – Convergencia del valor final de la capacidad operable. (Elaboración Propia)

Tomando como base el grado de saturación horario obtenido se calcula la capacidad operable aplicando la media de dichas saturaciones siempre que sea superior al 60%. En caso contrario la demanda de la estación no es suficiente para adoptar el resultado del estudio de saturación como válido, ya que la reducción consecuente de capacidad no resultaría representativa de la capacidad operable de la estación. De esta forma, el modelo empleado permite discernir entre aquellos casos en los cuales la estación no se encuentra saturada, con un coeficiente igual al 60%; aquellos que poseen una saturación moderada, adoptando un 60% - 75%; y aquellas con una saturación considerable, con un coeficiente superior al 75%.

Como se ha establecido, el tiempo de estudio para la determinación de la capacidad va a ser el del horario de circulación, de 6:00 a 24:00, sin embargo, el horario práctico en el cual una vía puede prestar servicio se puede encontrar limitado por distintos elementos. El principal factor que va a limitar el horario de circulación de las vías son los trenes que las ocupan desde su llegada a la estación, en horas cercanas a la finalización del horario de circulación, hasta su partida a la mañana siguiente, cuya hora puede superar la de inicio del horario de circulación. En estos casos, se dice que un tren duerme en la estación, y para contemplar su impacto en la capacidad, se restringe el horario de circulación en función de la estancia que produzca. De esta forma, las horas en las cuales un tren quede estacionado por estos motivos en una vía, no se tendrán en cuenta a la hora de contabilizar la capacidad aportada por la vía en condiciones de circulación. Así mismo, para contemplar su adición de capacidad, estos trenes se suman a la capacidad operable aportada por cada vía o conjunto de vías, ya que en el tiempo en el cual se encuentren estacionados, se producirá una única circulación comercial.

5. CONCLUSIONES

En general, los métodos aplicables para el cálculo de la capacidad ferroviaria, así como su gestión, se han centrado predominantemente en líneas. Los estudios de capacidad de las estaciones, de gran importancia sin embargo, han quedado relegados a un segundo plano, lo cual se puede asociar a la dificultad de ejecutar modelos basados en el estudio de las incompatibilidades entre tráficos y la generación y propagación de retrasos en nodos ferroviarios complejos. Los modelos comúnmente basados en la simulación microscópica de la estación añaden a la dificultad de la modelización de una estación el elevado coste computacional que suponen, por lo que la aplicación de modelos analíticos resulta más efectiva a la hora de determinar la capacidad global pese a su dificultad de adaptación a los distintos casos.

La metodología y el modelo de cálculo propuestos se basan en la experiencia de explotación y en la configuración de la infraestructura disponible en las estaciones. Estas dos bases dotan al modelo de una gran flexibilidad a la hora de considerar la heterogeneidad de los tráficos y las características particulares de cada caso al que sea susceptible de ser aplicado, pudiendo aplicarlo en concepto de simulación de forma que se puedan evaluar distintos proyectos orientados a la ampliación de la capacidad.

La principal ventaja de la metodología presentada es la facilidad que muestra para la adaptación entre los distintos casos estudiados, capaz de representar las variaciones de capacidad inducidas por distintas variables, como pueden ser la composición del tráfico o la disposición de la infraestructura. Cabe destacar así mismo, que la variable de cálculo empleada, las circulaciones comerciales, permite determinar unos cupos de capacidad, análogos a los surcos establecidos en líneas, por lo que permite a los administradores de infraestructuras dimensionar la oferta de capacidad segmentada en función de las características que estime.

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DIGITAL SOCIETY AS A DETERMINING FACTOR IN MOBILITY, URBAN DYNAMICS AND CURRENT CITIES STRUCTURE

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ABSTRACT

The development and evolution of the digital society has brought about relevant changes in the way people experience the city today. In particular, its impact on mobility patterns is evident, especially in the Post-COVID-19 society, where it is possible to access different types of daily activities online (e.g. working, shopping, training, etc.). At the same time, this digital era brings with it new challenges for urban and transport planning, in which information and communication technologies (ICT) can play a relevant role as transformers of traditional urban structures. For this reason, studying and understanding how the digital society is transforming current cities is important and necessary to optimize planning patterns/guidelines and achieve more sustainable and inclusive cities.

To address this challenge, this project has implemented multivariate statistical techniques to characterize the city of Madrid (Spain) at urban level, in order to detect the impact of ICTs on the current urban structure of the city. The methodology incorporated both factorial and cluster analysis with spatial restriction, based on a set of starting indicators referring to urban equipment, demography, socioeconomics, transportation, as well as variables of the digital society (e.g., electronic mailboxes-online commerce, free public and commercial Wi-Fi points, etc.).

The results, among other things, show an optimal classification grouping, as well as the way it was obtained. In this case, the optimal classification grouping is the one conformed by 6 clusters, in which different relationships were detected between the space built, the equipment and aspects of the digital society such as online shopping and the proximity to transport equipment public and physical commerce. These results support a growing influence of the digital society in the urban characterization, suggesting the need to translate this influence into effective planning criteria.

1. INTRODUCTION

The emergence of the digital era in society triggered an unprecedented explosion in the multiple ways in which people experience the city, giving a new direction to its development and modifying urban dynamics, mobility and spaces (Batty et al., 2012). In this sense, the UN´s Agenda 2030 considers digital tools as an essential means in the study and understanding of cities, as well as to promote socioeconomic development, protect the environment, modernize infrastructure and improve human progress (United Nations, 2015). For this reason, there is a tangible need for developing and implementing innovative solutions that use criteria related to digital society in the analysis of the urban form.

The notion of digital society proposes that network infrastructures, as well as information and communication technologies (ICTs), are capable of generating a large amount of data (Butot et al., 2020) and facilitating development processes. Therefore, they can be used to provide solutions to social, economic, urban and territorial challenges (Townsend, 2013) , which guide the progress and growth of cities. On the other hand, urban characterization, defined by its capacity to identify and classify urban typologies through various attributes related to the city, allows the elaboration of quantitative analyses with multiple variables (principal component analysis, factorial, cluster, etc.), using a large amount of information (Song & Knaap, 2007). As a whole, digital society and urban characterization, promote the idea that "increasingly complex" urban processes (Kitchin, 2016), can be made understandable by integrating both concepts. However, ICTs bring new challenges in the planning and development of cities, because by themselves, these new technologies aren´t able to solve problems in a simplistic way (Barbosa et al., 2020). This also generates several inconveniences (e.g. accumulation of power of those who generate and manage a high volume of data) (Sadin, 2013), therefore, their role is and will be fundamental as transformers of traditional urban structures (Elias B., 2020).

Although the impact of the digital society on the structure of cities has been an area of interest in academia in recent years, (Batty et al., 2012; Butot et al., 2020; Elias B., 2020; Reddy & Reinartz, 2017; Ricaurte-Quijano et al., 2017; Townsend, 2013) it has not been widely explored from perspectives of urban characterization through multivariate statistical methods. In previous researches on urban issues and mobility, characterization methodologies have been developed using multivariate analysis that have ignored issues related to the digital society. These methodologies have focused mainly on indicators related to the population structure and its relationship to the metropolitan phenomenon (Martori & Hoberg, 2008; Santos P., 1991; Teoh et al., 2020; Yeh et al., 1995). Other studies have used variables related to the urban built environment (Berrigan et al., 2010; Porta et al., 2006; Song & Knaap, 2007; Vandenbulcke et al., 2009). While some other authors have developed methodologies of multivariate characterization using indicators related to attitudes and urban activities of the population (Balram & Dragićević, 2005; Jacques & El-Geneidy, 2014; Jiang et al., 2012; Steiger et al., 2015). Finally, some have even incorporated attributes with the ability to measure social welfare (Romillo B, 2013).

Furthermore, the influence of digitalization on society has been analyzed from various points of view. The first of these, focusing on the availability and access of the population to the internet, from the logic of those who have it and those who do not (Chen, 2012; El Colegio de la Frontera Norte, 2018; *Schleife*, 2010). The digital society has also been studied through the implementation of ICT´s in the identification of urban activity patterns (location of places of shopping, leisure, employment, study, etc.) using data from social networks (Steiger et al., 2015). Moreover, many studies have been developed without criteria of contiguity, obtaining significant results in relation to the attributes used, but maintaining high levels of fragmentation in these results.

Therefore, the importance of urban characterization methodologies with the capacity to incorporate attributes related to the information society is fundamental. The objective of this study is to apply a quantitative method able to characterize through a multivariate and spatial analysis, the urban typologies affected by the digital society existing in the metropolitan area of the municipality of Madrid. For this purpose, sociodemographic and socioeconomic indicators were used, as well as variables of the built urban space and, specifically, criteria related to ICT´s and spatiality.

2. CONCEPTUAL FRAMEWORK

(Song & Knaap, 2007) emphasize the usefulness of identifying and classifying urban typologies, because this facilitates understanding by organizing ideas and characteristics into defined elements. Likewise, it allows the elaboration of quantitative analyses using a large amount of information, grouping it into a set of components. They also highlight the need to characterize these areas for the development and implementation of public policies. At the same time, (Wu & Sharma, 2012), (Song & Knaap, 2007), agree that in general terms, the classifications referring to the conceptualization of urban areas, are divided into two major categories.

2.1. Descriptive classification

The first category is known as descriptive, and is mainly based on spatial divisions that are readily available or prepared from visual interpretations of maps and images (Jones, Leishman & Watkins, 2005; Thibodeau & Goodman, 2007; Watkins, 2001). Satellite images have played a key role in descriptive characterization and have been used in various approaches. Tapiador, Avelar & Tavares-Correa (2011) applied this type of images to detect the urban morphology of an area of Lima, Peru and to classify it by relating this information to socioeconomic aspects, this allowed them to characterize large areas in social terms and map social inequality. Jun, Jinmei, Guoyu & Jizhong (2011) characterized an urban-rural region of Qingdao with the help of high-resolution satellite images under the criterion of land use properties (such as buildings, roads, pastures, farmland and water).

This type of descriptive characterization has been used in studies of the real estate market to spatially classify housing sub-markets under generic attributes, such as the census blocks into which the dwellings are grouped (Thibodeau & Goodman, 2007), postcodes (Jones et al., 2005) or the physical characteristics of the houses (Basu & Thibodeau, 1998; Watkins, 2001). However, there is a notable lack of descriptive characterizations based on attributes of the digital society (e.g. proximity of the houses to places with public internet access).

2.2. Multivariate classification

The second category is based on the interaction of data from different variables, where the growth of GIS tools and technical innovations has allowed statisticians to process a wide variety of quantitative attributes simultaneously. There are two variations in this category: without and with spatial restriction criteria.

2.2.1 Multivariate classification without spatial criteria

This first modality allows vast amounts of information and attributes to be covered without considering elements of contiguity, so the urban structure can be characterized from different perspectives, although not in a localized manner.

One perspectives is through the urban structure of the population and its relationship with the metropolitan phenomenon using socioeconomic variables and educational level, age indices, diversity and habitability indicators, and using factor analysis (FA), principal components analysis (PCA) and cluster analysis (CA). This reveals that the oldest and most educated population lives in the areas with the highest socioeconomic level (Martori & Hoberg, 2008; Santos P., 1991; Teoh, Anciaes & Jones, 2020; Yeh et al., 1995).

Likewise, urban characterizations have been studied using the built environment through building type indicators (size of homes, apartments and building, number of levels, building density, etc.), section widths, accessibility to public transport, etc. (Berrigan et al., 2010; Porta et al., 2006; Song & Knaap, 2007; Vandenbulcke et al., 2009). This group does not included any built-environment attribute related to the digital society either.

City characterizations have been developed with attributes associated with the population´s activities (work, study, leisure, etc.) and travel behavior using origin and destination indicators, travel distances, schedules, mode of transport, activities during the trip, etc. (Balram & Dragićević, 2005; Ettema & Verschuren, 2008; Jacques & El-Geneidy, 2014; Jiang et al., 2012; Steiger et al., 2015; Varghese et al., 2018). This type of study analyzes the relationship between the digital society and travel behaviour, but with the aim of identifying the influence of digital media on multitasking and rather than as an attribute for effectively contributing to urban characterization.

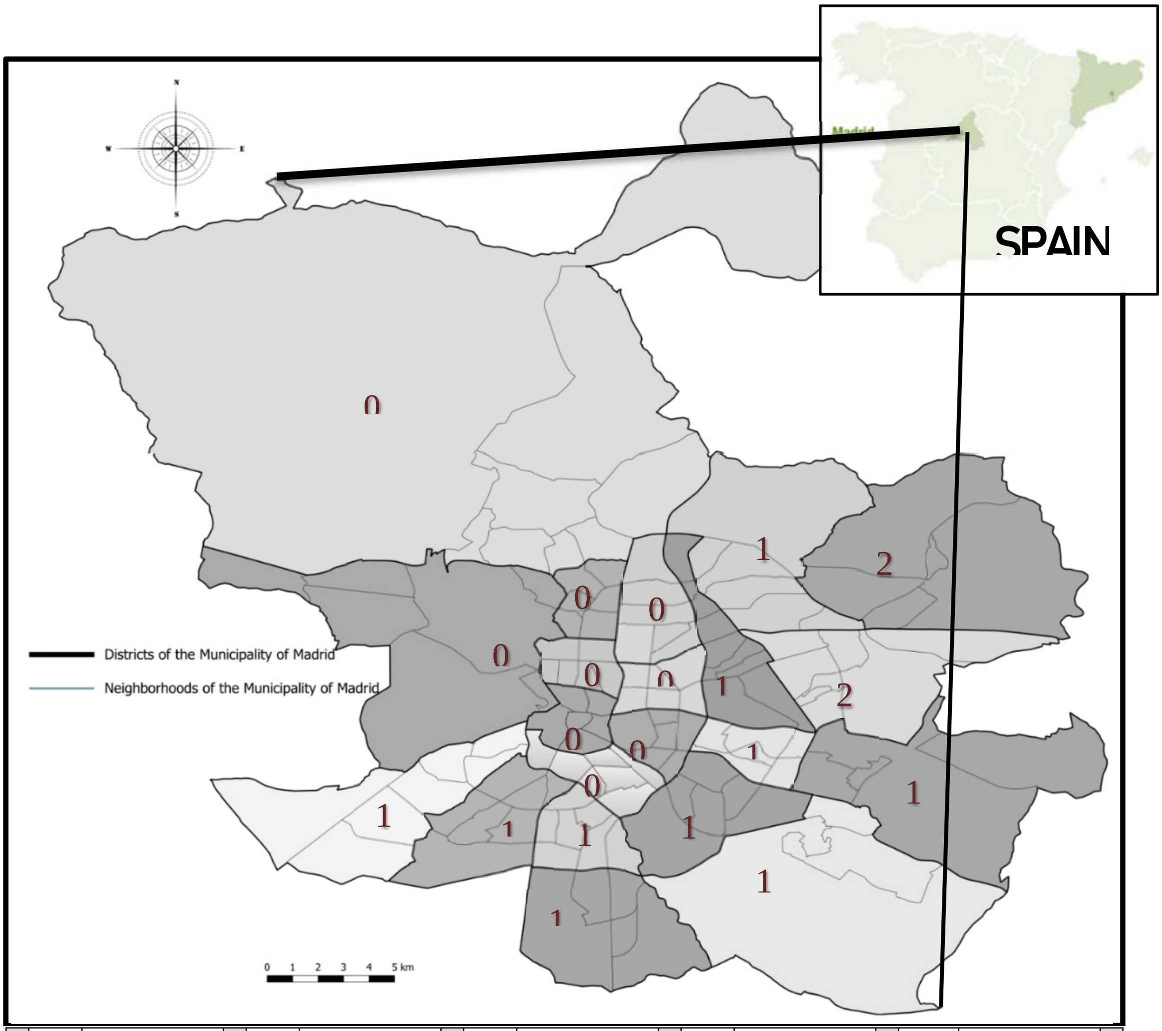
Some authors have used social indicators (percentage of active population and rates of: unemployment, divorce, infant mortality, life expectancy, etc.) in PCA and CA to group the sectors of an urban area according to territorial structures of social welfare (Romillo B, 2013), but without including parameters related to the digital society in their classifications.

Characterization with this technique has also been extremely useful in explaining the phenomenon or urban expansion, identifying sub-centers in urban areas (Cai, Huang & Song, 2017; Thomas, Riguelle & Verhetsel, 2007) and studying the effects of the compact vs. dispersed city (Thinh, Arlt, Heber, Hennersdorf & Lehmann, 2002). Or simply studying the phenomenon of sprawl by characterization the structure of the built environment and its connection with the growth of cities (Batty, Longley & Fotheringham, 1989; Piron, Dureau & Mullon, 2004).

2.2.2 Multivariate classification with spatial criteria

In the second mode, spatial restrictions can be incorporated simultaneously to the data being classified using criteria of location, distance or contiguity in the variables, or by including additional indicators that restrict the spatiality of the results.

Many studies incorporating contiguity restrictions have been undertaken in the real estate market, and include characteristics related to dimensions, costs, building heights, number of rooms etc. This allows similar areas to be identified and grouping geographically (Bates, 2006; Bourassa et al., 2007; Clapp & Wang, 2006; Tu, Sun & Yu, 2007; Wilhelmsson, 2004).



DIST.	NEIGHBORHOOD
01 CENTRO	011 Palacio 012 Embajadores 013 Cortes 014 Justicia 015 Universidad 016 Sol
02 ARGANZUELA	021 Imperial 022 Acacias 023 Chopera 024 Legazpi 025 Delicias 026 Palos de Morguer 027 Atocha
03 RETIRO	031 Pacífico 032 Adelfas 033 Estrella 034 Ibiza 035 Jerónimos 036 Niño Jesús
04 SALAMANCA	041 Recoletos 042 Goya 043 Fuente del Berro 044 Guindalera 045 Lista 046 Castellana
05 CHAMARTÍN	051 El Viso 052 Prosperidad 053 Ciudad Jardín 054 Hispanoamérica 055 Nueva España 056 Castilla
06 TETÚAN	061 Bellas Vistas 062 Cuatro Caminos 063 Castillejos 064 Almenara 065 Valdeacederas 066 Berruguete
07 CHAMBERÍ	071 Gaztambide 072 Arapiles 073 Trafalgar 074 Almagro 075 Ríos Rosas 076 Vallehermoso
08 FUENCARRAL-EL PARDO	081 El Pardo 082 Fuentelarreina 083 Peña Grande 084 El Pilar 085 La Paz 086 Valverde 087 Mirasierra 088 El Goloso
09 MONCLOA-ARAVACA	091 Casa de Campo 092 Argüelles 093 Ciudad Universitaria 094 Valdezarza 095 Valdemarín 096 El Plantío 097 Aravaca
10 LATINA	101 Los Cármenes 102 Puerta del Ángel 103 Lucero 104 Aluche 105 Campamento 106 Cuatro Vientos 107 Las Águilas
11 CARABANCHEL	111 Comillas 112 Opañel 113 San Isidro 114 Vista Alegre 115 Puerta Bonita 116 Buenavista 117 Abrantes
12 USERA	121 Orcasitas 122 Orcasur 123 San Fermín 124 Almendrales 125 Moscardó 126 Zofío 127 Pradolongo
13 PUENTE DE VALLECAS	131 Entrevías 132 San Diego 133 Palomeras Bajas 134 Palomeras Sureste 135 Portazgo 136 Numancia
14 MORATALAZ	141 Pavones 142 Horcajo 143 Marroquina 144 Media Legua 145 Fontarrón 146 Vinateros
15 CIUDAD LINEAL	151 Ventas 152 Pueblo Nuevo 153 Quintana 154 Concepción 155 San Pascual 156 San Juan Bautista 157 Colina 158 Atalaya 159 Costillares
16 HORTALEZA	161 Palomas 162 Piovera 163 Canillas 164 Pinar del Rey 165 Apóstol Santiago 166 Valdefuentes
17 VILLAVERDE	171 San Andrés 172 San Cristóbal 173 Butarque 174 Los Rosales 175 Los Ángeles
18 VILLA DE VALLECAS	181 C.H. de Vallecas 182 Santa Eugenia 183 Ensanche de Vallecas
19 VICÁLVARO	191 C. H. de Vicálvaro 192 Valdebernardo 193 Valderrivas 194 El Cañaveral
20 SAN BLAS-CANILLEJAS	201 Simancas 202 Hellín 203 Amposta 204 Arcos 205 Rosas 206 Rejas 207 Canillejas 208 El Salvador
21 BARAJAS	211 Alameda de Osuna 212 Aeropuerto 213 C. H. de Barajas 214 Timón 215 Corralejos

Figure 1. - Area of study – Municipality of Madrid

However, there are very few studies with the capacity to characterize urban areas incorporating spatial restrictions, and there continue to be considerable gaps in the methodology. As mentioned by Wu & Sharma (2012), authors that include spatial contiguity in their methodologies (Bates, 2006; Bourassa et al., 2007; Clapp & Wang, 2006; Tu et al., 2007; Wilhelmsson, 2004; Wu & Sharma, 2012), were successful in achieving some levels of restriction, although the groupings generated lack contiguous boundaries and their results didn´t coincide with the actual division of urban space. In addition, by focusing on spatial contiguity, the studies fail to highlight the importance of the attributes analyzed with respect to the complexity of the urban space (Wu, Wei & Li, 2019). This complexity is often addressed through features alien to the digital society, leading to significant gaps when incorporating spatial criteria and information society indicators.

This highlights the need for a feasible solution for the classification of urban areas, and suggests that an optimal procedure would strike a balance between the importance of emphasizing the required urban attributes (of the built space, the conditions and habits of the population and incorporating digital society variables) and including spatial restriction criteria. This balance would make it possible to achieve a homogeneous classification without mitigating the original attributes.

3. METHOD AND RESEARCH DESIGN

3.1. Case of study

The municipality of Madrid, in the metropolitan area of Madrid, Spain, was selected for this study (Fig. 1), as it is considered to fulfil many of the characteristics that exemplify the influence of the use of new ICT´s in Spain and Europe.

According to the survey *"Equipamiento y Uso de Tecnologías de la Información y Comunicación en los Hogares de la Comunidad de Madrid. TIC-H(2019a)"* 94.5% of the homes in this community had access to internet, and it is also in second place in the province of Madrid, in terms of internet users with 94.1% of people connected (Instituto Nacional de Estadística, 2019b).

In addition to this, a digital transformation has been developed in various areas of the urban structure of Madrid, with transport being one of the main ones by focusing its attention on four lines of action. The traveler´s experience, security, intelligent platforms and routes (automating a wide variety of services, and offering digitally information related to trips, waiting times, routes, etc.) and finally from the line of environmental impact, addressing urban space management strategies to reduce congestion and environmental pollution (Public Sector Observatory, 2018).

3.2. Description and data

Our analysis was performed using indicators from the municipality of Madrid, created according to the urban and digital characteristics of the study area, and classified into six groups as shown in Table 1.

VARIABLES			
GROUPS	**VARIABLE**	**No.**	**UNIT**
1.- Socio-demographic variables	Housing Density	**1**	(Inhab / dw)
	Employment Density	**2**	(Inhab/Emp)
	% of population without education	**3**	%
	% of population with "University Studies"	**4**	%
	% of population dedicated to the "Industry" sector	**5**	%
	% of population dedicated to the "Construction" sector	**6**	%
	% of population dedicated to the "Services" sector	**7**	%
	Housing rental levels by neighborhood	**8**	(Euros /m2)
	Housing price levels by neighborhood	**9**	(Euros /m2)
2.- Diversity Variables	Youth Index	**10**	Index
	Ageing Index	**11**	Index
	Index: Structure of the working population	**12**	Index
	Shannon Diversity Index	**13**	Index
3.- Design and urban structure variables	Density of public transport stops and stations	**14**	(Stops/1000inhab)
	Proximity of the population to public transport stops (bus, metro, suburban)	**15**	Distancia
	% of land use dedicated to "Residential"	**16**	%
	% of land use dedicated to "Green areas"	**17**	%
	% of land use dedicated to "Tertiary services"	**18**	%
	% of land use dedicated to roads (streets and sidewalks)	**19**	%
	Number of intersections per unit of analysis	**20**	No.
	Density of intersections per neighborhood	**21**	Intersec./1000inhab
4.- Physical commerce variables	Density of basic physical stores	**22**	Physical stores/1000inhab
	Proximity of the population to physical commercial activities of daily use	**23**	Distance
	Number of shopping centers per unit of analysis	**24**	No.
	Number of municipal markets per unit of analysis	**25**	No.
	Number of supermarkets per unit of analysis	**26**	No.
	Density of supermarkets per unit of analysis	**27**	Superm/1000 inhab
5.- Information society variables	Density of electronic mailboxes	**28**	Elec. Mail./1000 inhab
	Density of Free Public Wifi Points	**29**	(F.W.P. / 1000 inhab)
	Density of Commercial Public Wifi Points	**30**	(W.P.C./1000 inhab)
	Proximity of the population to electronic mailboxes	**31**	Distance
	Proximity of the population to free public wifi points per unit of analysis	**32**	Distance
	Proximity of the population to public wifi points of stores per unit of analysis	**33**	Distance
	Number of electronic mailboxes per analysis unit	**34**	No.
	Number of points with free public wifi per unit of analysis	**35**	No.
	Number of points with public wifi of stores per unit of analysis	**36**	No.
6.- Location variables	Distance to the centroid	**1**	Distance
	District of belonging	**2**	No.
	Geographic coordinates	**3**	Coordinates
	Cluster of belonging	**4**	No.

Table 1. - Variables

These variables were developed using the 131 neighborhoods in the 21 districts in the municipality of Madrid shown in Figure 1 as units of analysis. They were obtained with the help of different official databses, as well as various digital platforms (NOMECALLES, NavegaPorMadrid, GoogleMaps, QGis, etc.), websites of official national agencies or of the Madrid regional government (INE, website of the Madrid City Council and the Madrid Transport Consortium, the open data portal of the Municipality of Madrid, etc.), websites of stores, parcel services, supermarkets, tourism, digital services, among other sources.

A data based urban characterization model was applied through factor analysis (FA) and cluster analysis. This methodology without spatial contiguity parameters has been previously tested in several studies focused on urban structure and metropolitan phenomena (Jacques & El-Geneidy, 2014; Martori & Hoberg, 2008; Piron et al., 2004; Santos P., 1991; Song & Knaap, 2007; Thinh et al., 2002; Thomas et al., 2007; Yeh et al., 1995). Including criteria of contiguity and spatial constraints some of them, mainly focused on the analysis of the housing market (Bates, 2006; Bourassa et al., 2007; Clapp & Wang, 2006; Tu et al., 2007; Wilhelmsson, 2004).

4. RESULTS

4.1. Factorial analysis (FA)

The application of FA allowed seven factors to be extracted that can reproduce approximately 71% of the total variation of our original 36 variables, given their scores. Principal component analysis was used for factor extraction. Varimax with Kaiser Normalization was applied as the rotation method in the analysis, as this combination explains the greatest variation in the data by maximizing the loading squared for each component (Campos, Pitombo, Delhomme & Quintanilla, 2020; Khan, Ahmad & Bano, 2020; Wu & Sharma, 2012).

The results of the FA are shown in Table 2, where the variables are listed in the order of magnitude of their factor loadings sequentially for each factor. This shows the seven dimensions (factors) of the attributes originally proposed (socio-demographic, diversity, information society, etc.) resulting from the analysis.

The first factor reflects the dimension “*Information Society: Proximity and distribution of equipment*”. It mainly highlights the variables of the information society and then, those related to public urban equipment’s. The high correlation between ICT variables and public equipment’s (public transportation stops and physical commerce) is a clear indicator that there aren´t physical barriers that interfere with the user´s choice to make purchases and develop activities in a traditional way or using digital media.

The second factor includes variables of "*Diversity and surplus value of urban areas*", with high positive loads existing among the variables related to the cost of renting, the indices of the active population and of Shannon´s diversity.

The third factor reflects the "*Socioeconomic*" level. High positive loads among the variables: percentage of population with university studies (PPUNS) and housing costs per m^2, and high negative loads in the variables: percentage of population without studies (PPWS), percentage of population dedicated to the service sector (PPSS) and employment density.
The fourth factor is related to the variables of "*Density of urban and digital equipment*". Maintaining high positive loads between the density of physical commerce, density of wifi points in stores (WPC), density of supermarkets and density of public transport stops (DPTS). Thus corroborating the capacity of this factor to represent aspects related to the public equipment's in the analysis units.

FACTORIAL ANALYSIS Rotated component matrix Components	1	2	3	4	5	6	7
1.-Hous_Density	0.472	-0.656					0.231
2.-Emp_Density	0.390		-0.627	-0.221		-0.505	
3.-Youth_index	0.431	-0.362					0.623
4.-Aging_index	-0.338	0.522					-0.516
5.-Pop%(Witho_stud)			-0.902				
6.-Pop%(Univ_stud)			0.952				
7.-Pop%(Indus)							
8.-Pop%(Constr)			-0.666	-0.303			
9.-Pop%(Serv)			0.506	0.202			
10.-Rent(Eu/m2)	-0.392	0.614	0.452				
11.-Cost(Eu/m2)		0.324	0.863				
12.-Act_pop_index	0.251	0.715					
13.-Shannon_Ind	-0.294	0.787		0.221	-0.204		
14.-P.T. Density		-0.346		0.719			0.203
15.-P.T. Distance	0.730				0.210		
16.- %Resid_Use	-0.360	0.521	0.203		-0.493		
17.-%Green_Areas_Use		-0.200		-0.254	0.687		
18.-%Serv_Use							0.747
19.-%Road_use	-0.243	0.375		-0.218	-0.502	-0.236	0.280
20.-Intersections	0.484				0.304	0.542	0.223
21.-Inters_Density	0.702			0.468			
22.-Phys_Com_Dens.		0.225		0.880			
23.-Phys_Com_Dist.	0.822					0.201	
24.- No.Shop._Center						0.272	0.542
25.- No. Municip_Mark		0.603					
26.- No. Superm.		0.659				0.459	
27.-Superm_Density		0.212	0.369	0.760			
28.-Mailbox_Density				0.530		0.604	
29.-F.W.P. Density				0.639	0.645		
30.-W.P.C. Density		0.239		0.819			
31.-Mailbox_distance	0.930						
32.-F.W.P. Distance	0.912						
33.-W.P.C. Distance	0.859		-0.243				
34.-No.Mailbox		0.305				0.821	
35.-No.F.W.P.		0.478			0.739		
36.-No.W.P.C.		0.641	0.335	0.316		0.225	0.207
Extraction method: principal component analysis							
a. The rotation has become 9 interactions							

Table 2. - Matrix of components/factors

The fifth factor incorporates variables of “*Digital Society as a function of Land Use*”, keeping mainly high factorial loads between the number and density of free wifi poins (FWP) and the percentage of land use dedicated to green areas (PLUGA). Highligthing the capacity of this factor to cover information regarding the sites where there is greater possibility of finding FWP according to the type of land use present in each unit of analysis.

The sixth factor reflects interesting parameters among the variables related to “*Online Shopping vs employment density*”. With high positive factorial loads among the variables: number and density of electronic mailboxes, and relatively high negative factorial load with the variable employment density.

Finally, the seventh factor includes variables related to the “*Structure of the population*”. Having high positive factorial loads between the youd index and the land use dedicated to services, with a high negative factorial load focused on the aging index. This allows us to differentiate the areas where the young population predominates, and in which of them, on the contrary, there is an aging population structure.

4.2. Cluster analysis (CA)

One of the main objectives of the research is to understand the dimension, variation and influence of the characteristics described in the previous factors incorporating spatial restrictions. It was therefore necessary to identify the optimal number of groups in which to incorporate our units of analysis. However, due to the lack of previous studies specific to the metropolitan area under the characteristics considered, a hierarchical cluster analysis was used to determine the appropriate k-value (number of groups).

With the factors extracted in FA, the variables of spatial constraints and the number of cluster (k-value) defined, six k-means cluster analysis (CA K-means) with 125 units of analysis were performed. To form clusters with the influence of spatial contiguity from smallest to largest measure, a sequence of incorporation of spatial constraints variables was assigned for each cluster analysis.

Table 3 shows the number of cases grouped in the clusters formed. It was observed that the number of cases is more homogeneously distributed in the clusters with a greater number of spatial constraints variables.

The results were reviewed to select the optimal classification method according to the objective of the study. The result was that Group V, comprising seven FA factors and four spatial constraint variables, is the cluster that best defines the structure of the metropolitan area of the municipality of Madrid according to the characteristics considered (Fig. 2).

Clúster #	**7 Factors** **Group I**	**7 Factors +** **1 Var. Restriction** **Group II**	**7 Factors +** **2 Var. Restriction** **Group III**	**7 Factors +** **3 Var. Restriction** **Group IV**	**7 Factors +** **4 Var. Restriction** **Group V**	**Constraint Spatial** **"K-means clustering"** **Group VI**
1 (Blue)	50	58	53	47	32	12
2 (Pink)	17	17	15	24	16	34
3 (Orange)	3	2	4	2	7	20
4 (Green)	53	46	51	45	43	38
5 (Light blue)	2	2	2	7	27	21
Subtotal	**125**	**125**	**125**	**125**	**125**	**125**
6 (Atypical cases)	6	6	6	6	6	6
Total	**131**	**131**	**131**	**131**	**131**	**131**

Table 3. - K-means cluster analysis (K = 5)

The map represents the 131 units of analysis (Fig. 2). Except for the atypical cases that make up cluster six, the formation of homogenous sub-groups can be seen with units that maintain a contiguous boundary with another unit belonging to the same group, or at least have a location close to the subgroup. Achieving with this, an adequate level of spatial integrity and a balance between the location parameters used, the characteristics of urban structure and the variables of digital society considered (Table 4).

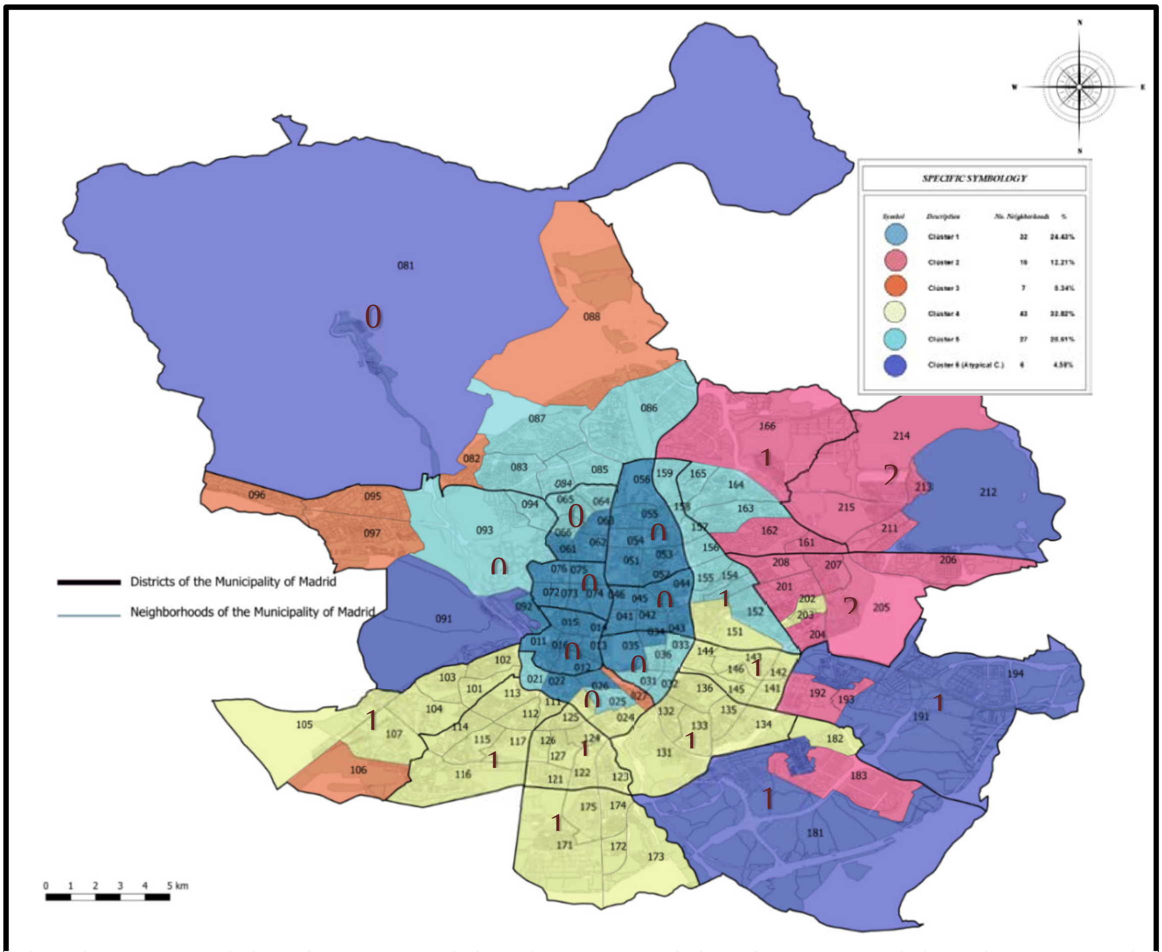


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Fig. 2. - Group V – 4 Spatial constraints variables (Best grouping)

CLUSTER´S	
CLUSTER	**Main features**
1	Central zone with ederly population
	High ICT services (electronic mailboxes, Wifi Points Commerce)
	High urban services (public transport stops, basic retail outlets, municipal markets)
	High rent and housing cost and high socioeconomic level
	High percentage of population with university studies
	Shorter travel distances to access digital society services
	Lower number of free wifi points.
2	Northeast zone with young population
	High number of electronic mailboxes
	Low density of public services and low active population and Shannon diversity indices
3	Mixed zone with High percentage of land use dedicated to green areas
	High number of free wifi points
	Longer travel distances to acces digital society services
	Structure population is mainly young
	Electronic mailboxes is relatively low
4	Southwest zone with low socioeconomic level and ederly population
	Minimum density of urban and digital services
	Low quantity of electronic mailboxes
	Low rental and housing costs with high percentage of population without studies (PPWS)
5	Peripheral zone to the center with few free wifi points and green areas
	Low density of urban and digital services
	Relatively low travel distances to access digital society services
	Above-average diversity and surplus value according to the high values of the Shannon and active population indices.
	High rental and housing costs.
6	These units are that they are located on the periphery of the study area,
	Urbanized land of less than 50%, few public and digital amenities

Table 4. - Clusters formed

5. CONCLUSIONS

The multivariate and spatial analysis developed allowed the identification of the typologies existing in the metropolitan area of Madrid based on sociodemographic, socioeconomic, urban structure and diversity criteria, and specifically relating to the digital society. A classification methodology was successfully developed with two levels of spatial restrictions: the first was incorporated into the FA, where it reduced the dimension of 36 attributes in seven factors that explained over 70% of the total data; and the second involved four more contiguity variables that were gradually incorporated in the cluster analysis.

The results suggest that 125 of the 131 units of analysis considered can be assigned to one of the five typologies, while the six remaining units were classified in a specific group of atypical cases due to their extreme characteristics. The largest group comprises 43 units of analysis (Cluster 4) and includes neighborhoods with a low socioeconomic level, minimum density of urban and digital services, and a relatively low number of electronic mailboxes, meaning that they have limited access to both physical and online shopping.

The second largest group consisted of 32 units of analysis (Cluster 1) located in the central zone. They have an elderly population and a high level of digital and urban services, with the shortest distances to these facilities. The third largest cluster comprises 27 units of analysis (Cluster 5), and contains the neighborhoods with a low density of urban and digital services located on the periphery of the central zone, thus maintaining a significant diversity and surplus value with high rental and housing costs and a representative number of Wi-Fi point commerce (WPC).

The fourth (Cluster 2) and fifth (Cluster 3) clusters in order of size included 16 and 7 units of analysis respectively. Cluster 2 contains neighborhoods with a young population structure, a high number of electronic mailboxes and low densities of public amenities, while Cluster 3 is a mixed zone with extensive green areas and free Wi-Fi points (FWP), and a low proportion of housing areas.

Although the central area is closer to digital society services, this is not the area with the most digital public amenities; these are cluster 3 and 2, which have a greater number of FWP in relation to the population. Likewise, cluster 2 and 5, despite not having an high number of electronic mailboxes like other groups, maintain a considerable proportion of these facilities, pointing to the importance of online shopping in these areas, even though Group 5 has a mainly elderly population and Group 2 has a high percentage of population without studies (PPWS).

The results show the potential usefulness of obtaining a classification of urban areas using attributes of urban complexity, with spatial limits and restrictions that do not significantly affect the quality of the data, and of measuring this complexity through the structure and services of the areas analyzed. This characterization also offers a detailed view of how digital society attributes strongly influence cities, and how these indicators are capable of modifying urban structures, the inhabitants’ activities and behavior, and the general development of the urban form.

Public and private organizations can use classifications of this kind to carry out/adapt urban development plans and identify specific urban areas. This methodology can also be updated for various periods with current information, or with data from previous years to provide knowledge of the urban structure in specific years. As mentioned by Song & Knaap (2007), these classifications can be used in regression analysis to select sampling strategies, for the specific design of urban areas, and to measure progress in the implementation of urban development plans that incorporate information society criteria.

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SIGNAL PROCESSING AND MACHINE LEARNING FOR AIR TRAFFIC DELAY PREDICTION

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ABSTRACT

As data quality and quantity increase, the prediction of future events using machine learning (ML) techniques across engineering disciplines grows by the day. Air transportation cannot be an exception. Delay prediction is paramount in the aerospace industry, since air traffic delays are responsible for millions of dollars in losses to airlines and passengers, along with negative impacts on the environment. In this contribution, we leverage recent signal processing and ML advances to put forth a processing-and-learning pipeline for the prediction of air traffic delays. The proposed approach is executed in several steps. Firstly, we apply signal processing and data science techniques to filter and denoise the original information. Secondly, we run a descriptive analysis of the data and design new features tailored to the prediction problem. Thirdly, we implement a scheme to select the most informative of those features, contributing to a better generalization performance, and offering useful insights. Two algorithms are used to that end: one based on random forests and one employing a sparse logistic regression approach. Finally, once the features are selected, we implement, analyse, and compare several ML architectures (from classical classifiers to deep learning) to predict the delay. While the focus of the comparison is prediction accuracy, metrics such as sample and computational complexity are also discussed. Numerical experiments are drawn from the US domestic market for the year 2018, when more than 7 million flights between 358 airports were flown. The designed processing/learning pipeline reveals interesting insights and achieves better prediction results than the state of the art. The results confirm that air traffic delay prediction is a challenging problem, mainly because the delay is extremely airport-dependent and the data is highly unbalanced (i.e., only a small percentage of flights are noticeable delayed), and identify worth-pursuing future lines of work.

1. INTRODUCTION

During the year 2018, 46.1 million flights were operated in the world, with more than 4.4 billion passengers being transported (The International Air Transport Association (IATA), 2020), which represents 3.5% more flights and 6.4% more passengers than during the previous year. More importantly, traffic predictions for the next decade foresee that the growth of traffic will persist, further stressing the air traffic system and challenging its efficient operation. With these numbers in mind, and given the role that the aerospace system plays in our lives, initiatives targeted at a more efficient operation of the system can generate remarkable social and economic benefits. A particularly challenging aspect is that of air traffic delays. To illustrate the importance of this point, let us focus on the US domestic market. During 2018, the 7 million domestic flights connecting US cities experienced an average delay of 9.9 minutes, yielding an aggregated delay of more than 133 years. According to Eurocontrol, each minute of delay costs more than 100€ to the system (Mulligan, 2019), including all the stakeholders. The Federal Aviation Administration (FAA) and the Nextor consortium in the US estimated the delay cost to be greater than 28 billion dollars in 2018 (Airlines for America, 2019). From this point of view, being able to predict air traffic delays before they take place would provide substantial benefits in the context of daily operations. Although the costs associated with delays would not be fully eliminated, airlines could probably mitigate them by taking proactive actions, such as rescheduling or cancelling some flights in advance.

Using past and current information to predict future flight delays is, however, not an easy task. Precise mathematical models describing the delay dynamics are to be had, the available information is noisy and oftentimes incomplete, and the historic delays seem to depend heavily on the particular airport and time of the year. Hence, rather than pursuing a model-based approach, this paper puts forth a data-based approach that combines recent advances in signal processing (SP) and machine learning (ML) to address the problem of air traffic prediction using historical information. In recent years, ML and artificial intelligence algorithms have excelled in a number of engineering problems (from image recognition to language processing) beating the state of the art in areas where well-established model-based approaches had been used for decades, and providing a feasible alternative in areas where model-based designs were inexistent or poorly accurate.

The approach implemented in this paper proceeds in three steps. In the first step, we design SP and ML algorithms to identify, aggregate and extract relevant features from a database containing past information about air traffic delays. In the second step, we use the output of step 1, together with information of actual flight delays, to train different supervised ML architectures. The third step consists in using the trained ML architectures to predict current delays. The final goal is threefold: 1) providing a delay prediction accuracy that beats the state of the art, 2) testing and comparing a broad range of ML architectures that exploit different levels of information structure, and 3) gaining insights on the key factors and trade-offs that govern the problem of air-traffic delay prediction.

The number of works dealing with the prediction of air traffic delays is limited, which is likely a testament to the complexity of the problem. To the best of our knowledge, Rebollo (2012) was the first publication that addressed the problem of flight delay prediction over origin-destination (OD) pairs using ML algorithms, a problem further explored in Rebollo & Balakrishnan (2014), Hanley (2015), and Gopalakrishnan & Balakrishnan (2017). These works recast the delay prediction as a binary classification task, so that the problem reduces to estimating if the delay is going to be below or over a given threshold in a specific OD pair. Addressing the delay prediction as a decision task, which is also our approach, brings a number of advantages, but it also generates some challenges, being the so-called "unbalance" between the positive class (i.e., flights where delay exists) and the negative class (i.e., flights where delay does not occur) the most challenging one (see Section 4 for details). Regarding the ML architecture to predict the delay, those works rely mostly on decision trees (DT) and Random Forest (RF) classification algorithms, with Gopalakrishnan & Balakrishnan (2017) exploring other architectures and concluding that the best results were achieved by Neural Networks (NNs).

Relative to those works, our contributions are the following. Firstly, we predict not only delays at OD pairs but also at airports. Secondly, we implement several SP and data-science techniques for pre-processing the raw data, extracting relevant knowledge, and designing new features to serve as input to the classification problem. Thirdly, we design a problem-tailored feature-selection scheme to identify the most relevant features. Fourthly, we employ a range of (classical and modern) ML algorithms to address the classification, comparing pros and cons, and assessing their accuracy and computational complexity. Finally, we consider rebalancing training techniques to counteract the severe lack of balance present in the dataset. Regarding the ML algorithms implemented, it is also important to remark that some of the proposed architectures account for the specific structure of the data at hand, namely its temporal variation by using Long-Short Term Memory (LSTM) networks (Hochreiter & Schmidhuber, 1997), and the topology of the air-traffic network (specifically, the graph connecting the different airports) by using Graph Convolutional Neural Networks (GCNN) (Gama et al., 2019). Our numerical tests, which are based on the US domestic market for the year 2018, reveal that the proposed processing and learning pipeline yields a better prediction performance -namely better precision, recall and f1-score (Geron, 2017)-, than that achieved by the state-of-the-art air-traffic delay prediction algorithms.

Section 2 details the problem to solve and introduces notation. Section 3 designs the schemes to select the most relevant variables for the prediction. Section 4 describes the ML architectures and assesses their delay prediction performance.

2. PROBLEM DESCRIPTION, DATASET, AND DELAY-SIGNAL GENERATION

Given a planned (departure or arrival) time, the delay of a flight is defined as the difference between the originally planned time and the actual time when the event happens, namely the departure or the arrival. Air traffic delay can be due to different causes that may be grouped in five categories (US Department of Transportation, 2020) corresponding to delays caused by: a) the airline carrier, or circumstances under the control of the airline; b) elements in the National Aerospace System (NAS) (airport operations, high traffic, etc.); c) other flights arriving late and thus making the plane that must operate the flight unavailable; d) severe weather conditions; and e) security reasons. Clearly, the effects of a particular delay have impacts beyond the time and element for which the delay first takes place and, hence, the entire network must be considered.

The air transportation network may be regarded as a system composed of different elements, including airports and OD pairs. We will use E to denote the set of elements of interest (i.e., either the set of airports or the set of OD pairs), e to denote a generic element of E, and G to denote a graph capturing the connections between the elements in E. Rather than predicting the delay of a particular flight, our focus is on predicting the aggregated (average) delay experienced by a particular network element e (airport or OD pair) and a particular time t'. To be more specific, let $d(e,t)$ denote the delay that element e is experiencing at time t. Then, we aim at designing ML architectures that, after properly trained, at time t use as input global network information and the values of $d(e,\tau)$ for $\tau \leq t$ to predict if $d(e,t')$, the delay of element e at time $t'=t+h$, will be greater than a prespecified threshold δ. Hence, $h>0$ can be viewed as the horizon of the prediction (typically between 2 and 6 hours) and $d(e,t')\geq\delta$ (with the delay threshold δ typically set to 60 minutes) as the condition to trigger the delay alarm.

Note that $d(e,t)$, which constitutes the essential piece of information of our model, can be viewed as a spatiotemporal signal that varies both across time and across the nodes of the network graph G. Regarding the construction of G, when dealing with the "airports graph", we consider two nodes to be connected by an edge if there is any flight between them. When the nodes of G represent OD pairs, we use as graph G the line graph associated with the graph of airports; see Harary (1972) for details on the definition of a line graph. From this "delay-signal" point of view, one can reasonably expect $d(e,t_1)$ and $d(e,t_2)$ to be close if the difference between t_1 and t_2 is small, and $d(e_1,t)$ and $d(e_2,t)$ to be related if e_1 and e_2 are neighbouring nodes. Last but not least, we will handle (and predict) arrival and departure delays separately, since their causes can be different. However, to simplify the discussion and notation, in the following sections we will generically refer to a single type of delay.

Dataset: To train and test our architectures we use a database provided by the Bureau of Transportation Statistics from the US Department of Transportation, whose website publishes data for different means of transport in the US. Our focus is on the database for domestic flights, whose entries provide information for individual flights, including scheduled and actual departure and arrival times, origin and destination airports, delays and their categories, deviations, and cancellations. For 2018 only, this database features more than 6,000 OD pairs, 358 airports, and more than 7 million flights.

Pre-processing: One-third of the OD pairs show a frequency lower than 1 flight per day. These samples add computational complexity, without providing meaningful (generalizable) knowledge for a data-based delay-prediction approach, hence we only consider airports and OD pairs featuring more than 10 flights per day on average. Also, we remove cancelled flights, as we consider that they do not exhibit a causal relationship with the considered variables (departure and arrival times, delay, etc.).

Definition of the state signal $d(e,t)$: Time is slotted into one-hour intervals, with t denoting the slot index. Inspired by Rebollo (2012), the process to obtain $d(e,t)$ is as follows. For each hour t (say 3PM of Today), we consider a 120-minutes window that considers the previous and current hour (i.e., from 2:00PM to 3:59PM). Furthermore, let $F_{(e,t)}$ denote the subset of flights that took place within the 120-minutes window around t and involved element e. Then, the value of $d(e,t)$ is simply defined as the average of the delay experienced by the flights in $F_{(e,t)}$. Following this procedure, we obtain a first version of the signal $d(e,t)$ for all e and t. However, there are instances of (e,t) for which there was no flight within the considered two-hour interval (i.e., $F_{(e,t)}$ was empty) and, hence, the value of $d(e,t)$ is not defined. To deal with those, we implemented the following approach: if the number of consecutive hours where $d(e,t)$ is not defined is less than six, then we set $d(e,t)$ using linear interpolation based on the values of $d(e,t')$ for $|t-t'| < 6$. If the number of consecutive empty windows is larger than six, we do not consider $d(e,t')$ with $|t-t'| \geq 6$ to be informative and set $d(e,t)$ to zero, which is considered as the default delay value.

3. DESIGNING THE INPUT VARIABLES

This section details the design and selection of variables that will be used as input for our classification algorithms. This is an important issue oftentimes overlooked. For a data-based approach to succeed in the context of air-traffic delay prediction, a balance between the number of data points (samples) in the dataset and the dimensionality and complexity of the input variables needs to be reached. ML architectures that use the raw data as input will require many more training samples than those that use a reduced dimensionality (possibly quantized) representation of the data where relevant knowledge has been extracted. We split this design into two steps. Firstly, we extract (create) new variables from the dataset. Secondly, we implement a feature selection scheme to identify the subset of the most relevant variables for the prediction problem.

The input variables are split into two groups: time variables (hour, day, month, and year) and network delay-state variables (aggregating/encapsulating delays of one or several (e,t) pairs). When running a descriptive analysis of the data, we observe a seasonality pattern on the delays. For that reason, we generated a new categorical variable ***"season"***, which takes three values: low (September to November), medium (January to May) and high (June to August, and December). Similarly, to account for the congestion of the overall network we define two new variables: one accounting for the network delay in the last hour and another one accounting for the network delay in the last 24 hours. Rather than using an average across elements of the network, we rely on a (K-Means) clustering algorithm to split the delay levels into (six) different groups and use those to define a ***"network delay congestion index"*** for each hour and day. Lastly, when modelling the delay in an element *e*, it is reasonable to assume that the delay experienced by the neighbours of *e* is relevant. Since considering the delay of each of the neighbours can lead to a very high dimensional signal, we define a continuous variable that, for every (*e*,*t*) pair, aggregates (sums) the value of the delays *d*(*e'*,*t*) for all elements *e'* that, according to the graph *G*, are neighbours of *e*. Moreover, since the relation between delays of neighbouring nodes seems to depend strongly on the particular cause generating the delay, we define 5 different ***"neighbour-aggregated delay variables"***, each of them associated with one of the 5 causes of delay listed at the beginning of Section 2.

The information of the dataset with the addition of the variables described above yields more than a thousand input features (variables) for our classifier. Since this large number challenges learning and incurs a high computational-complexity cost, we put forth a feature-selection mechanism to identify the most informative variables. Two options are considered: one based on RF techniques and one based on lasso-regularized logistic regression (LR); see (Hastie et al., 2009). While not implemented in the context of air-traffic delay prediction, these two feature-selection techniques have been recently used in a number of ML approaches. The variable selection is carried out based on a "level of information" that depends on the effect/usefulness of the variable on the delay to be predicted. This guarantees that the fact of the goal being delay prediction is accounted for when running the proposed feature-selection mechanism.

The selection is run only for network-delay state variables (time variables are deemed informative, and their number is small, hence, they are preserved); it is carried out separately for each element of the network (delays seem to depend heavily on the airport, so we do not want to force the selected variables to be the same across the entire network); and it proceeds in two steps. Firstly, we run a single-shot selection step, where we reduce the number of features to 100. Secondly, we further reduce those 100 features to 10. That is achieved by running $I=10$ different instances of the feature selection algorithm. Each of those instances identifies the 10 most important variables, and the ones we finally select correspond to the 10 most important ones obtained after averaging the results across the $I=10$ instances.

As an illustration of the feature selection results, Figure 1 shows the selected variables by the two algorithms for the "O'Hare (ORD) to LaGuardia (LGA)" OD pair, which is the route with the highest number of flights. As we can see, the two methods assign the highest importance value to the NAS delay in the neighbours. They also assign a high importance to the current departure delay of the ORD-LGA pair (the one under analysis) and LGA-ORD. The arrival delay variable in ORD airport is also selected by both algorithms, with the remaining ones being different. Analysing these differences is certainly meaningful but beyond the scope and page limits of this paper.

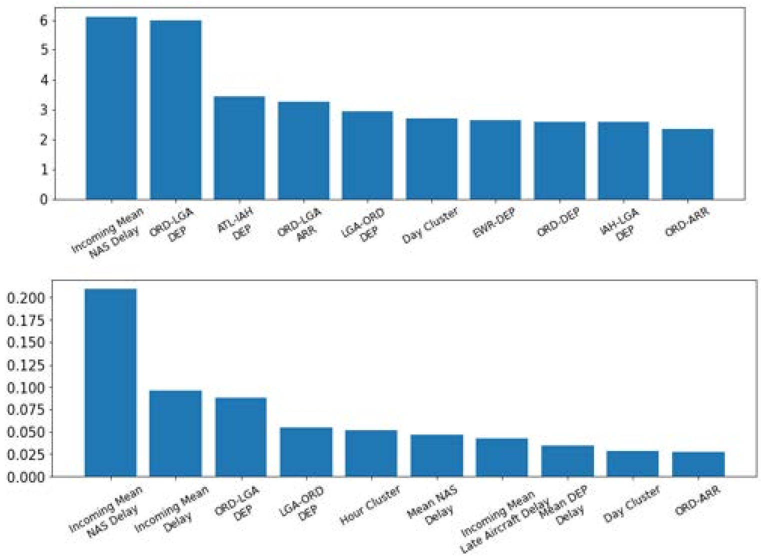

Figure 1: Features selected by the RF (top) and LR (bottom) schemes. The x-axis represents the selected features and the y-axis the "information level" given by the scheme.

4. ML ARCHITECTURES, TRAINING, AND TESTING RESULTS

Let x and y denote, respectively, the input and output variables of our classifier. The input x is a vector with as many dimensions as input features and y is a binary $\{0,1\}$ number. Suppose that: a) $\mathcal{T} = \{x^s, y^s\}_{s=1}^{S}$, where s denotes a sample index, is the set of training samples and b) $f(x|\theta) \rightarrow y$ is the input-output mapping implemented by a (nonlinear) parametric ML architecture whose parameters are collected in θ. The approach in a supervised ML setting is to use $\mathcal{T}$ to estimate $\hat{\theta}$, the value of θ, and then use the (learned) function $f(\cdot\,|\hat{\theta})$ to estimate the output associated with inputs x not included in $\mathcal{T}$ as $\hat{y} = f(x|\hat{\theta})$.

Recall that, at time t, our goal is to predict if $d(e,t+h)$, the delay of element e at time $t'=t+h$, will be greater than a prespecified threshold δ. The approach that we put forth to achieve that is to: i) train a different classifier per element e (so that the parameters can depend on the airport or OD-pair); ii) use as input the features described in Section 3; and iii) try a range of architectures defined in more detail soon. For the results presented in this paper, we set the prediction horizon to $h=2$ hours (so that time correlation is likely to exist, and companies have sufficient time to take mitigating actions) and the delay threshold to $\delta=60$ minutes (so that the incurred delay is meaningful). By recasting the prediction of a continuous variable as the prediction of a (quantized) binary version of it, the complexity of the output is reduced, rendering data-based learning more likely. The main drawback associated with this approach is that, for most (e,t) pairs, the associated output label is zero. That is, for the vast majority of the samples the network is not saturated and the continuous delay is less than 60 minutes.

The next step is to describe how the training of the ML architectures is carried out. The two key aspects are i) the definition of the training set and ii) how to deal with the unbalancing of the labelled data. Regarding the first aspect, we use the data of the US domestic market from the year 2018 to train, and test the results using the data from January 2019. More specifically, if the focus is on predicting the delay for the element e, we: i) select the samples of the dataset related to e; ii) compute the features introduced in Section 3; iii) associate each input sample with the corresponding value $d(e,t+h)$; iv) remove all the samples for which $d(e,t+h)$ is exactly 0 minutes; and v) compute the binary label y associated with the input by checking if $d(e,t+h)\geq\delta$. The reason for iv) is threefold: 1) many of those samples correspond to cases where $d(e,t+h)$ was not defined and set to zero, 2) if $d(e,t+h)$ was an actual measurement, an exactly zero value represents a stress-free scenario were predictable 1-hour delays are very unlikely to take place, and 3) it contributes to balance the dataset, reducing the number of samples whose label is $y=0$. Indeed, the second aspect to be handled is the lack of balance in the data. A descriptive analysis of the dataset reveals that 97% of the samples satisfy $d(e,t)<\delta$, so that the associated label y is zero. This is a significant challenge because it means that a (useless) classifier that always predicts zero and misses all the delays would have an accuracy of 97%, likely beating all other classifiers that try to find a balance between false alarm and miss detection errors. Indeed, if accuracy is the metric chosen to train the ML architectures and the original data is used as the training set, then the optimal ML classifiers always yield a zero prediction. To bypass this problem, we use an *undersampling and oversampling balancing approach* during the training phase (Chawla, 2010). More specifically, we train the ML architectures using 3,000 samples but, rather than choosing them uniformly at random from $\mathcal{T}$, which is the standard approach in balanced setups and in our case would yield 90 samples with $y=1$ and 2,910 with $y=0$ on average, we pick the samples as follows. We split $\mathcal{T}$ into two subsets, from the subset with $y=0$ we pick 1,500 samples uniformly at random and from the subset with $y=1$ (which contains less than 1,500 samples), we build a larger set with synthetic copies of the original samples (to obtain a set with more than 1,500 samples) and then pick 1,500 of those “original and synthetic” samples with $y=1$ uniformly at random. This *undersampling and oversampling* approach balances the data and exposes the classifiers to a large number of samples where delay took place, so that they are able to learn the patterns in the input data that are related to those events. To render the learning process more robust and less sensitive to the subset design, we construct 10 instances of $\mathcal{T}$, train the classifiers for each instance, and average the results.

ML architectures: To tackle the classification task, we consider eight different ML architectures. Six of them correspond to “traditional” classification algorithms with an increasing level of complexity: LR, DT, RF, K-Nearest Neighbours (KNN), Gradient

Boosting Trees (GBT), and Multi-Layer Perceptrons (MLP) (Hastie et al., 2009). The other two are more advanced classification architectures that account explicitly for the domain structure of the delay signal $d(e,t)$, either its time structure (using an LSTM-based classifier) or its graph structure (GCNN-based classifier).

Prediction results over the testing dataset: Once the architectures have been trained and the corresponding (element-and-architecture dependent) parameters $\hat{\theta}$ have been learned, we assess the classification performance using the data on the test set (January 2019). Let N_{ab} be the number of samples where the predicted output is $\hat{y} = a$ and the actual label was $y = b$, and note that, for binary classification, the cardinality of $\{N_{ab}\}$ is 4. Based on those values, we report the classification performance of each of the trained architectures using the following metrics: accuracy $Acc=(N_{00}+N_{11})/(N_{00}+N_{01}+N_{10}+N_{11})$, precision $Prec= N_{11}/(N_{11}+N_{10})$, recall $Rec=N_{11}/(N_{11}+N_{01})$, and f1-score $F1=2 \cdot Prec \cdot Rec/(Prec+Rec)$.

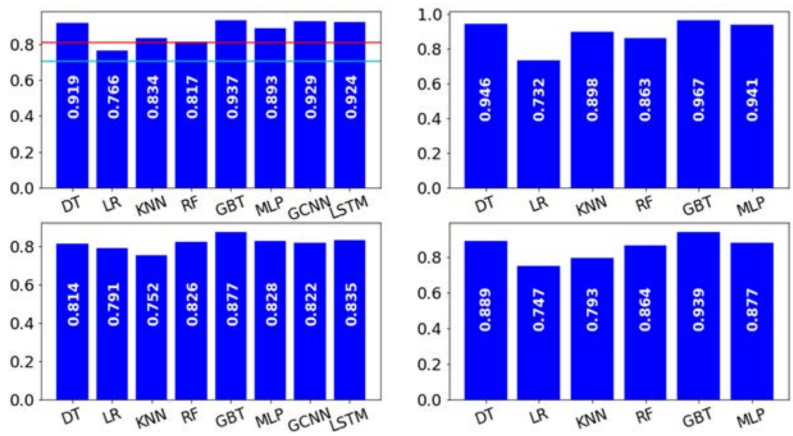

Figure 2: Comparison of the accuracy for OD Pairs (on the left) and airports (on the right), using balanced (on the top) and unbalanced (on the bottom) data.

Figure 2 shows the classification accuracy of our ML architectures both for the prediction of delays on OD-pairs (two panels on the left) and airport delays (two on the right), using balanced (top) and unbalanced (bottom) testing data. To facilitate comparisons with the state of the art, the results in Figure 2 only consider the 100 most delayed airports and the figures correspond to the averages across all the elements in the network. In addition to the results of our architecture, the top-left panel shows two horizontal lines: the red line corresponds to the accuracy of the approach in Rebollo & Balakrishnan (2014) and the blue one to that in Gopalakrishnan & Balakrishnan (2017). To keep the comparison fair, these two lines are not shown in the other panels because the state of the art addressed neither predicting airport delays nor testing on unbalanced data. The main observations are as follows: 1) The accuracy levels are relatively high but, as expected, below the 97% level achieved by the dummy all-zero classifier. 2) Our architectures (7 out of 8) beat the state of the art, in some cases by more than 10%. Since some of our classifiers are fairly simple, this outperformance confirms the importance of the pre-processing steps. 3) Predicting delays at airports is easier than at

OD pairs. 4) The results deteriorate when (actual) unbalanced testing sets are used. 5) Classifiers with a higher degree of sophistication seem to give rise to better results at the price of a higher computational and training complexity (which is the reason for not reporting the results of the GCNN and LSTM algorithms in plots on the right).

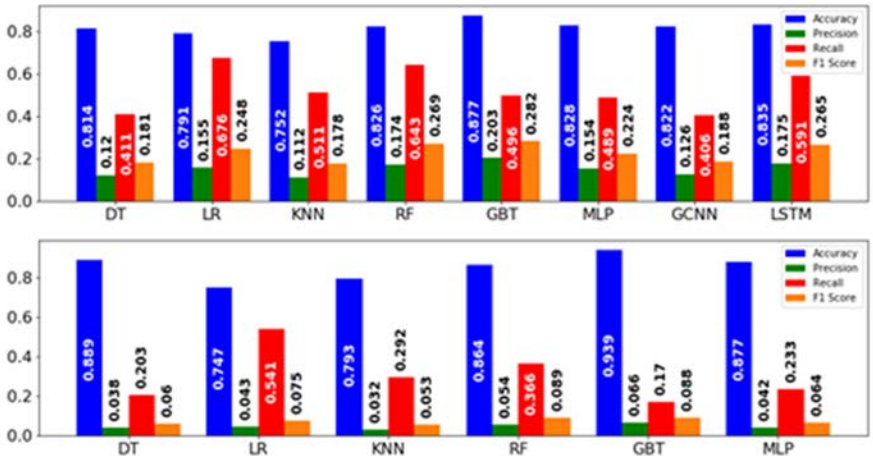

Figure 3: Accuracy, precision, recall, and f1-score for OD pairs (top) and airports (bottom) using unbalanced test data.

The reason for reporting accuracy was to establish a fair comparison with the state of the art. However, as already discussed, in unbalanced classification setups, accuracy must be complemented with precision, recall and f1-score metrics, with the last one being typically used as the main figure of merit to analyse. Figure 3 reports the four metrics for OD pairs (top) and airports (bottom) for our architectures using unbalanced test data. We observe that the results are noticeably worse, confirming that: a) most of the accuracy observed was due to the “trivial” prediction of non-delay scenarios and b) as expected, early prediction of a significant percentage of future delays based on present and past data is a challenging task. Interestingly, the results also show that better precision/recall/f1-score are obtained for OD pairs, suggesting that the higher accuracy in predicting delays at the airport level was associated with a larger number of zero labels. Regarding the ML architectures, the highest recall is achieved by the simple LR algorithm. However, the highest f1-score (which is typically viewed as the most important classification performance indicator) is achieved by the GBT, with RF and LSTM also showing a good performance.

To gain further insights, Figure 4 reports classification results in two additional scenarios dealing with OD-pairs and unbalanced test data. In the first scenario (top panel) we constrain the prediction to the 25 busiest OD-pairs (largest number of flights). The motivation here is to focus on elements with more data and, also, a higher likelihood of a delay, to check if under those conditions, learning from past and previous data is more feasible. The second one corresponds to a classifier that proceeds in two steps. In the first step if $d(e,t)=0$ the “deterministic” prediction is that $d(e,t')<\delta$ and, hence, that $y=0$. If $d(e,t)>0$, we then use the output of the ML classifier as the predicted y. Note that, under this approach, $\mathcal{T}$ needs to be modified accordingly, so that all the training samples whose input contains *d(e,t)=0* are removed. The idea behind this scenario is to identify the "trivial cases" first and then let the classifier focus on the non-trivial ones. The results corroborate that in both cases, the accuracy and, most importantly, the f1-score improve, suggesting that our intuition was correct and motivating further research of "hierarchical" classifiers that focus on the elements where delay is more likely and more data exists.

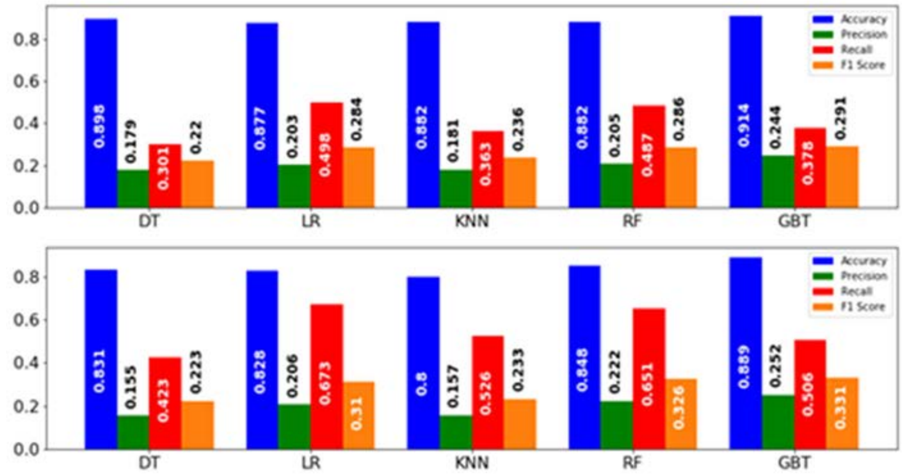

Figure 4: Accuracy, precision, recall, and f1-score for OD pairs using unbalanced test data for two additional scenarios (top and bottom). See the main text for additional details.

5. CONCLUSIONS

We put forth a data-based processing and learning pipeline to predict the delays in an air transportation network. Key novelties of our approach included the prediction of the delay not only across OD pairs but also across airports, the consideration of feature selection schemes, accounting for the (graph) structure of the network and the correlation of the delays across time, and the incorporation of rebalancing schemes to foster recall and precision performance. Our schemes were trained and tested using real data from the US domestic market in 2018 and 2019. The results outperformed the state of the art by more than 10% and confirmed that air-traffic delay is an inherently complex problem. Future research includes the prediction of delays for individual flights along with the implementation of network-segmentation schemes that enable tailoring the prediction to segments of the air transportation network that exhibit related delay dynamics.

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THE IMPACT OF COVID-19 ON INTERMODAL FREIGHT TRANSPORT: AN EX-ANTE AND EX-POST ANALYSIS

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ABSTRACT

It is well known that one of the most efficient ways of moving goods is the combination of two freight transport systems, rail and road. The purpose of this study is to evaluate factors that affect the competitiveness of intermodal rail-road transport (IRRT). Previous research has focused on the definition of a multi-criteria framework to identify and prioritize the determining factors. However, the assessments have been done before the coronavirus pandemic, but after the quarantine and post-quarantine period of the virus, the prioritization of these criteria has definitely changed in the view of experts and customers. The appearance of a drastic change in some of the influencing factors during this period, e.g. political decisions that affect regulation and operations, as well as changes in technology and the use of infrastructure, have make it necessary to reevaluate the IRRT.

In order to carry out this evaluation, a combination of two methods has been performed: (i) Laboratory-based hierarchical structure to test and evaluate the gray decision (gray-DEMATEL), and (ii) Network Analysis Process (ANP) to carry out the evaluation of the IRRT system in Spain. As a result of this work, an ex- ante and ex- post analysis of the evaluation of the criteria is shown, with respect to the evaluations made by decision makers during the post-pandemic.

This work shows how the importance and necessity of the criteria have changed as the world has changed due to Covid-19, and what factors have changed the priorities of customers, experts and operators based on the current situation. This research also provides theoretical and managerial insights for policy makers and researchers in this field.

1. INTRODUCTION

An intermodal or multi-mode transport system is a combination of two or more modes of transport (Steadieseifi et al., 2014). For achieving the most economical, efficient, and environmentally friendly way to transport goods and passengers to a destination (Kumar& Anbanandam, 2020).

To minimize the environmental impact of transportation, switching from roads to more sustainable modes such as railways and waterways is required (Eng-Larsson & Kohn, 2012). It is necessary to identify inter-model rail barriers (IRR) to transfer part of the road transport to rail transport (Tsamboulas et al., 2007).

Roso (2013) to reducing the negative impact on the environment and social activities, the government usually tries to change the mode from single-model transportation to inter-model transportation of goods. Therefore, managers must identify organizational challenges to increase the prosperity of inter-model transportation services and face the complexity of the supply chain network (Monios & Bergqvist, 2016).

The analyze of barriers in several dimensions such as economic, technical, environmental, social, and political is needed to develop an inter-model freight system (Tsamboulas et al., 2007). In this sense, Kumar & Anbanandam (2020) identify IRR criteria in various decision dimensions (policy, operating regulations, technology and infrastructure, knowledge, organization, and government).

For this purpose, the grey-DEMATEL method (Gabus & Fontela, 1972) is used to identify the mutual relationships of criteria and handle dependencies among criteria. Its dimensions are taken by ANP (Saaty, 1996). The DEMATEL technique is introduced and combined with ANP in can make up for the equal weighting assumption of ANP (Büyükeozkan & Güleryüz, 2016). Kumaer & Anbanandam (2020) develope an evaluation framework from multiple user perspectives and perform an integration of grey theory-based decision-making trial and evaluation laboratory (grey-DEMATEL) and Analytic Network Process (ANP).

While at the end of December 2019, China reported several cases of an acute respiratory infection in Wuhan City, Hubei Province, China. The World Health Organization (WHO) named the previously unknown virus severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and called the disease caused by the virus coronavirus disease (COVID-19) (WHO 2020).

This virus has disrupted global production lines, supply chains, international trade, and the world's maritime and aviation networks. Araz et al. (2020) emphasize that the COVID-19 outbreak constituted one of the crucial disruptions experienced during the half-century, “breaking many global supply chains.” (Other authors,e.g Dolgui, Ivanov& Sokolov 2020; Golan et al.,2020; Haren&Simchi-Levi 2020; Hobbs, 2020; Linton &Vakil, 2020; Remko, 2020, (consider theCOVID-19) as a global catastrophe that affects human life and economic activities such as production operations, supply chain and logistics, and several other sectors.

The constraints of this epidemic lead to labor shortages, followed by logistical disruptions, and ultimately supply shocks to the supply chain (Hobbs 2020). The current global supply chain has weaknesses that have led to a loss of revenue, demand, and supply shortages in the

Covid-19 situation (Linton & Vakil, 2020). Following the various destructive effects of this epidemic, the prioritization and impact of intermodal transportation indicators have also been affected by this situation.

This article aims to identify the different types of intermodal transportation criteria which are related to geographical location by reviewing the papers. We then turn to the changes resulting from the ranking of these clear criteria before and after the coronavirus epidemic. To analyze criteria interactions. we use the combined Gray Theory and Decision Making Test and Evaluation Laboratory (DEMATEL) method, e.g., Gray-DEMATEL.

The rest of the paper is structured as follows. Section 2 presents the background of the study. Section 3 shows the method that has been applied. Section 4 analyses the main results, and finally, Section 5 concludes the main findings.

2. BACKGROUND

2.1 Framework

Identifying the influencing factors to analyze the relationship between multiple criteria and appropriate measures to promote them has broadly been addressed in literature. In this sense, the most common factors for selection decisions are economic (Eng-Larsson&Kohn, 2012). To reduce the negative impact of road transportation, some modal shift measures, such as the promotion of intermodal freight transport, mitigation of intermodal freight transportation adoption barriers, and improving the utilization of rail and water-based transport systems have been adopted (McKinnon et al., 2015).

Most freight industries in developing countries face many challenges in obtaining real-time data on environmental, social, legal, and organizational factors for intermodal services.
For this purpose, a literature review and expert opinions are carried out to identify the relevant factors. Next, they are divided into five main dimensions: Operational, Technology, and infrastructure of organizational knowledge of government policy and regulations (Kumar & Anbanandam, 2020).

Kumar & Anbanandam (2020) illustrated operational indicators to relate to the factors that hinder the supply chain and the logistics performance of the inter-model transport system. The author concluded that freight shippers have not adopted intermodal services for short hauling to the additional cost of pre and post-haulage. Road freight is often the priority of transportation because inter-model freight transport does not exist in the underdeveloped rail transport infrastructure and hinders the popularity of inter-model freight (Lindholm & Behrends, 2012). Intermodal rail transport infrastructure factors point to the lack of physical infrastructure and the technology available for the intermodal transport system (Kumar & Anbanandam, 2020). Most of the criteria for purchasing transportation services focus on the economic aspect and quality of business delivery, while the environmental side is less advertised (Elbert & Seikowsky, 2017; Lammgård, 2012). Knowledge is one of the most critical factors to improve the organization's competitiveness by developing products, processes, and people (Cheng et al., 2008). Organizational barriers refer to the organizational structure of the organization and its relationship with other organizations. In the age of digitalization and information technology, sharing shipping information with other companies is an essential criterion for choosing a mode (Truschkin & Elbert, 2013). The lack of government policies and environmental regulation hinders the modal shift (Islam & Zunder, 2014). Monios & Bergqvist (2016) concluded that a poor modal balance between rail and road mode reduces the adoption of intermodal services. Policy Makers to improve the intermodal services, might assess incentives that enable the use of intermodal services (Elbert & Seikowsky, 2017; Tsamboulas et al., 2007).

2.2 DEMATEL & ANP method

Multiple criteria decision-making (MCDM) methods are prevalent methods to deal with the complicated problems, including conflicting objectives, hierarchical structure, and involvement of various stakeholders (Demirel et al., 2010).

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is used to find the cause-effect interdependencies of the factors and measure in relation values. The relative importance is measured by the prominence value of factors (Geolcük & Baykasoı, 2016). The priority weight of factors cannot be determined by the DEMATEL method; however, ANP method help to compute the structural dependency of the decision problem (Büyükeozkan et al., 2017; Büyükeozkan & Çifçi, 2012). The integration of DEMATEL with the ANP method reduces the complexity of the problem and helps to identify the global influence strength of factor (Büyükeozkan & Güleryüz, 2016). In the DANP method, the DEMATEL method is used to collect the data, identify interrelationships, and measure interdependences. In contrast, the ANP method is used to drive the unweighted supermatrix, weighted supermatrix, and the limiting matrix for computing the influential weights of the factors (Ju-Long, 1982). This method can combine grey's theory with different MCDM methods to improve the accuracy of the decision-making process (Xia et al., 2015). The benefit of the grey systems idea over the fuzzy approach is that it does not need any robust fuzzy membership function (Xia et al., 2015).

2.3 Impact of Covid-19 on the supply chain

According to World Trade Organization (WTO) figures, the worldwide economy gross domestic product (GDP) is projected to consent 2020 sharply by up to eight, and global trade will decrease by up to 32% in 2020 thanks to the COVID-19 pandemic (World Trade Organization, 2020). Supply chain disruptions cause significant challenges and may affect organization performance (Hendricks & Singhal, 2003). Pettit et al., (2019) offer a review of the literature on supply chain resilience that predates COVID-19. The severity of the business disruption of the COVID-19 pandemic has challenged much of our previous understanding of what constitutes a resilient supply chain. Recent research has indicated that this crisis has led to the rapid deterioration of several business and economic indicators, including productivity and global GDP (Harris, 2020). These impacts are due to the imposition of travel and trade restriction (Baveja et al., 2020) and the shutting down of workplaces. Ivanov (2020), considered the pandemic and the respective supply chain risks, provided a simulation model for global supply chain disruption, and predicted the severity of COVID-19 impact on supply chain performance.

In summary, COVID-19 has put some significant and unprecedented strain on global supply chains across most product categories. Past literature has provided some indication of the factors that may cause disruption on the supply chain. However, at the same time, it has exposed a number of challenges related to identifying and responding to significant changes within the demand patterns during an outbreak. However, the power to forecast excess demand during the pandemic early could have substantial implications for supply chain managers and policy makers.

3. METHOD

The proposed method consists of three steps to solve the interrelationships and prioritize the problem of IRR criteria.

3.1 The grey-DEMATEL methodology

The gray-DEMATEL decision matrix usually uses a gray 5-digit spectrum that includes the expressions without impact (0.25 and 0), very low impact (0.25 and 0.5), low impact (0.5 and 0.25), high impact (0.75 and 0.5), impact is very much (1 and 0.75). Therefore, the first step of the gray DEMATEL method is forming a direct communication matrix. In the next steps, the normalization operation is performed, the matrix is determined, the matrix is multiplied, and finally, the total communication matrix (T) is obtained.

As indefinite numbers, we have the operations of multiplication, division, and addition. In gray numbers, these relations are also established.

The gray-DEMATEL method is a decision-making method for performance and a way to help visualizing a complex causal relationship using useful matrices and diagrams. Matrices or diagrams depict the relationships between system components with the strengths of the relationships within these quantitative relationships. The gray-DEMATEL consists of four main steps, including developing a direct pairwise relationship matrix between system components through the evaluator or decision-maker inputs, the determination of the initial impact matrix through the normalization of the natural relationship matrix. Determining the matrix (impact) of total relationships and finally determining causal relationships (causal-salient diagrams) are among the components and relative strengths. A summary of the steps is shown next:

Step 1: Form a group of experts to gather their group knowledge to solve the problem.

Step 2: Determine the criteria to be evaluated and design language scales. In this step, experts' opinions, research factors and indicators are the main outcomes.

The criteria to be evaluated will be selected according to the areas under study. The gray numbers used in this study are of the fuzzy triangular type. As can be seen, this spectrum is the same as the spectrum of the DEMATEL method, except that gray numbers are used.

Step 3: Create a gray matrix of direct initial communication with the collection of expert opinions.

To measure the relationships between criteria, we need to put them in a square matrix and ask experts to compare them in pairs based on how much they affect each other. In this survey, experts will express their views based on gray numbers. Assuming we have n criteria and p experts; we have a gray matrix, each of which corresponds to the opinions of an expert with gray numbers as its elements.

Step 4: Normalize the direct connection gray matrix.

For this purpose, linear scale conversion is used as a normalization formula to convert benchmark scales to similar criteria.

Step 5: Calculate the matrix of the total connection. In this step, first, calculate the inverse of the standard matrix and then subtract it from the matrix I, and finally multiply the standard matrix by the resulting matrix.

Step 6: Create and analyze the causal chart.

For this purpose, we first calculate the sum of the elements of each row (Di) and the sum of the elements of each column (Ri) of the gray matrix. The sum of the elements of each row (D) for each factor indicates the extent to which that factor influences other factors in the system. The sum of the column (R) elements for each factor indicates the degree to which that factor is affected by different factors in the system.

Then we get the values D + R and D-R. To draw a causal diagram, we must de-fuzzy these two values, like the definitive DEMATEL method. Therefore, the horizontal vector (D + R) is the influence of the system's desired factor. In other words, the higher the D + R vector, the more it interacts with other system factors. The vertical vector (D - R) indicates the power of each aspect. In general, if D - R is positive, the variable is causal, and if it is negative, it is a disability. After deactivating the numbers, a Cartesian coordinate system is drawn. The longitudinal axis shows the values D + R, and D-R is the transverse axis in this device.

Therefore, the horizontal vector in the coordinate system is the degree of impact of the desired factor in the system. In other words, the higher the value for an aspect, the more the factor interacts with other system factors.

The vertical vector of the coordinate system shows the effect of each factor.

3.2 DANP

This approach is one of the newest techniques for combining gray-DEMATEL with ANP, known as fuzzy DANP.

As mentioned, the degree of importance of each element under the control of the other component was measured using the ANP method. Because of facilitating the work and reducing the number of pairwise comparisons required, the internal connections and the degree of influence of the elements on each other are measured by the DEMATEL method. The number of even comparison matrices and the volume of calculations are reduced, the speed of calculations is increased, and its complexity is reduced. In this technique, after forming the total gray-DEMATEL communication matrix, the threshold value is no longer calculated, i.e., no relation is eliminated. From this matrix, the ANP supermatrix is formed with a series of other steps, and then it is possible to converge. The converged matrix is the limit supermatrix that represents the final weights of the factors.

In the integration of gray digital technique and network analysis process in the first phase, the external weight coefficients required to form the initial heterogeneous supermatrix are obtained from matrices pairwise comparisons of elements to the target cluster.

Yang & Tzeng (2011) expansion analysis technique can be used to determine the weighting coefficients of factors in this section. In the second phase, the internal weighting coefficients required to form the initial unbalanced supermatrix are obtained from the diffuse communication matrix of the DEMATEL technique at the level of clusters and elements. In this method, the initial heterogeneous supermatrix is formed according to the defined pattern and finally converges. This method was invented by Tezang and has been used by many people, including (Kahraman et al. 2014). Due to its positive features and capabilities, this method is used in this research.

3.3 gDANP

Step 1. We formulate the effect matrix of all the criteria. Gray-DEMATEL method is used to calculate the total effect of the matrix from each dimension or inhibitory measure with different degrees of effective relationship.

Step 2. Formulation of the weightless supermatrix. After obtaining the standard matrix, the normalization of the initial matrix with the degree of overall effect will be accepted.

Step 3. Calculation of supra-matrix weight matrix of total dimension relations matrix obtained by the gray-DEMATEL method.

Step 4: Limit the supermatrix. As with the conventional ANP method, limiting the supermatrix to power provides a stable weight of criteria. Likewise, the proposed gDANP supermatrix must reach sufficient power. Therefore, the effective weights of each criterion can be obtained.

4. EXPECTED RESULTS

In this study, the gray network analysis method will be used to determine the weight of the criteria and model indices.

Railway policymakers will be able to develop the proposed gDANP evaluation framework between models and logistics operations organizations to evaluate IR more effectively. IRR upgrades and having a strategic plan to upgrade their barriers. Managers can gain valuable managerial insights from many charts

Use the above convergent cause, effect, and criteria to identify insightful decisions.

If procurement and transportation policymakers want to reach the highest level of performance, they will be advised to pay more attention to "deterrence". This level is because factors have a significant effect on the criteria.

The findings of this study will provide a list of priority criteria before and after the spread of coronavirus. By prioritizing impact indicators in both pre- and post-virus situations, logistics policymakers will be able to revise transportation policies. Logistics policymakers can use the proposed framework to analyze the impact of IRR factors on future IRR system development. This study will also provide the next important IRR metrics that may suggest that adequate policy action be taken.

5. CONCLUSIONS

The rail-based freight system has become essential to policymakers in recent years due to its commitment to a sustainable strategy.

Therefore, road freight transportation towards rail transportation and their integration have been given priority. In a complex process of decision and evaluation, many criteria include subjective and qualitative judgments. In such circumstances, MCDM methods can be an effective solution for calculating the barriers to cross-communication of priority importance.

The proposed framework analysis was considered by using an integrated MCDM method, for example, DEMATEL-ANP gray (gDANP), to validate the proposed framework. Experts from different departments of freight organizations are considered.

It is hoped that the results of the post-searcher computational results will confirm that the proposed model will help transport policymakers and stakeholders to improve them.

The decision-making process improves the share of intermodal services, especially in cases where many criteria are interrelated.

The results of future calculations will be presented in the form of ranking and correlation of all criteria.

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CAN RAIL INFRASTRUCTURE DETERMINE PERCEIVED QUALITY OF SERVICE OF SUBURBAN TRAINS? INSIGHTS FROM CERCANÍAS MADRID

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RESUMEN

Public transport modes in urban peripheries have a twofold function: buses provide the territorial capillarity, while the suburban rail acts as the backbone of mobility. Despite its relevance there, suburban rail usually runs on pre-existing tracks for heavy rail services. Moreover, in the current context of rail liberalization in Europe, the infrastructure manager and the rail operator are separate organizations with impacts on suburban rail. Therefore, it is important to discern the responsibilities of both agents in providing a better service, to promote a more sustainable mobility. This work aims to explore how the perceived quality of service (QoS) of suburban rail services can be influenced by the rail network infrastructure. The suburban rail network of Madrid (Cercanías) has been selected as case study because of the combination of pre-existing and new tracks as well as having a total of 9 regular lines, enough to perform this analysis. Data is gathered from the 2019 annual Cercanías traveler satisfaction survey. First, different aspects of the lines are thoroughly examined, such as the travel time between stops, shared sections or the location of the different sections within the metropolitan area. These factors are transformed into indicators to ease comparison. Based on the main indicators and the average QoS, lines are classified into 4 groups. The joint analysis of the infrastructure indicators and the attributes from the traveler satisfaction survey suggests that lines with similar QoS also have features common regarding to infrastructure and operation such as line length or travel time between stations.

1. INTRODUCTION

In the last decades, cities have greatly increased their population that overgrow the cities' limits and settling in nearer population centers, thus configuring metropolitan areas. As an instance, 55% of citizens of main European metropolitan areas dwells in metropolitan rings, which remarks the incoming importance of these areas (EMTA, 2020). Compared with urban centers, these metropolitan peripheries have often lower population densities and less land use mix. That clearly conditions the current metropolitan mobility, since citizens must travel longer for both their daily home-to-work commuter trip and their non-obliged trips (shopping, leisure, etc.). For that reason, mobility policies should go towards a sustainable mobility not only in main cities but also in the whole metropolitan areas, as the European Commission's new Sustainable and Smart Mobility Strategy states (European Commission, 2020).

Currently, mobility in metropolitan rings highly relies on cars (Wolny, 2019). The lower population density and lack of land use mix difficult public transport agencies and operators to provide a high frequency public transport, consequently reducing its competitiveness. Nevertheless, metropolitan areas get configured through corridors given the existing transport infrastructures that previously connected the city with some others: roads upgraded to highways and railway tracks. This is because inhabitants aim to reduce their transport cost living close to these infrastructures (Müller et al., 2010). Public transport can profit from these infrastructures to serve the population in these peripheries. Two main services emerge there: metropolitan buses and suburban railways, using each type of infrastructure. Metropolitan bus services provide the territorial capillarity and accessibility, reaching most of dwellers, and may benefit of high-capacity roads to provide faster connections. However, with great capillarity and low density comes lower frequency, and traffic jams – out of control of bus operators – clearly also affect bus regularity. Suburban rail often provides more frequent, reliable, and higher-capacity services, connecting metropolitan passengers with the main urban transport hubs, thus becoming the backbone of metropolitan mobility.
Furthermore, the previous stages in the liberalization of the railway sector in the European Union has caused, for suburban rail services, the coexistence two agents: the infrastructure manager (IM) and one railway undertaking (RU). Unlike metro networks, where a single company manages both infrastructure and rolling stock, for suburban railways the transport service is offered by the RU, whose rolling stock runs on tracks and stops at stations under the control of the IM. Some key variables for RU such as the track layout, the distance between stations or the maximum speed of each stretch are determined beforehand. In addition, under a railroad disruption to be fixed by the IM, trains cannot take an alternative route. Therefore, this situation can compromise the overall quality of the rail service provided by the RU despite not being its direct responsibility.

The concept of Quality of Service (QoS) in PT is oriented to fulfil the requirements of passengers. With this aim, the EN 13816 Standard (CEN, 2002) proposes 8 categories that comprise the criteria from the user's point of view: availability, accessibility, information, time, customer care, comfort, security and environmental impact. The most widely method used to evaluate QoS in PT is the Traveler Satisfaction Survey (TSS), whose questionnaire is often based on the aforementioned categories. It must be stressed, however, that QoS and satisfaction are not the same concept – user satisfaction may be interpreted as the comparison between the expectations and the perception of the provided service (Mouwen, 2015). These TSS not only make it possible to measure the most highly valued attributes, but also to estimate their relative importance on the overall satisfaction.

Most studies about quality of PT services are focused on bus services or subway systems, which have different characteristics compared to suburban rail services. Nevertheless, several studies estimate the most important service attributes for suburban railway passengers: main factors are related to service supply (e.g. regularity and punctuality), vehicle cleanliness service supply, information and station accessing (de Oña et al., 2015, Weinstein, 2000). When working with TSS in PT services, two consideration must be bear in mind. First, the existence of a psychological “rail factor”, which makes rail services more attractive than buses. In terms of TSS, it results in a better valuation of train services than bus services (Scherer & Dziekan, 2012). Second, there are socio-economic and spatial differences on the perception of the quality of public transport services. As an instance, Grisé and El-Geneidy (2017) found an inverse relationship between socially deprived neighborhoods and passengers’ satisfaction with bus services. Besides, Eboli et al. (2018) found that areas with lower density of rail network leads to lower perceived QoS of Milan’s regional and suburban rail.

To the best of our knowledge, only Eboli et al. (2018) find a relationship between suburban rail network characteristics and perceived QoS. Furthermore, the studies analyzing the QoS on suburban rail does not focuses on the effects of both infrastructure manager and railway undertaking. This work aims to explore how the perceived quality of service of suburban rail services can be influenced by the rail infrastructure characteristics, taking into account the different responsibilities of both infrastructure manager and railway undertaking..

2. CASE STUDY: CERCANÍAS MADRID

We have chosen as a case study the Madrid Region’s suburban rail service, Cercanías Madrid. Madrid Region, located in the center of Spain, had about 6.7 million inhabitants in 2019, of those 3.3 million live in Madrid, the capital of Spain, and about other 3 million live in its metropolitan ring. GDP per capita in Madrid Region was 35,041 euro in 2018, 36 % over the national average (INE, 2020). However, Madrid Region presents a southwest-northeast line of social inequality, with lower incomes and higher unemployment in the southeastern half of the region (Leal & Sorando, 2015).

The public transport network in Madrid is composed by 440 metropolitan bus lines, 205 urban bus lines, 13 Metro lines and 4 light rail lines, 5 multimodal interchange stations – managed by the regional Public Transport Authority (PTA) – and 10 Cercanías lines. Cercanías is the suburban rail division of Renfe Operadora, the Spanish national railway undertaking. Cercanías Madrid was first put in service in 1985 using the long-distance, pre-existing railroad tracks. Currently, their trains run on ADIF tracks, the Spanish national IM. In addition to the pre-existing tracks, some sections specifically designed for suburban rail have also been built. It is noteworthy that Cercanías Madrid manages most stations (access, furniture, etc.) although they are owned by ADIF.

Cercanías Madrid has 9 regular lines and 1 touristic line. The infrastructure network lengths 370 km and has 90 stations. Cercanías Madrid also follows a clear radial structure, with a central area in the inner center of Madrid. That includes a main trunk section with two tunnels connecting the most important rail stations in Madrid (Atocha and Chamartín) and a partially tunneled section from Atocha to Principe Pío (Green Railway Corridor) based on the 19th century railroad track. A more in-detail scheme of the network can be found in Figure 1, including the southwest-northeast line of social inequality and the central area.

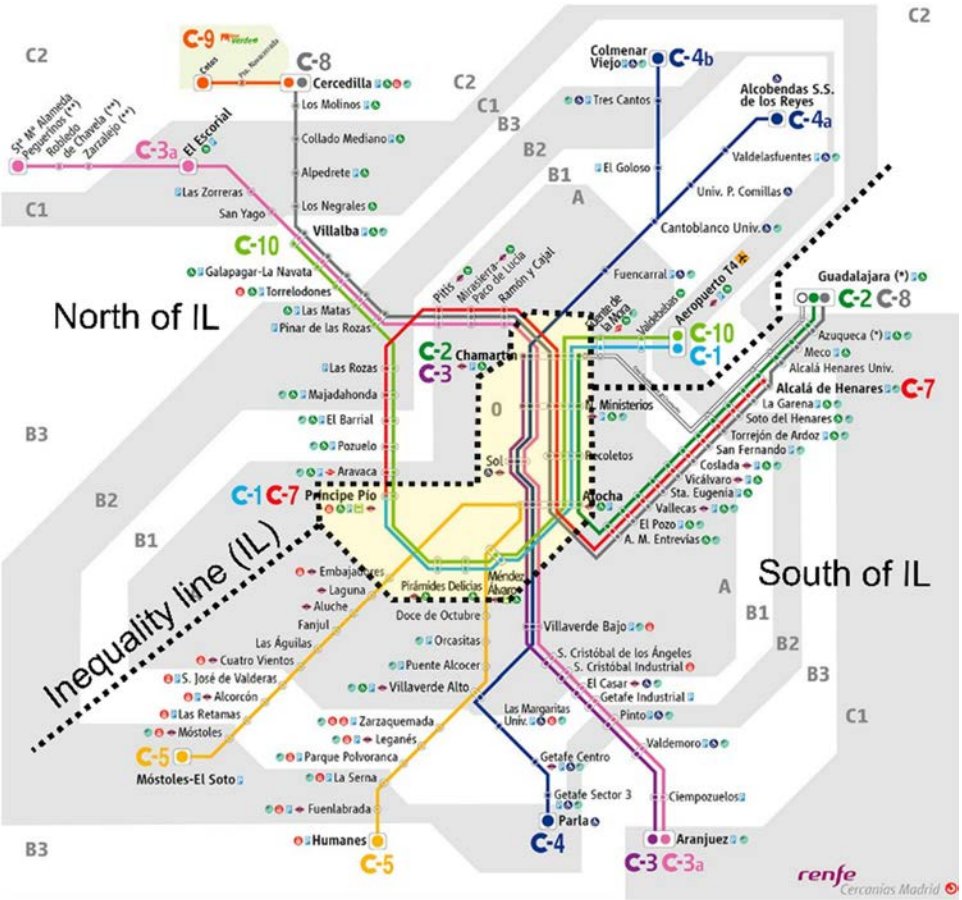

Fig. 1 – Cercanías Madrid network, with the inequality line and the central area (shaded in yellow).

3. METHOD AND DATA SOURCES

The analysis framework is divided in two steps. First, a description of the lines based on several key variables of railway infrastructure and operation. Then, a grouping of the different lines based on the passengers' satisfaction that leads to a comprehensive analysis considering the previous infrastructure and operation variables. This section presents the data acquisition and next it explains the method of each step.

3.1 Data sources

This study needs to compile two different type of information for each line: infrastructure and operation key variables and data about quality of service. First, data on infrastructure and operation has been gathered from several sources. Travel times have been manually collected from Renfe Operadora website. Last, length of lines is obtained from Madrid Region PTA open data portal and the average commercial speed at peak hour and the number of train circulations in peak and off-peak hour are taken from Madrid Region PTA annual report (CRTM, 2021).

On the other hand, data about quality of service derive from the 2019 annual TSS carried out by Renfe Operadora. The survey was conducted in November and December 2019 to about 2,600 passengers, what means that about 200 – 250 surveys per line. The survey questionnaire includes general questions about trip habits (trip frequency, access and dispersion modes…) and passenger characteristics. It also asks to rate a list of service attributes on a scale of 0 to 10. For this work, there were only available the average values for each line.

3.2 Indicators

To properly describe the lines, a set of indicators are selected. Following Alonso et al. (2015), the indicators should ideally meet seven requirements: target relevance, validity, transparency, sensitivity, standardized for comparison, unambiguity, and data reliability and availability. In this case, we prioritize the last criterion over the others. Based on Nicholson et al. (2015) railway evaluation KPIs and public availability of data, 6 indicators are chosen: line *length*, number of *stations* per line, percentage of *shared sections* with other line/s, average *travel time between stations* (i.e. between two consecutive stations), operational *speed* at peak hour, and number of daily *services* per line. The indicators *stations* and average *travel time between stations* have been divided in 3 parts, based in the Madrid Region's southwest-northeast line of social inequality: north (N), central (C) and south (S). That is expected to help in the comparative analysis. Table 1 contains the values of the indicators for each of these lines, which are analyzed in detail in Section 4.

3.3 Grouping

In this step, lines are grouped according to passengers' satisfaction and some key infrastructure characteristics for better understanding the similarities and differences in QoS among lines. Furthermore, it will allow discussing which variables drive the perception towards the different services' attributes. It would be preferable to aggregate the infrastructure attributes into composite indicators. Nevertheless, to the extent of our knowledge, there are not composite indicators of railway infrastructure at line level which may serve as a reference. The solution taken here is to obtain the relative importance of the previous variables on the QoS by using the Pearson's correlation coefficients (Weinstein, 2000). Although it does not provide a direct relationship between these variables, it serves to rank the relative importance of service variables.

Then, groups are compared taking into account their infrastructure and operation characteristics as well as the different variables included in the Cercanías TSS: train supply, regularity and punctuality, travel time, information to passengers, easiness of access to station, station comfort, train comfort, station and train cleanliness, staff attention, customer relationship, security and fares. In the Cercanías Madrid case, the responsibility for train supply, regularity and punctuality, travel time and easiness of access can be shared between ADIF (the IM) and Renfe Operadora (the RU), while the rest of attributes lie predominantly with Renfe Operadora.

4. DESCRIPTIVE ANALYSIS OF LINES

Prior to the analysis of the lines of Cercanías lines, it is pertinent to point out some operational peculiarities of certain lines which may affect to the proper comprehension of the results. First, lines C3 and C3a are commercially two different lines although they run as a single line up to Chamartin, with some services ending at Chamartin (C3) and a few others running northwest. In this paper we have opted to consider it as a single line. Second, lines C4a and C4b operate as a single line with two branches in the north side, with different infrastructure characteristics.

The main variables of the lines are shown in Table 1 (infrastructure) and Table 2 (operation). The average length of lines is 70.5 km. However, it varies considerably from more than 120 km for lines C3a and C8 to just over 20 km for line C1. This clearly affects to the commercial speed: on average it is 50.1 km/h at peak hour, overpassing 55 km/h in the two longest lines and being lower in shorter lines (C1, C5). Despite that, C1 and C5 are the lines with lower average travel time between stations, along with the lines C4a and C4b. On the other side, C3a presents the longest travel time between stations (4.7 minutes), almost a minute above the average (3.8 minutes). It is also noteworthy to glance at the travel times between stations in the central area, since most lines share some sections. More in detail, travel time between Atocha and Chamartin is longer via Recoletos (4.3 min/section) than via Sol (3.7 min/section).

It is also interesting to point out the spatial distribution of lines (Figure 1): C2, C3 and C5 only connects the southern areas of the region with the center of Madrid, while C1 and C10 are exclusive-northern lines. The remaining half of lines links north and south, among them the two longest lines (C3a and C8) are found.

Line	Length (km)	Stations				Shared sections (%)
		Total	S (%)	C (%)	N (%)	
C1	24.5	11	0	73	27	100
C2	64.2	19	79	21	0	100
C3 + C3a	128.9	24	38	17	46	85
C4a	48.2	15	40	27	33	73
C4b	59.2	15	40	27	33	73
C5	45.0	23	87	13	0	0
C7	79.4	24	46	21	33	100
C8	122.4	32	47	13	41	82
C10	62.3	21	0	38	62	100
Avg.	70.5	20.4	46	25	29	79

Table 1 – Main infrastructure variables of Cercanías lines

Line	Travel time between stations (min)	Speed (km/h)	Services (% peak h.)	Average QoS
C1	3.6	38.2	75 (37%)	7.21
C2	4.1	53.9	211 (45%)	7.01
C3 + C3a	4.7	58.9	160 (46%)	6.57
C4a	3.7	51.7	285 (49%)	7.08
C4b	3.3	46.4	302 (54%)	7.03
C5	2.5	46.4	302 (54%)	7.40
C7	4.0	50.2	101 (57%)	7.36
C8	4.4	55.4	46 (50%)	6.64
C10	4.3	39.2	165 (51%)	7.26
Avg.	3.9	49.5	149 (49%)	7.13

Table 2 – Main operation variables of Cercanías lines

5. COMPARATIVE ANALYSIS OF LINES BASED ON THE PERCEIVED QUALITY OF SERVICE

The descriptive analysis of the lines provides a general overview of the lines, with clear differences on length, operational speed at peak hour or travel time between stations. This may give a broad idea of the service offered, but it does not relate to the QoS perceived by travelers. To that extent, the relative importance of each service attribute is obtained using Pearson’s correlation coefficient. Then, the most important variables are line length (-0.79) and travel time between stations (-0.68). The negative sign implies that the longest the line and the travel time, the worst QoS. These three variables (QoS, line length and travel time between stations) are displayed in a scatter plot (Figure 2) where four groups of lines can be extracted. This analysis based in groups was carried out to ease the description of the results, without aiming to provide a statistically consistent classification of lines.

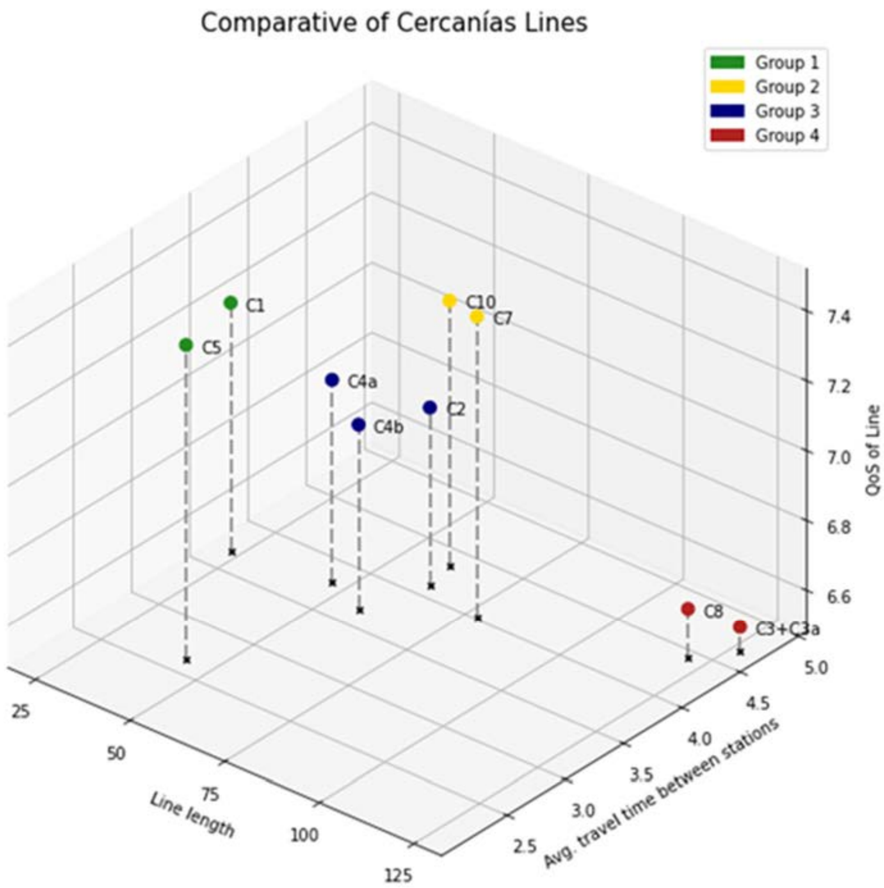

Fig. 2 – Grouping of lines according to the passengers' satisfaction and key infrastructure satisfaction as defined in Section 3.2

The four resulting groups are sorted based on their average QoS, resulting in Group 1 (C1, C5), Group 2 (C7, C1, C10), Group 3 (C4a, C4b, C2) and Group 4 (C3, C8). Hereby, Group 1 has the higher overall perceived quality (+0.27 above average), followed by Group 2 (+0.18). At this stage, we include into the analysis the passengers' perception towards the different service attributes mentioned in Section 3.3. To ease comparison, Table 3 shows the difference, for each attribute, between the groups' rating and the network average and also the highest difference between groups. Overall perceived quality is also included in Table 3 to facilitate the discussion. Below the four groups are analyzed in detail, followed by some considerations on infrastructure issues.

Attribute	Group 1	Group 2	Group 3	Group 4	Max. difference among groups
Supply	0.19	0.25	0.09	-1.06	1.31
Regularity	0.33	0.00	-0.09	-0.69	1.01
Travel time	0.41	0.12	-0.29	-0.56	0.97
Information	0.11	0.29	-0.06	-0.47	0.76
Access to station	0.11	0.17	-0.11	-0.38	0.55
Station Comfort	0.15	0.09	0.06	-0.53	0.68
Train Comfort	0.16	0.09	-0.08	-0.26	0.41
Cleanliness	0.11	0.08	0.00	-0.39	0.50
Staff attention	0.08	0.22	-0.19	-0.13	0.40
Customer relationship	0.19	0.31	-0.08	-0.60	0.91
Safety	0.11	0.36	-0.05	-0.29	0.65
Fares	0.11	0.09	-0.04	-0.32	0.43
Overall perceived quality	0.22	0.18	-0.09	-0.54	0.76

Table 3 – Attribute rating among clusters. Difference between value of group and Cercanías Madrid average.

5.1 Group 1: Short, well-perceived lines

The first group consists of C5 and C1. This is the group with less travel time between stations (3.0 min on average) and with more daily circulations (188 on average), although its operational speed is lower than the average. This situation clearly impacts to the satisfaction results. In addition to being the highest-rated group, the service's attributes where the group overperforms are regularity and travel time, which seems to be in consonance with the operational characteristics of the lines.

5.2 Group 2: Long, well-perceived lines

The second-best rated group comprises lines C7 and C10: two long lines (70.8 km on average) that connect the city of Madrid with one edge of the metropolitan area. They share a common section at the northwest of the inequality line, and they mostly serve to the northern half of the network, which could explain why this group is perceived as the most secure (+0.36) and with the best customer relationship (+0.31)). This group is also well rated at train supply (+0.25) – while they are below average in daily services (11% below average), this is the group that most concentrates its supply during peak hours (53% of services) and furthermore two or more lines stop at every station of this group, so passengers may perceive a greater supply than other groups.

5.3 Group 3: Balanced lines

The third group includes the lines C2, C4a and C4b. While C4a and C4b lines share most of the route and only split at the north, line C2 does not have any section in common with the former lines. Their most distinctive feature is the number of daily services, 10% above average, while the other attributes are quite close to the network average. In addition, this group has most of their service attributes rated just a bit below the average: only station comfort (+0.06) and train supply (+0.09) overperform; the latter having a meaning given the high volume of daily services.

5.4 Group 4: Underperforming longest lines

The remaining lines C3 and C8 form the last group. This group has the lowest overall perceived quality (0.52 below average) and being the worst rated group in every attribute except for the "staff attention" (-0.12). In contrast to the Group 2, train supply (-1.06), regularity (-0.69) and travel time (-0.56) are three of the most underperforming attributes. As already mentioned, they are the longest lines. In addition, they are the lines with the highest number of stations and the longest travel time between stations, despite being the lines with highest operational speed.

5.5 Effects of rail infrastructure on QoS and stakeholders' responsibilities

It is also possible to perceive some effect of the infrastructure on QoS, based on similarities and differences of attributes ratings among groups, with data extracted from Table 3. The attributes with the least variation among groups are train comfort (0.41), staff attention (0.40) and fares (0.43), which are independent of the infrastructure characteristics. Conversely, the most divergent attributes are train supply (1.31), regularity (1.01) and travel time (0.97), in which both the infrastructure manager and the railway undertaking are involved.

6. DISCUSSION AND CONCLUSIONS

This study aims to obtain an overview of the quality of service in suburban rail considering general infrastructure and operational parameters. To achieve that objective, we take a line-based approach and apply a two-steps procedure to the Cercanías Madrid case study. We first analyze the general characteristics of that lines and then we classify the lines in four groups according to the average passengers' satisfaction and key characteristics of lines, leading to a comprehensive examination of the service considering both sides.

The most relevant line attributes seem to be the travel time between stations and the total line length. In fact, the best rated group (Group 1, 0.22 above average) has the lower travel time between stations (3.0 min), which may be coupled with a much higher ratings of regularity and travel time. On the other hand, the worst rated group (Group 4, 0.54 below average) only comprises the longest lines, having the higher average speed but also the higher average travel time between stations. We find that the most constant attributes from the TSS depend solely on the RU, while the most varying ones depend both on RU and IM, thus having the infrastructure some sort of effect on the perceived QoS. Last, as for the socioeconomic or territorial effects on the service, we can only suggest a slight positive relationship with perceived security in north-based lines, but that deserves to be analyzed more in depth.

Future work should be directed at quantifying the effect of the different parameters of infrastructure (e.g. length, travel time) on passengers' satisfaction and, more specifically, on some attributes such as the passengers' satisfaction with regularity or travel time. There is also room for exploring the responsibility of IM and RU by including variables related to railroad capacity and/or blocking. That gained knowledge will help both agents to enhance certain aspects of the service, leading to the identification of areas for individual and joint improvements. In the end, it will result in an increase in satisfaction and a potential increase in the ridership of the suburban railroad, promoting a more sustainable mobility in metropolitan areas

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RELACIÓN ENTRE TIEMPOS DE OPERACIÓN DE AUTOBUSES URBANOS Y TIEMPOS DE RECORRIDO DE TRÁFICO GENERAL

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RESUMEN

El presente estudio tiene por objetivo comparar los tiempos de viaje en autobús con los tiempos de recorrido del tráfico general en A Coruña. Esta comparación permite, por una parte, determinar la relación existente entre la velocidad de circulación de los autobuses y el tráfico general a lo largo del mismo trayecto y sentido de la calzada, y por otra, determinar y cuantificar otros factores que influyen en la misma. Esta información puede ser útil para la planificación de nuevas líneas o la determinación de la necesidad de implantación de plataformas reservadas.

Para llevar a cabo el estudio se han utilizado, por un lado, datos de llegada de autobuses urbanos a cada una de las paradas situadas dentro del tramo a analizar. Esta información se obtiene a partir de la base de datos del Sistema de Ayuda a la Explotación de la Compañía de Tranvías de La Coruña. Por otro lado, el tiempo de recorrido del tráfico general se obtiene explotando los datos recogidos por el Ayuntamiento de A Coruña mediante sensores localizados en diferentes puntos de la ciudad, que detectan dispositivos bluetooth activos y registran la información cada 3 minutos.

Por el momento, el análisis se ha centrado en la relación entre los tiempos de operación de los autobuses urbanos y el tiempo de recorrido del tráfico general en los días naturales del mes de febrero de 2019, en un corredor en concreto, que constituye una de las principales vías colectoras de la ciudad: Ronda de Outeiro entre la Estación de Tren y la intersección con la Tercera Ronda en A Coruña, con una distancia recorrida de 2400 m.

1. INTRODUCCIÓN

El tiempo de recorrido del transporte público urbano, así como su relación con el tráfico general, ha sido objeto de análisis en numerosos estudios desde hace décadas. En Levinson (1983) se calculan las velocidades de tránsito y demoras del autobús en una muestra representativa de varias ciudades de Estados Unidos. En este mismo estudio se concluye que la velocidad del coche es entre 1.4 y 1.6 veces más rápida que la del autobús, utilizando como variables la distancia entre paradas, congestión del tráfico, embarque y desembarque de viajeros, y número de aceleraciones y deceleraciones.

En estudios posteriores se ha continuado con el objetivo de relacionar ambos tiempos de recorrido, utilizando modelos de regresión lineal y añadiendo nuevas variables para llevar a cabo la comparación (McKnight *et al.*, 2004). Estos modelos se han perfeccionado en los últimos años con la incorporación de datos GPS (Bertini y Tantiyanugulchai, 2004; Mazloumi, Currie y Rose, 2010), favoreciendo la creación de marcos teóricos de predicción de tiempos medios de recorrido, hora de llegada a parada o velocidades del transporte público a partir de datos de entrada como el tráfico general (Chien, Ding y Wei, 2002; Chakroborty y Kikuchi, 2004; Mazloumi et al., 2011).

Los teléfonos móviles proporcionan gran cantidad de información que puede ser utilizada para estimar la demanda de viajes de autobús a través de la utilización de aplicaciones como Twitter que geolocaliza las publicaciones (Liao *et al.*, 2020). Por otro lado, estos dispositivos con bluetooth activo pueden ser localizados por sensores que calculan y registran las velocidades y tiempos de recorrido del vehículo en el que se encuentran (Imam, Bhaskar y Chung, 2017), y permiten comparar estos datos con los del transporte público (Kieu, Bhaskar y Chung, 2015). En Banik, Vanajakshi and Bullock (2020) el tiempo de recorrido de los vehículos de tráfico general en Chennai (India) se registra a partir de sensores Wi-Fi y se compara con el tiempo de recorrido del autobús equipado con GPS.

En Liao et al. (2020) se concluye que el transporte público tarda de media entre 1.4 y 2.6 veces más que el automóvil privado en recorrer la misma distancia en cuatro ciudades diferentes. En el presente estudio se analizará la relación entre tiempos de recorrido de autobús y tráfico general en la ciudad de A Coruña.

La ponencia se estructura de la siguiente forma: tras este primer apartado introductorio se presenta la metodología seguida para realizar el análisis, en el tercer apartado se exponen los resultados obtenidos y, en el cuarto, se presentan las primeras conclusiones y futuras líneas de investigación a desarrollar a partir de este estudio inicial.

2. CASO DE ESTUDIO Y METODOLOGÍA

En el presente estudio se analizará la relación entre el autobús urbano de A Coruña y el tráfico general durante el mes de febrero de 2019 en la Ronda de Outeiro a lo largo de un corredor de 2400 m de longitud, entre la Estación de Tren y la intersección con la Tercera Ronda. La Ronda de Outeiro es una de las arterias principales de A Coruña: todas las vías de salida y entrada a la ciudad se conectan con esta Ronda. Además, comunica con el Polígono de la Grela, con más de 500 empresas instaladas en una superficie de 1.400.000 m^2, por lo que el tráfico es elevado en hora punta. El tramo objeto de estudio consta de dos carriles de circulación y 10 paradas de autobús a lo largo de su recorrido pertenecientes a diferentes líneas regulares de la Compañía de Tranvías de La Coruña: 5, 7, 12A, 14, 20 y BUH (nocturna). De las líneas diurnas solo la 12A y la 14 recorren el corredor completo. Para el presente estudio se ha tenido en cuenta la línea 14, que comunica los barrios de Los Rosales y Castrillón. La ubicación de las paradas y de los sensores en el tramo se muestra en la Figura 1.

Para analizar la relación entre tiempos de operación de autobuses urbanos en A Coruña y los tiempos de recorrido de tráfico general se han utilizado dos fuentes de datos. Por un lado, se obtienen los tiempos de llegada del autobús a las paradas seleccionadas, entre las 7:00 y las 23:45 horas, a partir de la base de datos del Sistema de Ayuda a la Explotación de la Compañía de Tranvías de La Coruña. Por otro lado, el tiempo de recorrido del tráfico general se obtiene a partir de los datos recogidos por el Ayuntamiento de A Coruña a través de sensores localizados en diferentes puntos de la ciudad. Estos sensores detectan los dispositivos bluetooth activos, los codifican y registran la información cada 3 minutos. Obteniendo esta información de varios sensores se deduce la procedencia de los vehículos y se conocen los tramos por los que han circulado, así como sus tiempos medios de recorrido cada 3 minutos.

Figura 1. Paradas de autobús y sensores bluetooth en el tramo objeto de estudio. Fuente: Elaboración propia a partir de mapa de paradas de autobús y sensores en A Coruña.

El primer paso para llevar a cabo el análisis será obtener el tiempo total de recorrido de los autobuses urbanos a partir de los tiempos de llegada de los mismos a cada parada durante los días naturales del mes de febrero de 2019. El tiempo total de recorrido se calcula como la diferencia entre el instante de llegada a la parada final (559) y el instante de llegada a la parada inicial (119). En la Tabla 1 se presentan los datos obtenidos para uno de los días estudiados.

No se han considerado para el análisis los tiempos de viaje de autobuses con situaciones anómalas, como inexistencia de registros del instante de paso por alguna parada del tramo, o servicios con cambios de turno de personal en alguna de ellas que dan lugar a aumentos adicionales del tiempo de viaje no atribuibles a las condiciones de tráfico ni de operación normal.

El siguiente paso para realizar la comparación entre ambos tiempos de recorrido será calcular el tiempo que tarda el tráfico general en recorrer el mismo corredor. Este corredor se encuentra delimitado por cuatro sensores de detección bluetooth (numerados en la Figura 1), que forman, entre cada par, tres vectores:

- Vector 44. Tramo entre sensores 1-2.
- Vector 62. Tramo entre sensores 2-3.
- Vector 23. Tramo entre sensores 3-4.

Autobús urbano										
Hora de llegada a parada										Tiempo de recorrido total autobús (s)
119	120	121	122	123	124	125	126	127	559	
07:53:48	07:54:42	07:55:34	07:56:32	07:57:56	07:58:28	07:59:32	08:00:07	08:01:34	08:02:30	522
08:09:47	08:11:07	08:11:31	08:12:33	08:13:51	08:14:21	08:14:47	08:15:35	08:16:23	08:17:41	474
08:28:42	08:29:28	08:30:16	08:31:32	08:32:50	08:33:20	08:34:42	08:35:18	08:36:22	08:37:34	532
08:41:49	08:42:48	08:43:33	08:44:24	08:45:39	08:47:19	08:47:49	08:48:51	08:50:35	08:51:52	603
08:57:40	08:58:42	08:59:32	09:01:13	09:01:56	09:03:14	09:03:52	09:04:44	09:06:10	09:07:11	571
09:13:12	09:13:44	09:14:30	09:15:30	09:16:15	09:17:30	09:18:08	09:18:56	09:19:49	09:20:58	466
09:32:06	09:33:32	09:33:55	09:34:48	09:36:24	09:37:58	09:38:24	09:38:42	09:39:40	09:40:38	512
09:54:40	09:55:46	09:56:29	09:57:00	09:58:20	10:00:14	10:01:02	10:01:54	10:03:16	10:04:24	584
10:03:58	10:05:04	10:05:26	10:06:32	10:06:58	10:08:12	10:09:02	10:10:04	10:11:28	10:12:20	502
10:24:34	10:25:58	10:26:18	10:28:20	10:28:46	10:30:21	10:31:00	10:31:49	10:33:32	10:34:34	600
10:45:00	10:46:14	10:47:08	10:48:55	10:49:26	10:50:48	10:51:30	10:52:20	10:54:02	10:55:00	600
10:59:38	11:00:33	11:01:04	11:03:15	11:04:50	11:06:44	11:08:03	11:08:46	11:10:11	11:11:55	737
11:11:58	11:13:18	11:13:44	11:15:58	11:17:42	11:19:20	11:20:04	11:20:50	11:22:24	11:23:39	701
11:34:00	11:34:35	11:35:34	11:36:56	11:38:20	11:38:48	11:39:44	11:40:32	11:41:45	11:42:52	532
11:55:02	11:56:04	11:57:22	11:58:54	12:00:22	12:01:08	12:02:14	12:02:48	12:04:18	12:05:54	652
12:12:00	12:12:49	12:13:38	12:14:49	12:15:17	12:17:02	12:17:50	12:18:37	12:20:18	12:21:58	598
12:21:48	12:23:28	12:24:04	12:25:22	12:25:56	12:27:28	12:28:10	12:29:06	12:30:12	12:31:30	582
12:48:49	12:50:32	12:51:58	12:53:47	12:55:13	12:56:05	12:57:17	12:58:02	12:59:26	13:01:55	786
12:59:10	13:00:00	13:01:04	13:02:10	13:02:56	13:04:18	13:05:58	13:06:44	13:07:54	13:08:47	577
13:20:12	13:21:04	13:21:49	13:23:02	13:25:02	13:25:45	13:27:01	13:27:50	13:28:58	13:29:55	583
13:32:28	13:33:33	13:34:19	13:35:29	13:36:16	13:37:34	13:38:20	13:39:11	13:40:50	13:42:07	579
13:55:13	13:56:53	13:57:37	13:58:33	13:59:59	14:00:43	14:02:06	14:02:51	14:04:19	14:06:31	678
14:04:50	14:05:40	14:06:27	14:07:14	14:07:44	14:08:54	14:09:48	14:10:38	14:11:38	14:13:36	526
14:25:00	14:25:47	14:26:44	14:28:09	14:28:44	14:30:07	14:31:37	14:32:41	14:34:23	14:36:29	689
14:42:28	14:43:21	14:44:24	14:45:48	14:47:17	14:49:14	14:50:47	14:51:25	14:52:59	14:53:59	691
15:01:47	15:03:21	15:04:21	15:06:21	15:07:19	15:08:29	15:09:29	15:10:48	15:12:25	15:13:27	700
15:15:46	15:16:47	15:17:31	15:18:55	15:19:26	15:20:54	15:22:21	15:23:02	15:24:23	15:25:31	585
15:38:37	15:39:21	15:40:18	15:41:40	15:43:11	15:43:50	15:45:14	15:46:09	15:47:20	15:48:27	590
15:57:07	15:58:40	15:59:32	16:01:11	16:02:52	16:04:29	16:06:15	16:07:07	16:08:25	16:10:42	815
16:13:05	16:14:13	16:15:13	16:16:45	16:18:18	16:20:13	16:21:07	16:22:07	16:24:03	16:25:23	738
16:27:48	16:29:08	16:30:54	16:32:34	16:34:00	16:36:04	16:37:42	16:38:30	16:39:48	16:40:52	784
16:53:55	16:55:23	16:56:16	16:58:27	17:00:14	17:01:08	17:02:12	17:02:56	17:04:14	17:05:09	674
17:22:01	17:23:38	17:25:07	17:28:05	17:29:58	17:32:01	17:33:48	17:35:23	17:37:32	17:39:05	1024
17:30:31	17:32:07	17:33:43	17:35:13	17:36:59	17:37:43	17:39:07	17:40:40	17:42:23	17:44:11	820
17:55:06	17:56:36	17:58:15	18:00:00	18:01:31	18:03:33	18:05:04	18:06:00	18:07:16	18:09:56	890
18:25:07	18:27:12	18:28:48	18:31:07	18:33:00	18:34:51	18:36:43	18:38:18	18:40:01	18:41:28	981
18:45:47	18:48:12	18:49:48	18:52:05	18:54:03	18:56:01	18:57:32	18:58:34	19:00:29	19:02:26	999
19:01:11	19:03:23	19:04:53	19:06:38	19:08:18	19:10:05	19:11:37	19:12:40	19:14:07	19:15:46	875
19:27:57	19:31:05	19:32:42	19:34:11	19:36:01	19:37:59	19:39:44	19:40:36	19:42:00	19:44:35	998
19:42:08	19:43:40	19:45:01	19:46:43	19:48:13	19:49:05	19:50:15	19:50:59	19:52:21	19:53:29	681
20:11:18	20:13:06	20:14:01	20:16:09	20:18:04	20:20:01	20:21:49	20:22:34	20:24:03	20:26:35	917
20:25:44	20:27:05	20:27:53	20:30:03	20:30:45	20:32:35	20:33:59	20:34:41	20:36:17	20:38:19	755
20:50:37	20:52:47	20:53:52	20:54:56	20:56:25	20:57:15	20:58:27	20:59:09	21:00:09	21:01:34	657
21:00:46	21:02:29	21:03:42	21:05:17	21:06:47	21:08:20	21:09:51	21:11:24	21:12:57	21:14:17	811
22:17:04	22:18:25	22:18:49	22:20:48	22:21:38	22:23:03	22:24:21	22:25:00	22:26:03	22:27:08	604
22:36:06	22:37:18	22:37:59	22:38:41	22:39:55	22:40:44	22:41:53	22:43:16	22:44:51	22:45:47	581
22:50:13	22:51:41	22:52:51	22:54:01	22:54:32	22:56:03	22:56:51	22:57:31	22:58:57	23:00:31	618
23:05:29	23:06:13	23:06:31	23:07:09	23:07:33	23:07:57	23:08:51	23:09:09	23:10:15	23:10:58	329
23:23:29	23:24:12	23:24:47	23:25:38	23:26:08	23:27:23	23:28:07	23:28:47	23:30:04	23:30:54	445

Tabla 1. Tiempo de recorrido del autobús en el corredor durante el día 03.02.2019.

Para el cálculo del tiempo de recorrido del tráfico general se considerarán los tiempos de recorrido de los vectores en los intervalos temporales en los que el autobús estuvo circulando por dichos vectores. De esa forma solo se tendrán en cuenta las condiciones de tráfico de cada vector que realmente han podido influir en la velocidad del autobús. Tal y como se representa en la Figura 1, los sensores no coinciden de forma exacta con las paradas del autobús urbano. Para considerar que el autobús ha salido de un vector se tiene en cuenta la parada inmediatamente posterior a la posición del detector de bluetooth que determina su fin. Se ha utilizado este criterio porque el sistema de ayuda a la explotación (SAE) de la operadora registra el instante de llegada a la parada cuando el autobús se encuentra a una distancia de alrededor de 30 m de la misma. Por tanto, considerando la parada inmediatamente posterior se ajusta de forma adecuada el tiempo de estancia en el vector para tomar datos del tráfico general.

Por tanto, para cada vector se considerará el tiempo medio del tráfico general en los períodos en que el autobús se encuentre entre las siguientes paradas:

- Vector 44. Paradas 119 a 122.
- Vector 62. Paradas 122 a 124.
- Vector 23. Paradas 124 a 559.

Como se ha mencionado anteriormente, los datos obtenidos de los dispositivos bluetooth activos se registran cada 3 minutos. En cada instante temporal se registra el tiempo medio que han tardado en recorrer el vector los vehículos que han llegado al segundo sensor del mismo en los 3 minutos anteriores. Por lo tanto, no se obtiene el dato de tiempo de recorrido medio del tráfico general en un vector a la hora exacta de llegada del autobús a la parada. Para llevar a cabo la comparación de datos de forma rigurosa, se empezarán a considerar los datos de un vector desde el instante de registro inmediatamente posterior a la llegada del autobús al mismo, de manera que se obtendrán los tiempos de tránsito de los vehículos que han estado simultáneamente con el autobús en ese tramo. En la Figura 2 se muestra un ejemplo del registro de tiempos de recorrido del tráfico general mediante sensores bluetooth a partir del recorrido del autobús urbano.

Una vez hecha la aproximación a los instantes de registro inmediatamente posteriores a la llegada del autobús a la parada final e inicial de cada vector, se procede a calcular el promedio de tiempos de recorrido del tráfico general en los vectores 44, 62 y 23 a partir de los datos recogidos por el Ayuntamiento de A Coruña. Si el autobús urbano llega a la parada 119 a las 11:02:50 y a la parada 122 a las 11:05:30, se hará el promedio del tiempo de recorrido del tráfico en el vector 44 para los registros de las 11:03 y 11:06. Calculando el promedio de estos dos tiempos registrados se obtiene el tiempo de recorrido medio del tráfico general en el vector 44 en el período en el que el autobús circuló por el mismo. Este procedimiento se repite de forma análoga para los vectores 62 y 23. Por último, la suma de estos tres promedios será el tiempo medio total de recorrido del tráfico general para el corredor considerado.

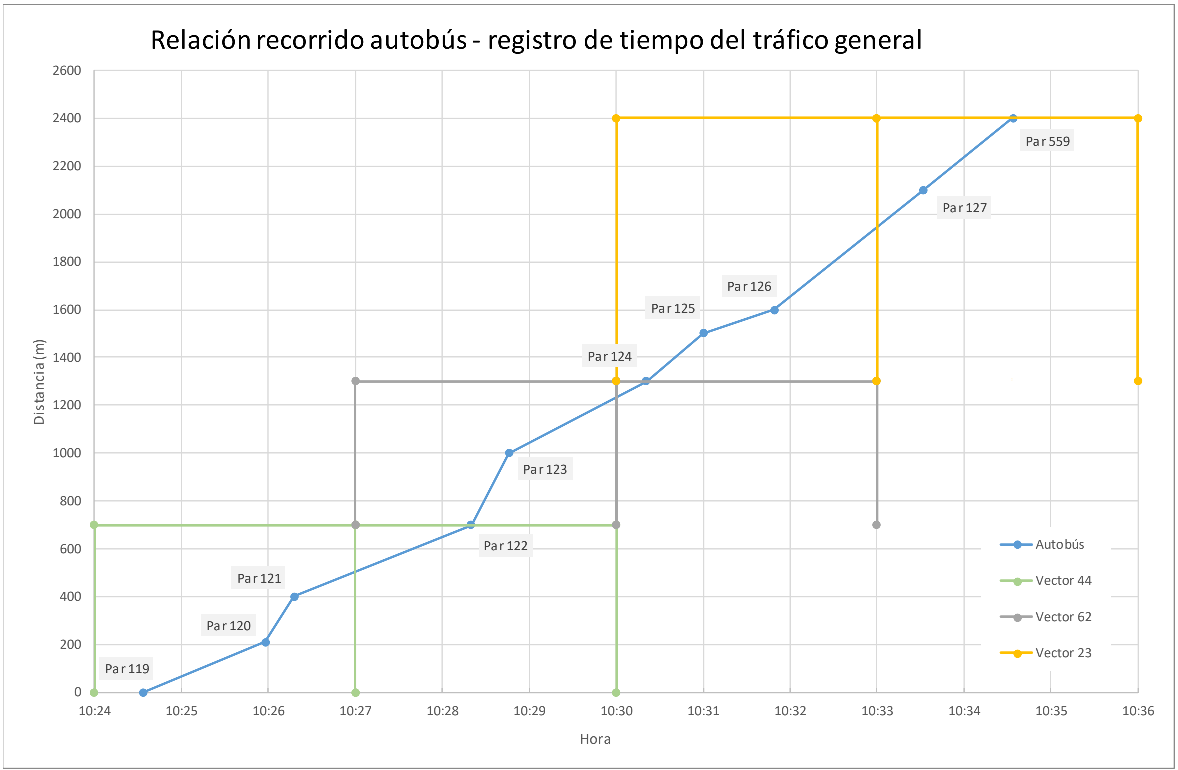

Figura 2. Representación del recorrido del autobús y el registro de tiempo de recorrido medio del tráfico general mediante sensores bluetooth activos. Ejemplo del día 03.02.2019.

3. RESULTADOS Y DISCUSIÓN

A partir de los tiempos de recorrido del autobús urbano y el tráfico general durante el mes de febrero de 2019, obtenidos siguiendo la metodología descrita en el apartado anterior, es posible conocer el ratio entre ambos en el tramo objeto de estudio.

En la Tabla 2 se presentan los tiempos totales de recorrido del tráfico general correspondientes a cada uno de los autobuses considerados para una fecha concreta. En la tabla se incluye también esta proporción entre el tiempo de recorrido del autobús y el tiempo medio del tráfico general, así como el intervalo de paso con respecto al autobús anterior de la misma línea.

Hora llegada autobús Parada 119	Tiempo de recorrido total autobús (s)	Tráfico general				Proporción autobús - tráfico	Intervalo entre autobuses (min)
		Promedio tiempos de recorrido (s)			Total tiempo recorrido (s)		
		Vector 44	Vector 62	Vector 23			
07:53:48	522	111.49	54.79	125.90	292.18	1.79	
08:09:47	474	109.35	73.64	139.41	322.40	1.47	15.69
08:28:42	532	91.40	81.17	138.26	310.83	1.71	19.25
08:41:49	603	96.68	96.69	164.08	357.45	1.69	13.46
08:57:40	571	84.78	100.35	169.34	354.47	1.61	15.96
09:13:12	466	100.82	83.23	139.59	323.64	1.44	14.43
09:32:06	512	102.65	86.03	132.23	320.91	1.60	19.76
09:54:40	584	82.43	78.21	130.49	291.13	2.01	22.70
10:03:58	502	82.98	89.86	145.35	318.19	1.58	8.60
10:24:34	600	106.54	69.07	128.10	303.71	1.98	21.61
10:45:00	600	91.56	79.97	196.65	368.17	1.63	20.52
10:59:38	737	100.20	77.06	162.94	340.19	2.17	15.46
11:11:58	701	101.77	92.77	130.46	325.00	2.16	12.40
11:34:00	532	115.97	94.33	133.13	343.43	1.55	20.42
11:55:02	652	104.10	65.90	155.13	325.13	2.01	22.10
12:12:00	598	108.34	57.96	129.43	295.73	2.02	16.02
12:21:48	582	100.73	56.14	145.41	302.27	1.93	10.28
12:48:49	786	102.65	84.35	126.98	313.98	2.50	28.60
12:59:10	577	100.09	120.56	136.46	357.11	1.62	8.59
13:20:12	583	112.72	65.03	138.18	315.93	1.85	21.16
13:32:28	579	86.48	93.93	148.53	328.93	1.76	11.95
13:55:13	678	99.10	63.13	144.57	306.79	2.21	23.46
14:04:50	526	92.80	114.47	177.12	384.38	1.37	8.17
14:25:00	689	96.88	62.32	122.93	282.12	2.44	21.32
14:42:28	691	118.66	89.21	129.57	337.44	2.05	18.20
15:01:47	700	110.27	71.47	154.45	336.19	2.08	19.61
15:15:46	585	97.01	72.54	155.85	325.39	1.80	12.68
15:38:37	590	109.67	75.22	151.31	336.20	1.75	22.95
15:57:07	815	89.54	65.19	140.68	295.41	2.76	20.22
16:13:05	738	107.75	65.78	131.01	304.53	2.42	15.41
16:27:48	784	86.40	73.40	131.30	291.10	2.69	15.69
16:53:55	674	106.96	68.24	152.78	327.98	2.06	25.26
17:22:01	1024	92.24	60.98	128.25	281.47	3.64	30.67
17:30:31	820	123.25	82.92	133.86	340.03	2.41	6.60
17:55:06	890	93.73	81.01	133.80	308.54	2.88	25.07
18:25:07	981	99.16	82.16	148.15	329.47	2.98	31.33
18:45:47	999	109.87	88.43	132.02	330.33	3.02	20.84
19:01:11	875	134.75	102.87	132.52	370.13	2.36	14.37
19:27:57	998	115.14	94.38	142.93	352.45	2.83	27.82
19:42:08	681	113.14	68.65	138.91	320.69	2.12	11.51
20:11:18	917	99.97	76.50	142.66	319.13	2.87	30.58
20:25:44	755	108.88	65.40	143.73	318.01	2.37	12.97
20:50:37	657	137.22	86.87	189.33	413.42	1.59	24.78
21:00:46	811	143.49	85.73	151.32	380.54	2.13	11.07
22:17:04	604	128.75	101.01	140.23	369.99	1.63	74.65
22:36:06	581	102.25	81.06	111.03	294.34	1.97	18.42
22:50:13	618	104.41	85.45	149.17	339.03	1.82	14.67
23:05:29	329	80.64	75.40	160.88	316.92	1.04	12.69
23:23:29	445	99.71	74.41	135.75	309.86	1.44	18.94

Tabla 2. Tiempo de recorrido medio del tráfico general durante el día 03.02.2019.

Como se puede apreciar en la Figura 3, cuanto mayor es el tiempo de recorrido del tráfico general, mayor es el tiempo de recorrido del autobús urbano, observándose en el gráfico cierta correlación entre las dos variables. En la primera semana de febrero, representada en la Figura 3, se han analizado un total de 452 autobuses correspondientes a la línea 14. Durante estos primeros 7 días analizados se concluye que el transporte público tarda entre 1.04 y 3.64 veces más que el tráfico general en recorrer la misma distancia, con una proporción promedio de tiempos de recorrido de 2.03. De forma visual, se puede apreciar en la Figura 3 que la mayoría de registros se sitúan entre los límites marcados por las rectas que representan, por un lado, el tiempo de recorrido de autobús equivalente al del tráfico general (y=x) y, por otro lado, el tiempo de recorrido del autobús triplicando el valor del tráfico general (y=3x). Para los días considerados en la Figura 3, el tiempo de recorrido medio del autobús urbano es de 773 s mientras que el del tráfico general se sitúa en 381 s.

Se ha considerado como umbral de condiciones de tiempo medio mínimo del tráfico general, aquel valor en minutos enteros con al menos 10 valores por debajo. De la misma forma, se ha considerado el umbral de tiempo máximo como el valor con al menos 10 valores por encima. En condiciones de tiempo de tráfico general mínimo, menores que 300 s (5 min), el tiempo de recorrido medio del autobús es de 662 s (11 min). Si se consideran los tiempos máximos del tráfico general, mayores que 480 s (8 min), se obtiene un promedio de tiempo de recorrido del autobús de 1020 s (17 min). Por consiguiente, se puede observar que, entre la situación más y menos favorable para el autobús urbano respecto a la presencia del tráfico general, existe un aumento de tiempo medio de recorrido de 1.54 veces.

Por otro lado, analizando los tiempos de recorrido mínimos y máximos del autobús, por debajo del percentil 5 y superior al percentil 95 de los datos, se obtienen tiempos de recorrido promedio de 487 s y 1162 s respectivamente, produciéndose un ratio de aumento de 2.39. Este dato contrasta con el ratio de 1.94 en el caso del tráfico general, ya que el rango de tiempo de recorrido entre ambos casos extremos es de 5 a 9 min mientras que el autobús se mueve entre los 8 y 19 min, aumentando el tiempo de recorrido máximo en 10 min.

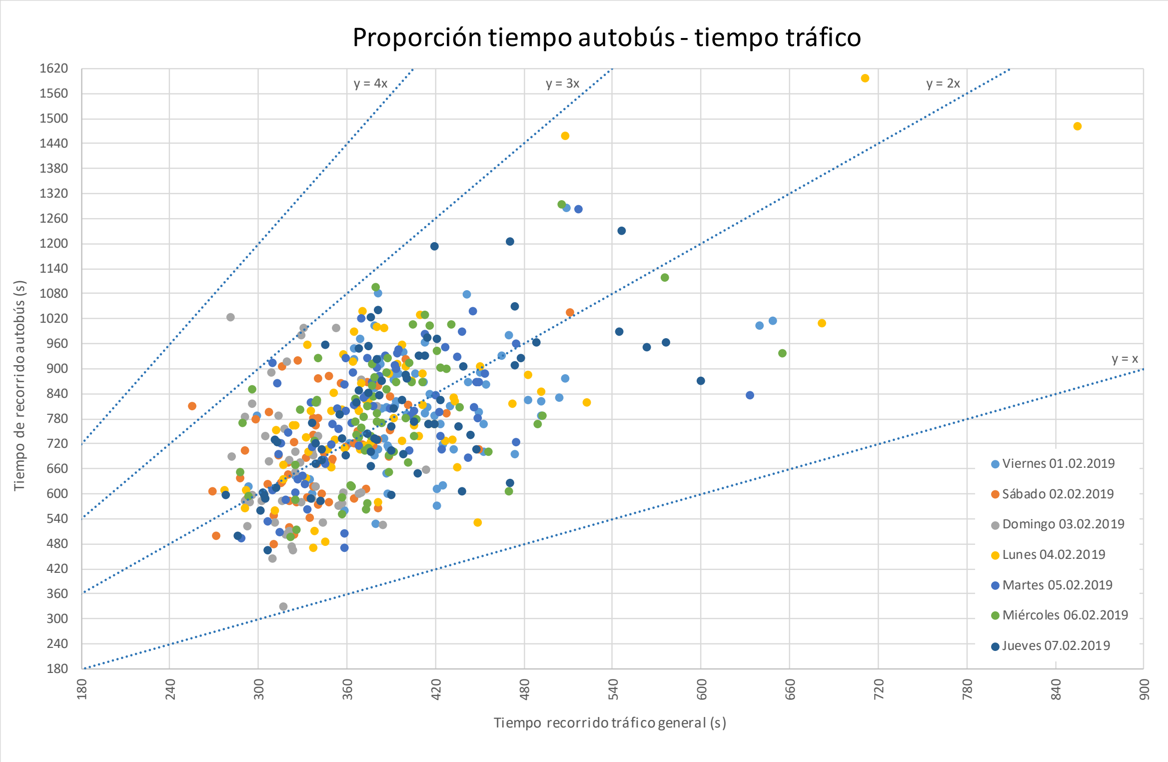

Figura 3. Proporción entre tiempo de recorrido del autobús urbano y tráfico general durante la primera semana de febrero de 2019.

En la Figura 4 se representan los datos calculados para el mes completo. Se observa que el autobús tarda en promedio 2.08 veces más (entre 1.04 y 3.64) que el tráfico general en recorrer el corredor completo, obteniendo resultados similares a los expuestos en Liao et al. (2020), donde se establece una proporción de tiempos entre 1.4 y 2.6. Para llevar a cabo el análisis del mes de febrero de 2019 se han tenido en cuenta 1855 autobuses de la línea 14.

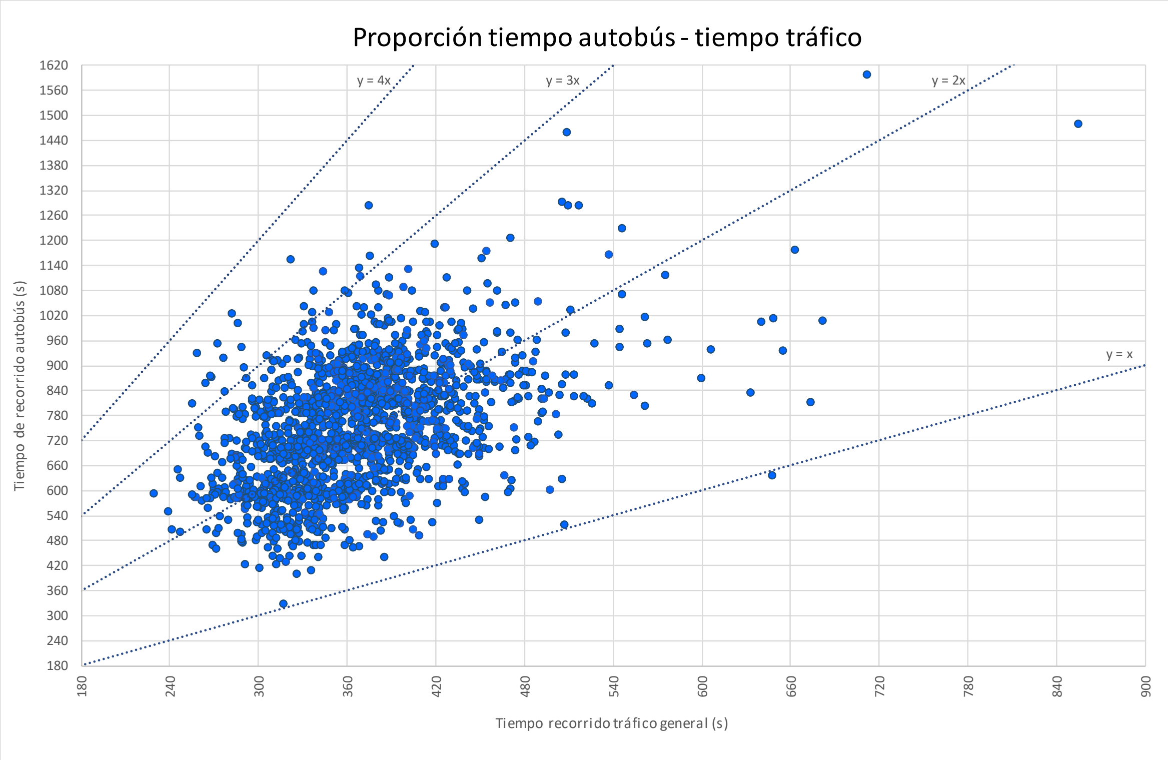

Figura 4. Proporción entre tiempo de recorrido del autobús urbano y tráfico general durante el mes de febrero 2019.

La correlación observada pone de manifiesto la influencia del tráfico en el tiempo de viaje en autobús, pero, sin embargo, la variabilidad de dicho tiempo de viaje para un mismo valor de tiempo de tráfico general indica que existen otros factores que influyen en el tiempo del autobús, como pueden ser la distancia entre paradas, el número de subidas y bajadas en la parada, los ciclos semafóricos, la tipología de paradas o la climatología.

Además de la presencia del tráfico general, los tiempos de operación del transporte público se ven afectados por la frecuencia con la que llegan a la parada los autobuses de la línea. La acumulación de viajeros por el aumento del intervalo entre los vehículos de la Compañía de Tranvías de La Coruña aumentará el tiempo de parada y, por consiguiente, el tiempo de recorrido total. Este hecho se muestra en la Figura 5, que presenta los tiempos de recorrido del autobús y del tráfico general para un día concreto, así como el intervalo entre autobuses en cada momento.

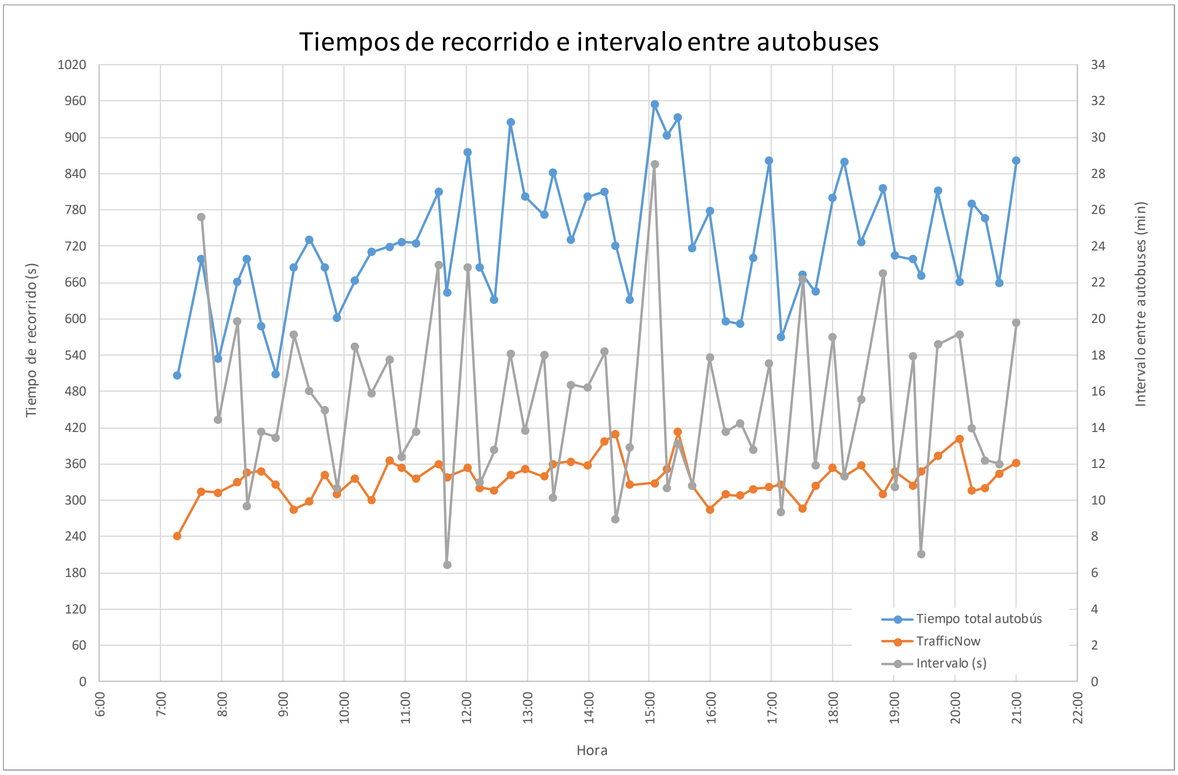

Figura 5. Relación entre tiempos de recorrido e intervalo entre autobuses el día 16.02.2019 en Ronda de Outeiro.

Como se aprecia en la Figura 5, a determinadas horas del día, el aumento en el tiempo del autobús urbano no se justifica con el incremento del tiempo de recorrido del tráfico general. A las 9:10:59 horas del 16 de febrero de 2019 se observa una disminución del tiempo del tráfico y un aumento considerable del tiempo de recorrido del transporte público. Una vez incluida la variable del intervalo entre autobuses, señalada en color gris en la Figura 5, se puede explicar el aumento del tiempo de operación del autobús a las 9:10:59 horas debido al incremento del intervalo. Por otro lado, en el autobús de las 9:41:17 ocurre lo contrario: aumenta el tiempo del tráfico general en el tramo analizado y, sin embargo, el tiempo de recorrido del autobús disminuye. En este caso, el intervalo entre autobuses también puede explicar esta variación, aumentando a la vez que lo hace el tiempo de recorrido del transporte público.

4. CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

Los resultados presentados en la ponencia han sido las primeras conclusiones obtenidas de una línea de trabajo que se encuentra en estado inicial. Se espera trabajar en el futuro con un mayor número de registros, considerando para el análisis un período temporal más largo, así como diferentes tramos de diferentes líneas en calles con características diferenciadas, para tratar de determinar la influencia de ciertas variables en el ratio entre el tiempo de viaje en autobús y en transporte público. Están en curso otros trabajos para cuantificar los tiempos empleados por el autobús en las paradas y para estimar el número de viajeros que descienden en cada parada a partir de registros históricos de subidas. Esto permitirá diferenciar la influencia del tráfico, tanto en las maniobras de salida de las paradas como en la propia circulación de los autobuses, de la influencia de la demanda del autobús.

En el presente estudio se ha puesto de manifiesto la variabilidad de la relación existente entre el tiempo de recorrido del tráfico general y el autobús urbano. A partir de los resultados obtenidos y replicando este análisis para otros tramos de la ciudad, se puede considerar la implantación de plataforma reservada en aquellas zonas en las que la influencia de los vehículos sobre el autobús sea mayor. Con esta medida disminuirá el tiempo de recorrido del autobús y no se verá repercutido por atascos ocasionados en el tráfico general.

Por otro lado, se ha evidenciado que el intervalo de tiempo entre autobuses es otro factor que influye sobre el tiempo de recorrido. La información proporcionada por estas dos variables consideradas será útil para la planificación de nuevas líneas de transporte público.

En análisis posteriores se intentarán determinar y cuantificar nuevas variables que influyan en la relación entre el tiempo de recorrido del tráfico general y del autobús, como pueden ser, entre otras: el número de viajeros que suben y bajan en las paradas, el número de intersecciones en el corredor, así como los ciclos semafóricos en las mismas, la sección de la calle (número de carriles, anchura), la tipología de las paradas (bahía, bahía invertida), la meteorología o la intensidad de tráfico medida mediante espiras.

Todos los resultados tienen por objetivo conocer y analizar el comportamiento del autobús urbano y sus causas para así realizar mejoras y conseguir un transporte público más eficiente y más atractivo para los usuarios no cautivos.

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QUANTIFYING THE SAFETY IMPACT OF CONNECTED AND AUTONOMOUS VEHICLES IN MOTORWAYS: A SIMULATION-BASED STUDY

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ABSTRACT

Connected and Autonomous Vehicles (CAV) is the developing summit of the integration between artificial intelligence (AI), robotics, automotive design and information technologies. Many researchers are investigating their effects on traffic safety. This study tries to quantify the volume of incidents when sharing the road human-driven vehicles and fully CAV. After modeling the geometry of 4.5 km of motorway and the parameters of connectivity and automation using Aimsun Next platform, several scenarios of the percentages of CAV (0%, 25%, 50%, 75%, and 100%) were driven in microsimulation runs. Then the microsimulation generated vehicles trajectories that are used to identify conflicts using the Surrogate Safety Assessment Model (SSAM). The results of this analysis confirm previous research in that the reduction of number of conflicts will be up to 35% with low and moderate penetration rates of CAV and more than 80% if the road is operated only with CAV.

1. INTRODUCTION

The proposed advances in Connected and Autonomous Vehicles (CAV) will widely change the traffic system to make it more efficient. CAV's most common positive effects discussed in the literature are reducing traffic congestion, delay time, and vehicles emissions (Poczter & Jankovic, 2014; Fagnant & Kockelman, 2015) to the way in which CAV are expected to operate in traffic flow. In addition, ongoing CAV manufacturers' field trials expect that CAV are capable to enhance traffic safety. Theoretically, NHTSA (2008) expected that vehicle automation (i.e. limiting human controls and performing the bulk of driving tasks without the need for a human) can play an important role in achieving the target of zero collisions as the majority of traffic conflicts are due to human errors. Connectivity goes besides and strengthens automated vehicle capabilities by enabling them to share their location and other relevant data with nearby vehicles and infrastructures for safer repositioning and streaming (Petit & Shladover, 2015).

The Society of Automotive Engineers (SAE, 2014) developed a scale for manufacturing levels of CAV from zero to five to define their progression. Level 0 indicates that there is no driving automation. Level 1 is equipped with lateral or longitudinal system for driver assistance. Level 2 uses partial driving automation upon driver request. Level 3 represents the conditional driving automation (i.e. the car transfers the control to the driver and the driver should respond to the car request). Level 4 is with high driving automation and full responsibility for driving task. Finally, Level 5 is with full driving automation and able to operate the car everywhere.

In the last five years, the volume of work evaluating the safety gain hypothesis has increased (e.g. Xie et al., 2019; Papadoulis et al., 2019, Morando et al., 2018). Almost all the related research contend that the safety impact is primarily governed by market penetration rates of CAV. Due to a lack of enough real data, simulation-based microscopic, stochastic methods have been used. These methods involve the CAV penetration rates in car-following and lane changing driving models to reflect the individual vehicles interaction with other vehicles, geometry, and other road elements (HCM, 2016). Consequently, the potential traffic conflicts resulting from vehicles interaction is the measure to evaluate the safety impacts of CAV involved in microsimulation.

Traffic conflicts are situations in which vehicles travel close in time and space in such a way that they could potentially end up in a crash (Hydén & Linderhonm, 2012). To identify these risky situations (traffic conflicts), the vehicle trajectories resulting from simulation are scrutinized using surrogate safety measures indicators (e.g. time-to-collision (TTC), post-encroachment time (PET), etc.).

This study expands the insight into the dynamics of CAV and their impact on safety. It provides a connectivity and automation modeling with the microsimulation platform that enables the modeler to deal with driving dynamics with more details, control, and reliability. In this platform (Aimsun Next platform with V2X extension) many penetration rates of CAV are operated on the case study (motorway segment). Later, the Surrogate Safety Assessment Model (SSAM) is used to quantify the effect of CAV on the corridor safety and compare the results with previous research.

The paper is organized as follows: next section, identifies the most relevant literature on CAV safety evaluation. A detailed description of the motorway segment drawn in Aimsun Next platform guided by Open Street Map, and modeling the car-following and lane-change behavior of the CAV are introduced in section three. The fourth section of the paper presents the results obtained from the simulation, and discusses them with previous literature. Finally, the last section summarizes the conclusions of the research, presents the study limitations and proposes future directions for CAV simulation research.

2. LITERATURE REVIEW

Most prior research performed traffic efficiency assessment of connected and/or automated vehicles (e.g. Guériau et al. 2016; Talebpour & Mahmassani, 2016; Stanek et al., 2018; Makridis et al., 2018) , but few safety evaluation studies exist (e.g. Morando et al., 2018; Papadoulis et al., 2019; Rahman; 2019). To these studies: introduction of CAV would increase the throughput of highway facilities and improve traffic flow stability (Talebpour & Mahmassani, 2016). CAV can also make about 20% of speed improvement (Stanek et al., 2018) and increase the road capacity with the increase in the CAV-penetration rate within even a heterogeneous flow (Ye and Yamamoto, 2018).

The initial work on CAV was based on stability analysis and simulating CAV using a proposed simulation framework (e.g. Talebpour & Mahmassani, 2016, Pereira & Rossetti, 2012). These studies created an integrated multi-level simulation framework that includes traffic, sensors (robotics), and network simulators in order to achieve detailed CAV simulation. Nevertheless, the results of these one-of-a-kind models were less reliable and difficult to compare.

Further studies started to use a traffic microsimulation platform and its internal/external extensions. This approach showed a considerable ability to model a large scale networks and gave reasonable results (Roncoli et al., 2015; Park et al., 2012). However, since the operational behaviour of CAV is described differently in each study, their results are not always comparable.

Particularly, most of researchers in this approach chose VISSIM to simulate CAV. ATKINS (2016) provided a milestone in simulating the CAV in VISSIM when they use the COM interface to change the CAV-related parameters, penetration rates, time headways that end up with changing driving behaviour when applying the driver model of VISSIM (Wiedemann 99 flow model). Following the criteria of ATKIN (2016) report, Jeong et al. (2017) improved an algorithm to control the longitudinal movement and gave powerful insights with micro safety results. But they still have a weakness since they did not develop a lateral movement control. Meanwhile, Stanek et al. (2018) changed the default VISSIM driver models parameters to show the effect on traffic behaviour. Similarly, Papadoulis et al. (2019) and Gueriau & Dusparic (2020) followed the mentioned approach for analyzing traffic safety.

In microsimulation-based studies, they used to apply the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration for CAV traffic safety evaluation. Rahman et al. (2019) investigated the safety effect of vehicles with low levels of automation and vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) connectivity technologies. From SSAM indicators, they integrated several measures (e.g. time exposed time-to-collision (TET), time integrated time-to-collision (TIT), lane changing conflicts

(LCC), etc.) to quantify the conflict risk on an intersection. They found that there is a significant safety enhancement resulting from introducing CAV.

Papadoulis et al. (2019) used the VISSIM API's External Driver Model to develop a decision-making CAV control algorithm and then SSAM time-to-collision indicator was used to measure the number of conflicts. A comprehensive safety evaluation study showed the percentage of conflicts reduction with different CAV market penetration rates: daily, in space, and by conflict type. A fully-CAV-operated motorway showed an extreme reduction in number of conflicts (about 94%) which is very close to the theoretical expectation made by NHSTA (2008).

Moreover, Gueriau & Dusparic (2020) studied the effect of CAV on both efficiency and safety in three types of networks (urban, national, and motorway), simulating different penetration rates of vehicles with various levels of automation. Their results showed that lower penetration rates result in a 30% rise in conflicts, but higher penetration rates result in a 50-80% reduction in conflicts, with steady growth of the increased penetration.

On the other hand, Zhang et al. (2020) developed a platoon control algorithm to represent the cooperation of CAV. To assess the safety impact of setting exclusive lanes for CAV, four surrogate safety indicators were used, including both longitudinal and lateral safety risk indexes. In high-truck ratios scenarios, setting exclusive lanes improves longitudinal and lateral protection up to 55% and 85% respectively.

Finally, it could be shown that safety evaluation of CAV depends primarily on the assumptions of CAV's simulated behaviour in movement. Once there is lack of information about CAV and Human Driven Vehicles (HDV) contact, a special and direct platform of calibrating CAV is need. To this intention this study uses the Aimsun Next API with new versions and extensions that are made especially to model CAV behaviour.

3. METHODOLOGY

The procedure was to design fully CAV (i.e. totally depending on the technology in driving process). This begins with understanding the driving behaviour difference between HDV and CAV. Accordingly, different parameters values affecting car following and lane-changing models used in Aimsun Next platform are applied to CAV and HDV.

3.1 Connectivity between vehicles

Vehicles connection was conducted by building the connection network using V2X Aimsun Next extension. This network includes: On Board Unit (OBU) in each CAV, that represents the receiver and transmitter in a vehicle; Channels, which is the simulated representation of the radio hardware and protocols that provide communication between vehicles; and Cooperative Awareness Messages (CAM), that provide information about the presence, activity and position of CAV. Channel design depends basically on the number of probable CAV in the channel range, their speed, and the channel reliability. This is expressed using three characteristics:

- *Latency*: The delay in packet transmission,
- *Range*: The range of transmission, and
- *Packet Loss*: The percentage of packets which are not received.

Following many research works (Teixeira et al., 2014; Mir and Filali, 2014; Ahmadvand et al., 2016; Chen et al., 2019) and based on our case (higher than 125 connected vehicles in the channel range if the speed is about 100km/h), the selected channel was: *IEEE 802.11p (250 m range) with 2100 ms latency and 0.75 packet loss.*

3.2 Automation parameters

As many studies did, vehicle full automation was modeled by calibration of all needed parameters that control both longitudinal and lateral movements on the road and distinguish the CAV over HDV. The traffic flow model used in Aimsun Next API is Gipps model, so the parameters discussed below are those entering the model' equations.

Specifically, vehicles parameters are modified according to vehicle behavior models: "Car-Following" and "Lane-Changing" as they move through the network.

Gipps (1981) car-following model was created by incorporating the parameters that are influenced by local parameters such as: the "type of driver" (speed limit acceptance of the vehicle), the geometry of the section (speed limits on the section, speed limits on turns, etc.), and the impact of vehicles on adjacent lanes.

However, acceleration and deceleration are the two main elements of Gipps model. The first reflects a vehicle's willingness to reach a certain desired speed, while the second simulates the restrictions imposed by the preceding vehicle when attempting to travel at that speed. The maximum speed that a vehicle (n) can accelerate during a time period (t, t+T) is given by this model:

$$V_a\,(n,\, t+T) = V(n,t) + 2.5a(n)T\left(1 - \frac{V(n,t)}{V*(n)}\right)\sqrt{0.025 + \frac{V(n,t)}{V*(n)}} \quad (1)$$

Where:

$V_a(n,t)$ is the speed of vehicle n at time t;
V*(n) is the desired speed of the vehicle (n) for current section;
a(n) is the maximum acceleration for vehicle n;
T is the reaction time.

At the same time, the maximum speed that the same vehicle (n) can reach during the same time interval (t, t+T), according to its own characteristics and the limitations imposed by the presence of the lead vehicle (vehicle n-1) is:

$$V_b\ (n,\ t+T) = d(n)\ T + \sqrt{d(n)^2T^2 - d(n)\left[2(x(n-1),t) - s(n-1) - x(n,t)) - V(n,t)T - \frac{V(n-1,t)^2}{d'(n-1)}\right]} \quad (2)$$

where:

d(n) (< 0) is the maximum deceleration desired by vehicle n;
x(n,t) is position of vehicle n at time t;
x(n-1,t) is position of preceding vehicle (n-1) at time t;
s(n-1) is the effective length of vehicle (n-1);
d’(n-1) is an estimation of vehicle (n-1) desired deceleration.

Gipps (1986a and 1986b) lane-change is modelled as a decision process, analyzing the *necessity* of lane change (such as for turn maneuvers determined by the route), the *desirability* of lane change (to reach the desired speed when the leader vehicle is slower, for example), and the *feasibility* of lane change (using forward, backward, and adjacent gap evaluation) depending on the position of the vehicle in the road network with respect to the lane geometry and adjacent vehicles.

			HDV		CAV	
Parameters	**Definition**	**References**	**mean**	**s.d.**	**mean**	**s.d.**
Main parameters						
Speed acceptance	How much vehicles could take a speed greater than speed limit	Atkin (2016), Stanek et al. (2018), Ye and Yamamoto (2019)	1.1	0.1	1	0.05
Clearance (m)	Distance that vehicle keeps with the preceding one when stopped	Atkin (2016), Stanek et al. (2018)	1	0.3	0.2	0.2
Max give-way time (sec)	Give-way time at a Yield or stop junction or an on-ramp	Atkin (2016)	10	2.5	7.4	0.5
Guidance acceptance (%)	The probability that a vehicle will follow the recommendations	Stanek et al. (2018)	70	10	100	0
Reaction time (sec)	The time to react in general	Zhang et al., (2020)	0.8	-	0.6	-
Reaction time at stop	The time to react at stop	Zhang et al., (2020)	1.2	-	1	-
Max acceleration (m/s²)	The highest value that the vehicle can achieve under any circumstances	Atkin (2016), Stanek et al. (2018), Karjanto et al. (2017)	3.28	0.2	3.72	0.15
Normal deceleration. (m/s²)	The maximum deceleration that the vehicle can use under normal conditions	Atkin (2016), Naujoks et al. (2016), Karjanto et al. (2017) Zhang et al., (2020)	3.27	0.25	4.12	0.18
Max deceleration (m/s²)	The most severe braking can be applied under special circumstances	Atkin (2016), Naujoks et al. (2016), Karjanto et al. (2017), Zhang et al., (2020)	5.39	0.5	6.2	0.3
Safety margin factor	a multiplier of a normal range of gap acceptance range	-	1	0	1.5	0.2

Table 1- Gipps models parameters affected by the type of driver

			HDV		CAV	
Parameters	**Definition**	**References**	**mean**	**s.d.**	**mean**	**s.d.**
Car-following model						
Sensitivity factor	How much the vehicle could be sensitive to the deceleration of the leader	-	1	0	1.5	0.5
Gap (sec.)	How much override the headway calculated by car following model	Karjanto et al. (2017)	0	0	0.6	0.1
Headway aggressivenes s	How much vehicles could enter with shorter gaps without forcing the rear vehicle to brake	Stanek et al. (2018)	0.8	0.2	0	0
Lane-changing model						
Overtake speed threshold	The threshold that delaminates an overtaking maneuver	Stanek et al. (2018)	90	-	95	-
Percentage staying in overtaking lane	The probability that a vehicle will stay in the faster lane instead of recovering to the slower lane after an overtake maneuvers	Naujoks et al. (2016)	40	-	20	-
Imprudent lane change	Defines whether a vehicle will still change lane after assessing an unsafe gap	Naujoks et al. (2016)	Ticke d	-	Non ticked	-
Cooperate in creating a gap	Vehicles can cooperate in creating a gap for a lane changing vehicle	Stanek et al. (2018)	non ticked	-	ticked	-
Aggressivenes s Level	The higher the level, the smaller the gap the vehicle will accept, being a level of 1 is the vehicle's own length	Stanek et al. (2018)	0-1	-	0-0.75	-
Distance Zone Factor	To modify the distance zones used in the Lane Changing Model to adjust where lane changes start to be considered and, if a range is given, to randomize behavior	Stanek et al. (2018), Talebpour and Mahmassani (2016)	0.8-1.2	-	0.6-1.5	-

Table 1 (cont.) - Gipps models parameters affected by the type of driver

Consequently, while default values in most of the model's parameters are supposed to represent HDV, CAV tend to keep smaller standstill distances, accelerate and decelerate faster and smoother, keep constant speed with no or smaller oscillation at free flow, form platoons of vehicles and follow the leader, perform more co-operative lane change as lane changes could occur at a higher speed co-operatively (Stanek et. al, 2018).

Table 1 shows the specific parameters that are affected by automation in Gipps' car following and lane-change models depending on previous research (Atkin, 2016; Stanek et al., 2018; Zhang et al., 2020; Karjanto et al., 2017; Naujoks et al., 2016) and logic. Parameters definitions are summarized from Aimsun user manual. Table 1 presents both mean and standard deviation (s.d.) values that were defined before microsimulation. The values follow a normal distribution as it is proposed in Gipps' model. The discussion about the values for both HDV and CAV is provided below.

3.2.1 The main parameters

It is supposed that CAV will respect the speed limits. CAV's clearance is directly adopted from ATKINS (2016) report as minimum space headway. Stanek et al. (2017) showed lower deviation values because of full-dependence on technologies. Maximum give-way time is suggested to be the same to the minimum time gap in ATKINS (2016) report. The report also showed lower deviation for CAV. Guidance acceptance is proposed to be 100% with no deviation in fully CAV.

No previous research has directly detailed CAV's reaction times and it is not a parameter considered in VISSIM car following model (Wiedemann 99). Also, in Aimsun Next old versions, it was considered a global parameter (i.e., with fixed value in the simulation). Recently, since version Aimsun Next 4.3, this parameter is subjected to calibration depending on the type of vehicle that allows the change for CAV. However, Zhang et al. (2020) suggested a hint value that was depending on Adaptive Cruise Control (ACC) platoons applied on the field.

In general, connection-automation technologies are supposed to show higher speed in reaction. Thus, it should be significantly lower when the driving is fully connected and automated (Zhang et al., 2020). The same behaviour will be on unexpected stops, that requires highly connection technology or referring to the driver.

For acceleration and deceleration**,** ATKINS (2016) and Stanek et al. (2017) suggested that CAV will be accelerating and decelerating faster and smoother, resulting in higher values. Besides, the deviation will be lower than in HDV values by 25% according to achieving higher uniformity in dynamic driving process (Stanek et al., 2017).

As CAV will be more cooperative in gap acceptance, a multiplier of 1.5 is proposed for safety margin factor.

3.2.2 Car-following parameters

It is supposed that CAV will be more sensitive to leader action. Thus, a multiplier of 1.5 is proposed for sensitivity factor. In addition, it could override the headway calculated by car following model by 0.6 sec (Karjanto et al., 2017), but without any aggressiveness (Stanek et al., 2017).

3.2.3 Lane-change parameters

As CAV show more co-operation in considering maneuvers, a slight increase of percentage of vehicles that travel at less than Overtake Speed Threshold is suggested. Moreover, they cooperate in creating a gap (Stanek et al., 2018). However, CAV prefer to go back to the original lanes and will not make a lane-change if the gap is not safe (Naujoks et al., 2016). Furthermore**,** in Stanek et al. (2017), CAV showed a reduction of 0.75 of human vehicle driven gap acceptance in lane changing. As a result, the zones that are considered as lane-change distance will be modified by the same factor (Stanek et al., 2017; Talebpour & Mahmassani, 2016).

3.3 Simulated scenarios

After adjusting car following and lane-change models' parameters, five scenarios were considered with different sharing percentages of both HDV and CAV (100/0, 75/25, 50/50, 25/75, and 0/100). The developed models, were calibrated for the times of the real-world trips; between 10:00 and 12:00 am (off-peak hours) in a regular day. The number of replications for each scenario needed in order to achieve a 90% confidence interval level for the simulation output was calculated using Shahdah et al. (2015) equation (Eq. 3). It was shown that 15 runs is a sufficient sample.

$$N = \left(\frac{t_{(1-\alpha/2),N-1} * \sigma}{E}\right)^2 \quad (3)$$

Where, N equals the required number of simulation runs, σ equals the sample standard deviation of the simulation output, t is the student's t-statistic for two-sided error of a $\alpha/2$ with $N-1$ degrees of freedom and E equals the allowed error range, where $E = \varepsilon * \mu$; μ is the mean of the number of simulated conflicts based on the initial set of simulations runs and ε is the allowable error specified as a fraction of the mean For example in 100% CAV scenario we tested a 15 runs trial (with $\sigma = 28.06$, t = 2.14 (with α = 0.05 and degree of freedom =14), E = (0.10*305) and it was a sufficient sample. Likewise, 15 runs were a sufficient value for all scenarios.

3.4 Safety evaluation

As expected, the model does not generate any crashes in the simulation. So, the model cannot be used to explicitly calculate collisions or traffic safety. In order to assess the safety, the outputs of vehicles trajectories from Aimsun microsimulation runs have to be analyzed using SSAM. The trajectories at each time step of simulation (0.2 s) are examined to check the existence of traffic conflicts instead of crashes.

The indicator that has been applied in most studies (Gueriau & Dusparic, 2020; Papadoulis et al., 2019; Rahman et al. 2019) to assess traffic safety is the time-to-collision (TTC). It is defined as the time that remains until a collision could occur if two successive vehicles maintain a speed difference (Hayward, 1972). The TTC of vehicle i with respect to a leading vehicle i + 1 at time step t can be calculated with:

$$TTC\ (i,t) = \frac{d\ (i,t)}{v\ (i,t) - v\ (i+1,t)} \quad \forall\ v(i,t) > v\ (i+1,t) \quad (4)$$

Where d(i, t) and v(i, t) denote the real space gap and the speed of vehicle i at time step t, respectively.

Following the recommendation of Papadoulis et al. (2019) and after a sensitivity analysis, we used a threshold value of TTC equal to 1.5 to identify conflicts.

4. RESULTS AND DISCUSSION

Safety assessment of CAV in this study is conducted on a modeled motorway segment in Aimsun Next platform. Imported Open Street Map was used as a background to create the geometry (i.e. curves of the road segment, lane width and the length of links, merging and diverging areas) of the segment using drawing tools and overlapping the sections created with the map. As case study, a three-lane motorway section was chosen of the GR-30 freeway, close to Granada city in Spain. The designed corridor was 4.57 km long, with fourteen on and off-ramps and nine vehicle input points (seven ramp entrances and two major entrances from south and north) After including the segment geometry, many information from the network has also been modeled, including speed limit, detectors location, and traffic volume. Directional traffic flow (pc/hr) was obtained from several detectors managed by the Dirección General de Tráfico (DGT) in Granada.

Firstly, this section provides a check of the simulation performance by presenting the distribution of TTCs, velocity difference, and acceleration during simulation steps along the five scenarios modeled. Then a sensitivity analysis of TTC thresholds is laid out. Afterwards, the resulted conflicts are discussed among scenarios.

4.1 Traffic flow dynamics

4.1.1 TTC distribution

The introduction of low CAV penetration rates increases both low and high TTC values due to non-consistent flow dynamics (Figure 1). Under high CAV penetration rates, smoother traffic flow reduces large TTC values while reducing the gaps by CAV increasing the ratio of small TTCs. This distribution is logic and agrees with Ye and Yamamoto (2019) research work.

4.1.2 Acceleration distribution

Figure 2 shows that under low penetration rates scenarios, acceleration ratio about 0 slightly decrease due to the lack of harmony in traffic flow, but with high penetration rates the ratio of acceleration rate about 0 increases obviously that indicates smoother dynamic flow. Similarly, this distribution is logic and agrees with Ye and Yamamoto (2019).

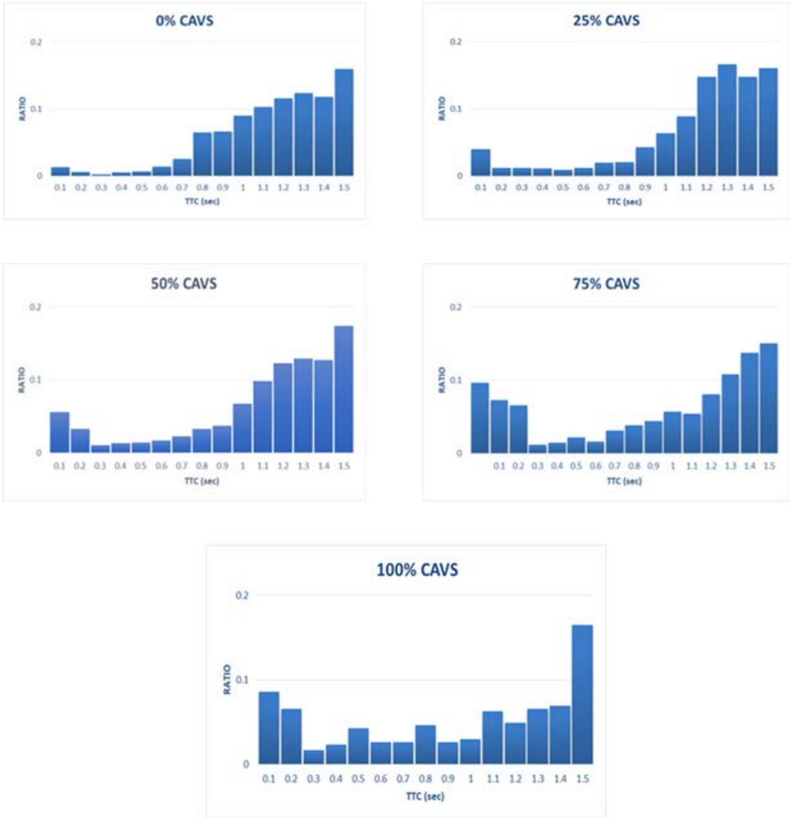


Fig. 1- TTC distribution under the proposed scenarios

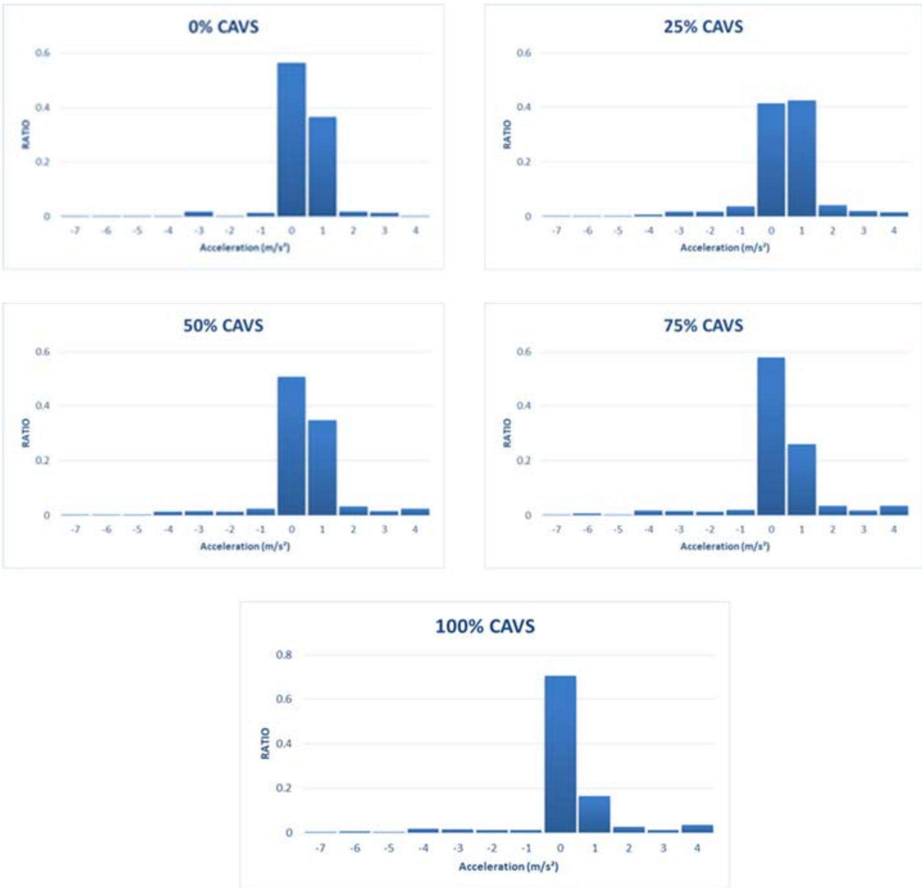


Fig. 2 - Acceleration distribution under the proposed scenarios

4.1.3 Velocity difference distribution

The distribution of difference between the vehicle and its leader velocities for each scenario are shown in Figure 3. A bell shape with a lower peak is present in the distribution of low penetration rates and covers a wider range. The velocity difference ratio of the bell peak slightly increases at high sharing percentages of CAV. The difference in velocity tends to cluster around small values (0, 1). This phenomenon shows that the velocity difference between vehicles is reduced and traffic flow is harmonized with the rise in the CAV penetration rate which is logic and agrees with Ye and Yamamoto (2019).

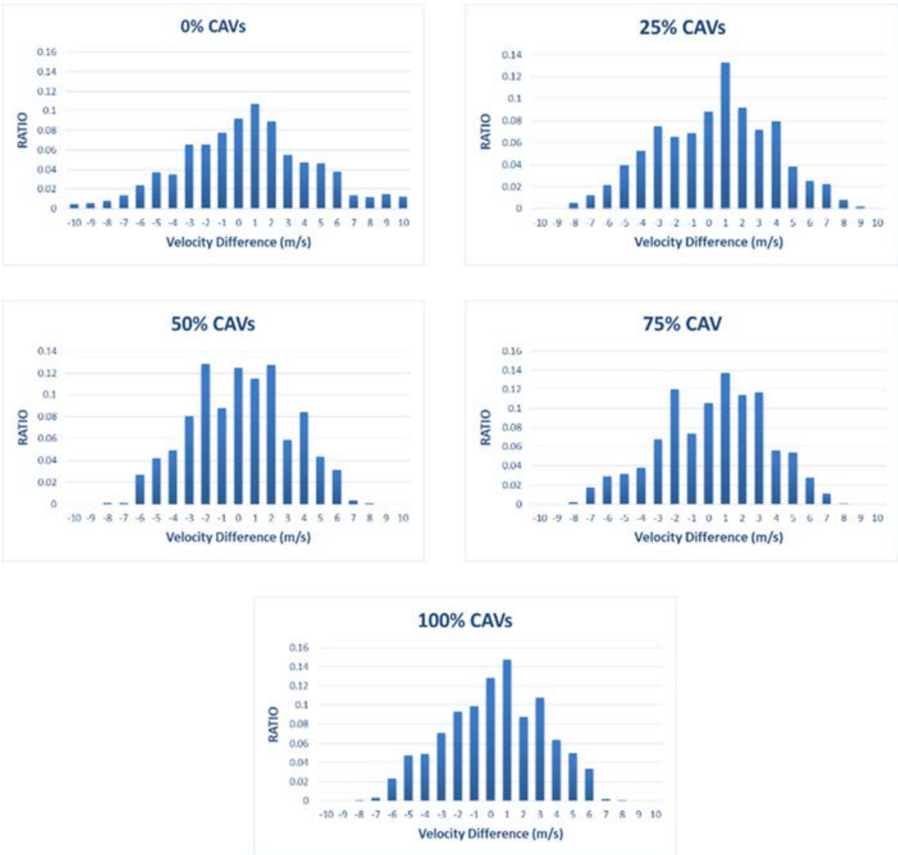


Fig. 3 – Velocity-difference distribution under the proposed scenarios

4.2 TTCs sensitivity analysis

TTC threshold is critical in analyzing traffic conflicts and it is more questionable for CAV. Thus, CAV traffic safety studies used to make a sensitivity analysis to check the effect of changing this value and chose a proper threshold (Zhang et al., 2020; Papadoulis et al., 2019; Morando et al., 2018). In this study, a sensitivity analysis for TTC thresholds of 0.5, 1.0, 1.5, 2.0, and 2.5 seconds has been conducted for CAV introduction scenarios (25% CAV, 50% CAV, 75% CAV and 100% CAV). Using the analysis of variance (ANOVA), the change in percentages of conflicts between each CAV penetration scenario and the HDV scenario was not significantly different in most cases when comparing 1.5 seconds and both 1.0 and 2.0 seconds. But 0.5 and 2.5 seconds (the lowest and the highest thresholds) were statistically significant from the other values (Table 2). Graphical illustration (Figure 4) of mean and standard deviation for the change in percentages of conflicts also showed the same results in variance. The significant values in 0.5 and 2.5 values is normal since the potential conflicts will noticeably change with such extreme time to collision thresholds. Meanwhile Papadoulis et al. (2019) have found non-significant variance even with extreme values; Zhang et al. (2020) have used just 1.0, 1.5, and 2.0 values in their analysis and found the same results of this study. Consequently, both studies used 1.5 seconds as a threshold value.

	Time-to-Collision (TTC)				
	0.5 s	1.0 s	1.5 s	2.0 s	2.5 s
Scenario 25% CAV	39.50 a	-21.54 b	-2.56 c	1.84 c	34.08 a
Scenario 50% CAV	11.39 a	-39.26 b	-35.90 b	-29.81 b	-3.67 c
Scenario 75% CAV	-9.57 a	-54.53 b	-60.83 b	-55.75 b	-29.01 c
Scenario 100% CAV	-47.07 a	-77.16 b	-82.66 c	-80.53 b,c	-68.42 d

For each scenario, a, b and c values denote differences statistically significant ($p < 0.05$). Two or more TTC values with the same letter denote a homogeneous subgroup.

Table 2-The percentage of change in the number of conflicts for each TTC value

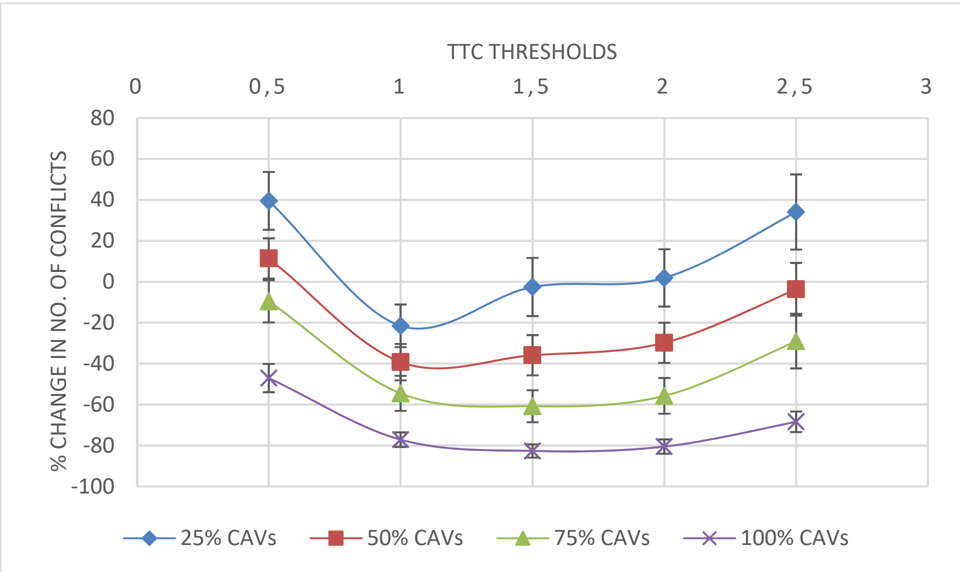
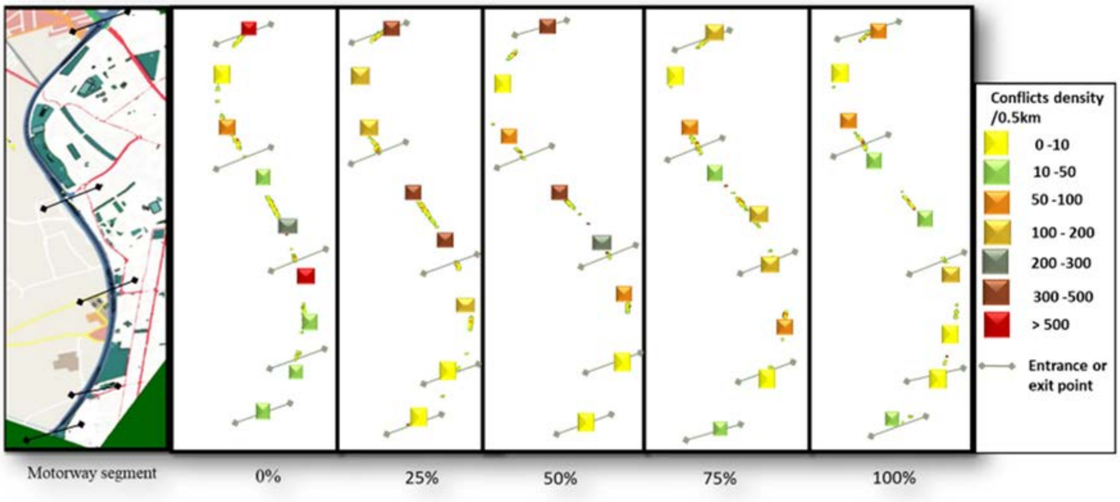


Fig. 4 – Sensitivity analysis of TTCs thresholds under the proposed scenarios

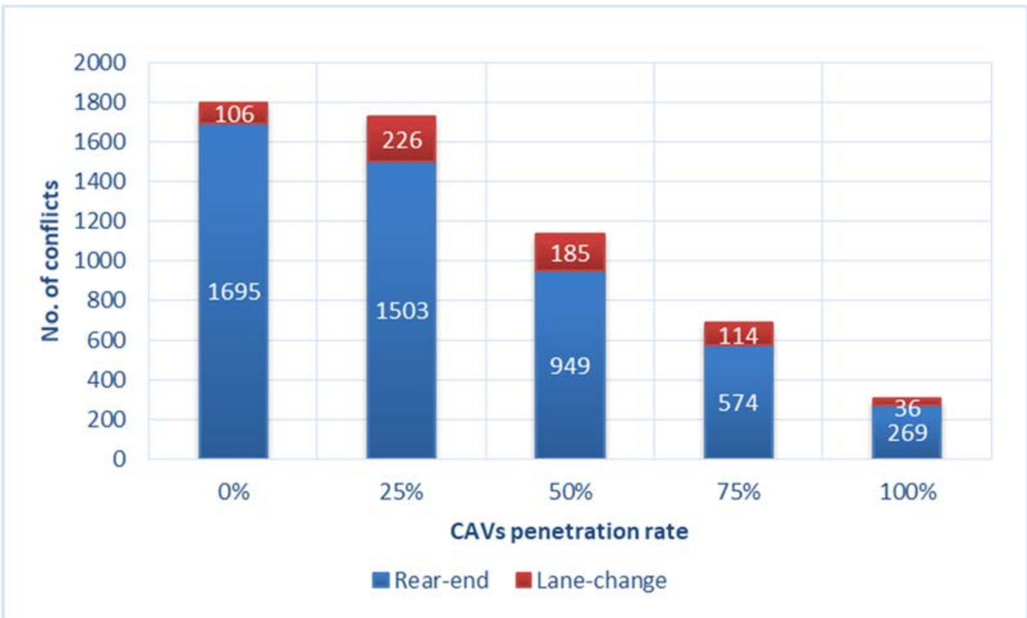
4.3 Quantifying the safety impact of CAV penetration

Using 1.5 s as TTC threshold, the average results of the conflicts tried out of microsimulation runs are shown in Figure 5. Increasing the penetration rates of CAV has positive effect on decreasing the number of possible conflicts. The reduction percentages of conflicts for 25%, 50%, 75% and 100% CAV scenarios are 2.56%, 35.9%, 60.83%, and 82.66% respectively. These results agree with Papadoulis et al. (2019) for motorways and Morando et al. (2018) for intersections. On the other hand, Gueriau & Dusparic (2020) and Xie et al. (2019) have shown that low levels of automation could increase the potential conflicts especially in low penetration scenarios.

Figure 5 (a) shows the previous main result by density of resulted conflicts within the segment at the conflicts distribution map. The density representative points of each 500 m range show decreasing in the number of conflicts by increasing the percentages of shared CAV that agrees Papadoulis et al. (2019) results. In addition, the figure shows that the probable conflicts are near to the entrances and exits of the motorway as it was observed in Gueriau & Dusparic (2020). This is due to speed differences at these points that affect the possibility of resulting conflicts.



(a)



(b)

Fig. 5 – Conflicts resulted by the proposed scenarios: (a) Conflicts density representative points. (b) Number of conflicts by type

Figure 5 (b) shows the effect of penetration rates of fully CAV on conflict type. The resulting conflicts at this motorway are mostly rear-end conflicts in the base scenario (only HDV scenario). While rear-end conflicts are probably to be 93.95%, 86.9%, 83.64%, 83.37%, and

88.12% of overall conflicts, lane-change conflicts will be of much lower percentages (5.96%, 13.09%, 16.32%, 16.59%, and 11.89%).

Whereas rear-end conflicts had the same direction of reduction of the total conflicts, the effect was different in the case of lane-change conflicts. Even sharing just 25% of CAV can over duplicate the percentage of lane-change conflicts. This is related to the significant difference in behaviour between HDV and fully CAV in lane-change process (imprudent lane change, cooperation in create gap, and aggressiveness level) (ATKINS, 2016; Stanek et al., 2018). After that the percentage of lane-change conflicts was not affected significantly with increasing CAV ratios.

5. SUMMARY, CONCLUSIONS AND LIMITATIONS

In this paper, it was applied a simulation-based safety assessment of introduction of fully connected and automated vehicles. It was conducted on a motorway segment with free flow condition. The modeling of CAV was done using Aimsun Next API by building connection network and calibration the automation behaviour of both longitudinal and lateral movements. This platform enables the user to calibrate the behaviour parameters with a range rather than fixed value (i.e. mean, min, max, deviation values) that improve the calibration to be realistic and reliable. Moreover, the used models (Gipps models) in this platform deal with parameters that reflect a direct and explicit driving behaviour such as reaction time, speed and guidance acceptance, driving aggressiveness.

Traffic flow dynamic was configured by drawing the distribution of some indicators (TTCs, acceleration and velocity-difference) resulted after traffic microsimulation. These distributions demonstrate that increasing the penetration rates of CAV will make the flow dynamics more harmonized and smooth.

The potential conflicts were detected by calculating the time to collision (TTC) indicator using SSAM. To test the proposed value of TTC threshold (1.5 s), a sensitivity analysis was applied for a range around this value (between 0.5 and 2.5 seconds) and the results showed a significant difference in case of extreme values (0.5 s and 2.5 s) but non-significant difference between the values 1.0, 1.5, and 2.0 seconds on the impact of CAV.

The effect of introducing the fully CAV is through with the theoretical and experimental exist research. The positive effect (i.e. the reduction in the total number of conflicts) reached about 35% for medium penetration rates and 80% for fully operated motorway of CAV.

This work is limited to various circumstances: it considers only HDV and fully CAV vehicles, while in the real world several type of vehicles, with several automation levels will be circulating simultaneously; and it considers only one type of road section. Further studies could deal with different levels of automation. Also, many types of road sections, traffic conditions, and vehicles could be simulated.

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REINFORCEMENT LEARNING FOR TRAFFIC SIGNAL CONTROL: COMPARISON WITH COMMERCIAL SYSTEMS

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ABSTRACT

In recent years, Intelligent Transportation Systems are leveraging the power of increased sensory coverage and available computing power to deliver data-intensive solutions achieving higher levels of performance than traditional systems. Within Traffic Signal Control (TSC), this has allowed the emergence of Machine Learning (ML) based systems. Among this group, Reinforcement Learning (RL) approaches have performed particularly well. Given the lack of industry standards in ML for TSC, literature exploring RL often lacks comparison against commercially available systems and straightforward formulations of how the agents operate. Here we attempt to bridge that gap. We propose three different architectures for RL based agents and compare them against currently used commercial systems MOVA, SurTrac and Cyclic controllers and provide pseudo-code for them. The agents use variations of Deep Q-Learning (Double Q Learning, Duelling Architectures and Prioritised Experience Replay) and Actor Critic agents, using states and rewards based on queue length measurements. Their performance is compared in across different map scenarios with variable demand, assessing them in terms of the global delay generated by all vehicles. We find that the RL-based systems can significantly and consistently achieve lower delays when compared with traditional and existing commercial systems.

1. INTRODUCTION

Traffic Signal Control (TSC) can be used to ensure the safe and efficient utilisation of the road network at junctions, where traffic can change directions and merge, having to manage conflicting individual priorities with the global needs of the network. Traffic congestion has a major financial impact. A study by (INRIX 2019) shows that traffic congestion in 2019 cost £6.9 billion in the UK alone, with similar patterns being observed in other developed countries.

Cities around the globe are starting to explore the deployment of smart Urban Traffic Controllers (UTCs) that use real time data to adjust their stage schedule and green time duration. Traditionally, fixed time plans have been used. Those fixed time plans can be managed by systems that try to optimise the green time splits in a deterministic manner such as TRANSYT (Robertson 1969). These types of systems require costly site-specific knowledge of the traffic lights placement and typical demand profiles to be able to provide effective control. These methods are not easily scalable and deteriorate over time as the traffic demand changes as explained by (Bell and Bretherton 1986). With the development of induction loops, real time actuated UTCs were created in two variants: those that optimize single isolated intersections with systems such as MOVA (Vincent and Peirce 1988), and those that cover multiple intersections such as SCOOT (Hunt et al. 1982). To remedy the scalability problem, other systems based on local rules that generate self-organising area traffic controllers were developed, such as SurTrac (Smith and Barlow 2013), which solves a forward implementation of Dynamic Programming.

With the recent breakthrough of Deep Reinforcement Learning (DRL) on complex problems such as Atari games or Go (Mnih et al. 2013; Silver et al. 2017; Hessel et al. 2018), attention has turned towards adapting these approaches to generate industry-grade controllers for traditionally noisy and difficult to control systems such as TSC.

The purpose of this paper is to reproduce some of the results of the main and most successful RL approaches on intersections of increasing complexity, while comparing different architectures of DRL TSC agents, since, given the complexity of their implementation, most available literature only deals with a single class.

2. STATE OF THE ART

2.1 Previous Work

Reinforcement Learning (RL) is an area of Machine Learning that tries to imitate how biological entities learn. In it, an independent agent evolves in an unknown environment and learns how to perform a task for which no prior information is given based on its interactions said environment via a set of allowed actions. The agent aims to maximise the total reward signal it receives as a feedback for each of its actions.

RL methods have been applied to TSC in experimental setups. A good review of early methods can be found here (Mannion, Duggan, and Howley 2016). More recent works (Liang et al. 2018; Genders 2018; Liu, Liu, and Chen 2018) use neural networks as function approximators to avoid the dimensionality and computing time limitations of table based methods in large state-action spaces, and show that DRL TSC can be more efficient than some earlier methods.

While there is a variety of approaches in the literature that craft successful RL-based TSC systems, most of them do no present direct comparisons against commercial systems that are the concern of this paper. Gao et al. (2017) used a Convolutional Neural Network (CNN) and discrete cell encoding with a Target Network for a value-based agent. The results were compared against a fixed time and a heuristic system (longest queue first), finding RL to perform better. In Mousavi, Schukat, and Howley (2017), raw pixels were used as input for a CNN that parametrises two agents: a policy-gradient agent and a value-based agent. The variation in the delay between actions was used as reward, and while both agents were found to have near-identical performance, they were not compared against any reference system. Later, in Wan and Hwang (2018) a DQN using discrete cell encoding as state was implemented. It used a CNN architecture and a delay-based reward. It was compared against a fixed time system, obtaining better performance. Liang et al. (2018), used the same approach and included speed information in the state, using a reward based on variations on aggregated wait time for all vehicles. It compared against two different fixed-time systems, ranking better than both and providing some early evidence of the benefits of using Double DQN, Duelling architecture and Prioritised Experience Replay. In Genders and Razavi (2018) different state spaces were evaluated using a policy-gradient algorithm, including: occupancy and speed for each incoming road, queue and a measure of density of incoming roads, and Discrete Cell Encoding, partitioning the incoming roads into cells of fixed lengths, in this case 2.5 metres. Genders found little difference in the performance of the agents as a result of the change in the magnitudes observed, but it could be argued that a discrete cell encoding would greatly benefit from a Convolutional Neural Network (CNN) architecture in the agent, which is not used.

Regarding comparisons with established systems, in Stevanovic and Martin (2008) the authors compare SCOOT with a Genetic Algorithm-based control method. It is shown that SCOOT's performance can be surpassed by more adaptive Genetic Algorithms that, in turn, tend to be less effective at learning than RL methods.

Despite these previous works, most results are hard or impossible to reproduce given the lack of industry standards in terms of simulators, performance metrics, the lack of availability of commercial algorithms for comparison and the fierce protection of their internal workings, and the lack of open-source code of proposed RL models.

2.2 Commercial Traffic Signal Control Optimisers

MOVA (Microprocessor Optimised Vehicle Actuation, (Vincent and Peirce 1988)) is a traffic controller designed by TRL Software. It aims to reduce delay on isolated junctions. The basic functioning of MOVA involves two induction loop detectors estimating the flow of vehicles in each lane. The system makes a virtual cell representation of the lanes within MOVA, and then it computes a performance index based on the delays calculated. If the index results lower than a certain threshold, the signal is changed to the next stage, otherwise the stage it is extended.

Surtrac (Scalable URban TRaffic Control, (Smith and Barlow 2013)) is an adaptive TSC system published in 2013. A real-world deployment on 20 intersections in Pennsylvania showed a performance improvement of 20-40% in performance. Its operation is decentralised, each intersection allocates green time independently and asynchronously based on incoming flows. Each intersection is controlled by a local scheduler and communicates projected outflows to the downstream neighbouring junctions, modelling vehicles as a sequence of clusters. This communication allows for locally balancing competing flows while creating larger "green corridors" by finding an optimal sequence such that the input jobs (ordered clusters) are cleared while minimising the joint waiting time of all vehicles.

3. METHODS

3.1 Traffic Control as a Markov Decision Process

The control problem can be formulated as a Markov Decision Process (MDP) defined in terms of a 5-tuple:

- A set of possible environment states $s \in \mathcal{S}$.
- A set of available actions to the agent $a \in \mathcal{A}$.
- A stochastic transition function $\forall a \in \mathcal{A}, \mathcal{T}_{s,s'}^{a} \triangleq \mathbb{P}(s_{t+1} = s' | s_t = s, a_t = a)$.
- A scalar real valued reward function $R(s_t, s_{t+1}, a_t)$ providing a performance measure to the transition generated by progressing into the state s_{t+1} after taking action a_t while in state s_t
- A discount factor γ that will provide the balance between immediate exploitation and approaches that aim to maximise returns over time.

Each time an action is required, the agent will receive a state vector s_t from the environment. Based on this state, the agent will produce an action a_t, which will be implemented in the simulator. The environment will then advance time until a next action is required, according to its dynamics represented by $\mathcal{T}_{s,s'}^{a}$. At this point, the next state s_{t+1} will be observable. Both states will be used to generate a reward r_t to serve as feedback to the agent. The agent will receive the state observation s_{t+1} and the cycle will start again.

In the case of TSC, the MDP is modelled as partially observable, following an unknown stochastic transition function. From here on, it is assumed that the traffic environment displays the Markov property, i.e. the process is memoryless, with the next state only depending on the current state and the action taken.

3.2 Reinforcement Learning

The goal of the agents will be to maximise their future discounted return, $G_t = \sum_{t=0}^{+\infty} \gamma^t \, r(s_t, a_t)$ with $\in [0,1]$. This is done by learning a policy π, parametrised by the weights θ of the neural network performing the approximation of the reward function and mapping states to actions: $\pi: f_1(s) \to a$. The reward function maps an action given a state to a reward scalar value: $r: f_2(s, a) \to \mathbb{R}$. The action-value function or Q-value is $Q_\pi(s, a) = \mathbb{E}_\pi[G_t | s_t = s, a_t = a]$. It represents the total episodic return by following policy π after being in state s and taking action a.

3.3 Value-based Reinforcement Learning Methods - DQN

Tabular value-based methods, such as Q-Learning, attempt to learn an optimal policy $Q_\pi^* = \max_\pi \mathbb{E}[r_t | s_t = s, a_t = a]$ by iteratively performing Bellman updates on the Q-values of the individual state-action pairs:

$$Q_\pi(s_t, a_t) \leftarrow Q_\pi(s_t, a_t) + \alpha\big(y_t - Q_\pi(s_{t+1}, a_{t+1})\big), \quad (1)$$

where α is the learning rate and y_t is the Temporal Difference (TD) target for the value function

$$y_t = r_t + \gamma \max_{a_{t+1}} Q_\pi(s_{t+1}, a_{t+1}, \theta'). \quad (2)$$

Deep Q-Network (DQN) agents are an evolution of Q-Learning. The purpose of the agent is to find an approximation of Q_π^* by tuning the weights θ of a neural network. The agent keeps a second neural network, the target network, parametrised by the weights vector θ' which is used to generate the TD targets:

The experience replay memory is used to increase training stability, obtaining samples that cover a wider number of situations. It can also increase the data efficiency since the same transition can be used several times for gradient descent. Three additional modules have been applied to the basic agent to improve performance, Double Q Learning (Hasselt 2010), Prioritised Experience Replay (Schaul et al. 2016), and Dueling Architecture (Wang et al. 2015).

Two variants of the DQN agent have been implemented, being described on the algorithms displayed in Figs. 1 and 2. The agents implemented used the hyperparameters described in Fig. 4.

Algorithm 1 Operation of the implemented Dueling DQN Agent with PER

```
Initialise agent network with random parameters θ
Initialise target network with random parameters θ'
Initialise memory M with capacity m
Define frequency N for copying weights to target network
for each episode do
    measure initial state s_0
    while episode not done do
        choose a_t = π(s_t) according to ε-greedy policy
        implement a_t and advance until next action needed
        measure s_{t+1}, and calculate r_t
        store transition (s_t, a_t, r_t, s_{t+1}) in M
        calculate TD error δ = r + γ max_{a_{t+1}} Q_θ'(s_{t+1}, a_{t+1}) − Q_θ(s_t, a_t)
        calculate priority sampling weight and store in M
        s ← s_{t+1}
    end
    b ← sample batch of transitions from M according to priority weights
    for each memory m_i = (s_i, a_i, r_i, s_{i+1}) in b do
        ŷ_i = r_i + γ max_a Q_θ'(s_{i+1}, a')
    end
    Stochastic Gradient Descent on θ over all (x_i, y_i) ∈ b
    if number of episode is multiple of N then
        θ' ← θ
    end
end
```

Figure 1 – DQN Agent Pseudocode.

Algorithm 2 Operation of the implemented Dueling Double DQN Agent with PER

```
Initialise agent network with random parameters θ
Initialise target network with random parameters θ'
Initialise memory M with capacity m
Define frequency N for copying weights to target network
for each episode do
    measure initial state s_0
    while episode not done do
        choose a_t = π(s_t) according to ε-greedy policy
        implement a_t and advance until next action needed
        measure s_{t+1}, and calculate r_t
        store transition (s_t, a_t, r_t, s_{t+1}) in M
        calculate TD error δ = r + γ max_{a_{t+1}} Q_θ'(s_{t+1}, a_{t+1}) − Q_θ(s_t, a_t)
        calculate priority sampling weight and store in M
        s ← s_{t+1}
    end
    b ← sample batch of transitions from M according to priority weights
    for each memory m_i = (s_i, a_i, r_i, s_{i+1}) in b do
        ŷ_t = r_t + γQ_θ'(s_{t+1}, argmax_a Q_θ(s_{t+1}, a))
    end
    Stochastic Gradient Descent on θ over all (x_i, y_i) ∈ b
    if number of episode is multiple of N then
        θ' ← θ
    end
end
```

Figure 2 - DDQN Agent Pseudocode.

3.4 Policy Gradient Reinforcement Learning Methods - A2C

Policy Gradient in RL is based on the idea that obtaining a direct policy $\pi(s)$ mapping states to actions can be easier than estimating the value function or the state-action values. It has an added benefit in that it can learn stochastic policies, generating a probability distribution over the potential actions. The goal is to find the policy that maximises the reward. To do so one has to perform gradient ascent on the performance measure $J = \sum_a [Q(s_0, a)\pi(a|s)]$. The Synchronous Advantage Actor Critic (A2C) method tries to reduce the variance in the policy method by combining the direct mapping from actions with the value-based approximation method. The goal is to learn an actor

$$\pi_\theta = \mathbb{P}_\theta[a_t = a | s_t = s], \quad \text{and a critic} \quad V_\pi^\theta(s) = \mathbb{E}_\theta[G_t | s_t = s], \tag{3}$$

both of which are parametrised by the neural network weights vector θ.

Algorithm 3 Operation of the implemented Advantage Actor Critic Agent

Initialise actor network with random parameters θ_a,
Initialise critic network with random parameters θ_c,
for *each episode* **do**
  reset gradients $d\theta_c = d\theta_a = 0$ measure initial state s_0
  choose action $a_t = \pi(s_t)$ according to $\pi_\theta(a_t|s_t)$,
  while *episode not done* **do**
    implement action a_t,
    advance simulator until next action needed,
    measure new state s_{t+1}, and calculate reward $r_t = V_{\theta_c}(s_t)$,
    choose action $a_{t+1} = \pi(s_{t+1})$ according to $\pi_{\theta_a}(a_{t+1}|s_{t+1})$,
    update actor $\theta_a = \theta_a + \alpha\nabla_{\theta_a} \ln \pi_{\theta_a}(a_i|s_i)Q_{\theta_c}(s_i, a_i)$,
    calculate TD error $\delta \leftarrow r_t + Q_{\theta_c}(s_{t+1}, a_{t+1}) - Q_{\theta_c}(s_t, a_t)$,
    update critic $\theta_c = \theta_c + \alpha\delta\nabla_{\theta_c}Q_{\theta_c}(s, a)$,
  end
end

Figure 3 - A2C Pseudocode.

Fully connected layers	2
Activation Function	ReLU
L2 kernel regularisation	0.001
Copy weight frequency	20
α	0.005
γ	0.95
PER η	0.6
PER β	0.4

Fully Connected layers for value	2
Size of neural network layers	48
Fully Connected layers for policy	2
Activation Function	ReLU
n-return steps	16
Cross-entropy loss	0.5
Value loss coefficient	0.5
γ	0.95
α	10^{-5}

Figure 4 - DQN/DDQN and A2C Hyperparameters.

3.5 State, Action and Rewards of the agents

The experiments presented in the following sections all use the same descriptions for simulator state and reward calculation, although they differ in the number of actions available to them.

The state of an intersection of l lanes will be presented to the agents as a state vector $s \in \mathbb{R}^{l+1}$. Each component will contain the length of the queue of vehicles measured upstream from the traffic light in metres. The last component will be the numeric ID of the current stage that the agent is implementing.

While marginal improvements in performance can be obtained by using different variables for reward (Cabrejas Egea et al., 2020.; Cabrejas-Egea and Connaughton 2020b), as per the discussion of Heydecker (2004), queues can be a reasonable choice for states and rewards, being able to transmit useful information to the agent relative to the mean rate of delay of the system. Based on this, the reward after an action will be calculated as the negative sum of the length of the queues of all lanes immediately upstream from the intersection:

$$r_t = -\sum_l q_l^t \, . \qquad (4)$$

The agent has a set of actions $\mathcal{A}$ that varies depending on the intersection being controlled. Once the agent chooses an action a, the stage corresponding with the ID of a is implemented. Green stages are set to a minimum of 6 seconds. Once this time has passed, the agent is requested a new action. If the agent chooses the same action again, the current stage is extended for a further 3 seconds. There are no inbuilt limitations as to how many times an agent can extend a stage, leaving it for the agents to learn. If the agent chooses a different action than the currently active one, a 3 seconds amber stage is implemented in the lights that were green, after which, the new stage is implemented.

3.6 Agent Benchmarking

In order to compare the agents' performance, a testing framework was defined. For each model, a demand profile will be created, following the shape found in a typical day as described by using the methodology introduced in (Cabrejas Egea, De Ford, and Connaughton 2018) and expanded in (Cabrejas-Egea and Connaughton 2020a). The profile will be split on 10 segments of length 6 minutes. Each of these segments will correspond with a level of demand. The levels of demand are obtained by setting out what will be the maximum demand the intersection will suffer, setting that magnitude to coincide with the peaks of the distribution that could be found on said typical day and are specified in each experiment's section.

Random seeds are changed and updated after every simulation episode, training or testing. The quantitative metrics on which the system will be evaluated are the Global Cumulative Delay (accounting for any deviations from the maximum speed) and the Average Queue Length generated by all vehicles during the execution of the evaluation.

4. EXPERIMENTAL RESULTS

4.1 Experiment 1: Cross Straight

The first test is conducted on the simplest junction, shown in Fig 5. The junction referred to as Single Cross is composed on 4 lanes distributed in 4 arms coinciding with the cardinal directions of the model. The controller for the junction has two stages, a north-south stage and an east-west stage, and turning is not allowed. The testing aim was to perform an initial performance comparison of DRL algorithms against MOVA, SUTRAC, and a cyclic controller. Here the goal for the agent was to exert fine adaptive timing control while extrapolating, rather than using complicated transitions between stages that would rarely, if ever, appear in sequence in cyclic control. MOVA was configured using loop detectors set in accordance to its manual, the implementation of Surtrac follows the work of Xie et al. (2012), and the cyclic controller was set on a 56 second cycle following both the methodology presented in (Salter 1996) and a parallel optimisation process, reaching the same result.

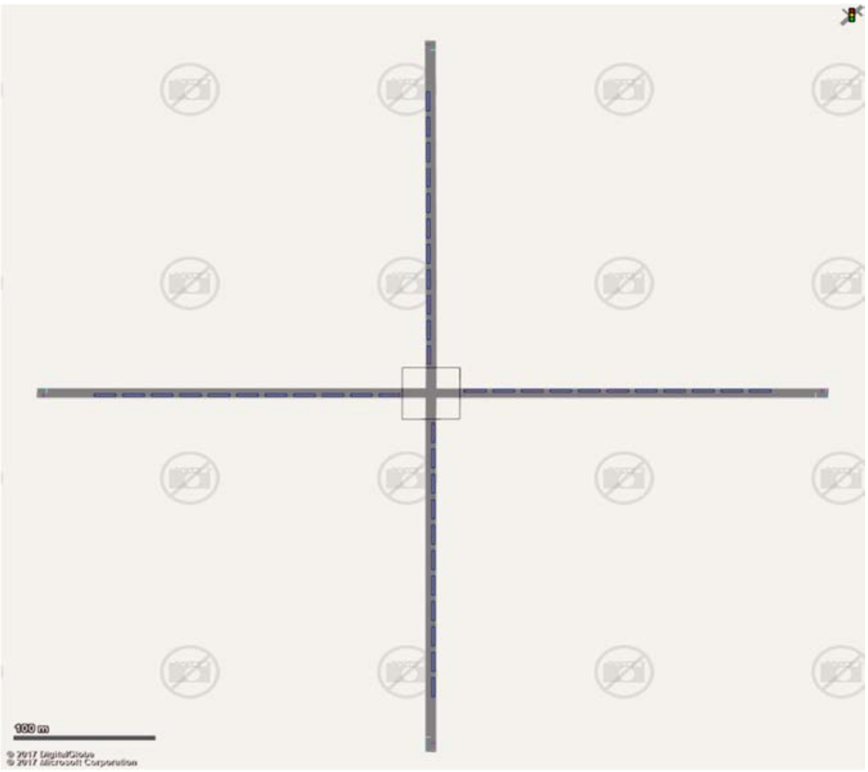

Figure 5 - Cross Straight Map.

The agents were trained using a fixed vehicle demand of 400 vehicles per hour on each of the incoming lanes. Both DQN variants were trained for 400 episodes, using an ϵ geometrically annealed from 1 to 0.001. The A2C agents were trained for 100 episodes until they converged. Best performing agents in each class were selected for benchmarking and evaluated in scenarios lasting one hour, as described in the previous section with the demands shown in Table 1. During evaluation, an average of 2120 vehicles are inserted in the model, with 2 peaks of demand of 3000 vehicles/hour for 6 minutes each. Figure 6 and 7 and Table 2 show the Global Cumulative Delay and average queue length for the network. As expected, the cyclic solution is outperformed by all adaptive controllers. The different controllers are on a par with a slight advantage for the DuelingDDQN which saves the community an average of 3000 seconds compared to MOVA on this hour of simulation, which represents on average 1-2 seconds per vehicle. RL agents also seem slightly more robust against changes in demand, producing lower slopes in the delay graphs in sections of extreme demand.

Time period [min]	North	East	South	West
0-6	200	200	200	200
6-12	400	400	400	400
12-18	900	500	900	500
18-24	1000	500	1000	500
24-30	700	500	700	500
30-36	500	700	500	700
36-42	500	1000	500	1000
42-48	500	900	500	900
48-54	400	400	400	400
54-60	200	200	200	200

Table 1 - Demand in vehicles/hour per cardinal direction over the benchmark in Cross Simple.

The cyclic controller resulted in saturated lanes during both peaks and queues in excess of 150 metres during a great part of the simulation. MOVA suffered two moments in which at least a sensor was saturated coinciding with the peaks in demand, however the queues were close to lengths of around 50 metres during the most part of the simulator. Surtrac followed a similar pattern, having a single lane saturated coinciding with the second peak in demand. RL agents as suffered no saturation in any of their lanes during the length of the evaluation. They all managed a more balanced distribution of queues in their respective lanes, displaying a higher ability to balance loads during peak times.

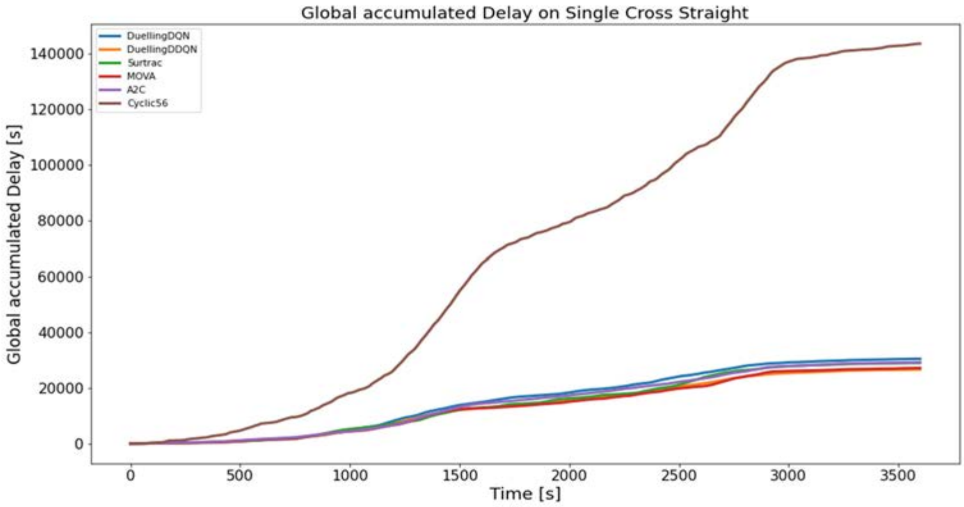

Figure 6: Global Cumulative Delay in Single Cross for DQN variants, A2C, Surtrac, MOVA and the reference Cyclic controller.

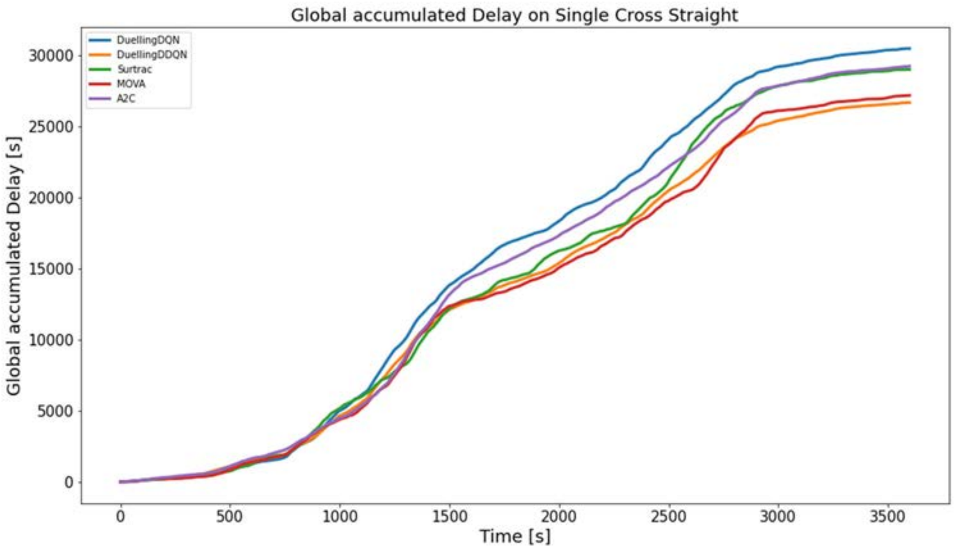

Figure 7: Global Cumulative Delay in Single Cross for DQN variants, A2C, Surtrac, MOVA and the reference Cyclic controller.

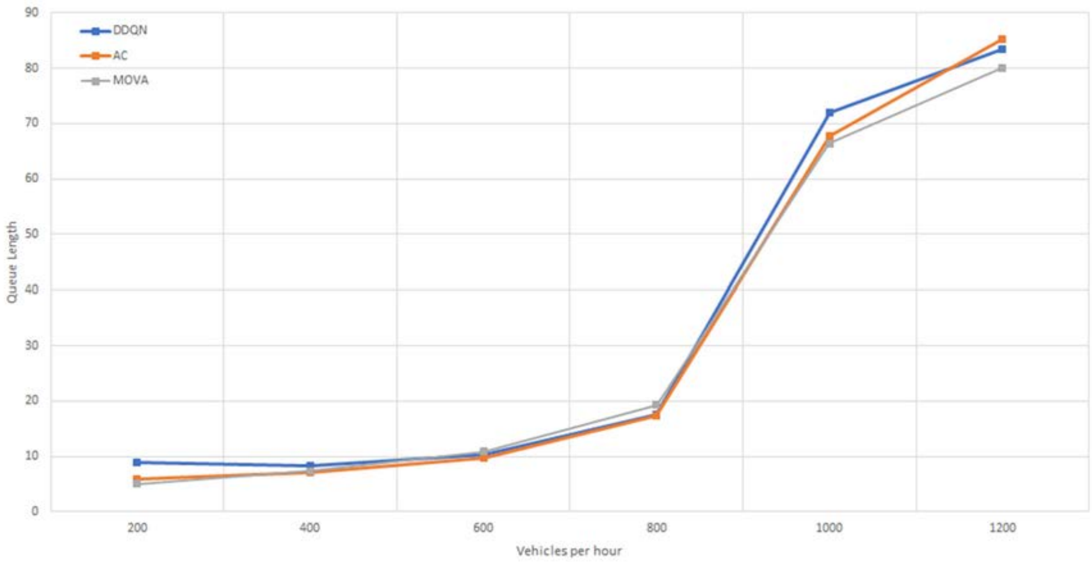

Figure 8: Queue length by demand level in Single Cross

When comparing the systems that obtain the best performance, RL agents and MOVA, across different constant demand profiles, we observe that MOVA obtains a small advantage at the extreme low and high demand levels, but this difference is overcome by the RL based systems in the middle demand levels. This gives another indication that while MOVA can obtain really good results, especially at constant demand, it is not optimal, having room for improvement in the control exerted while in situations of varying demand.

Controller	Cumulative Delay [s]	Average Sum of Queues [m]
Cyclic	143660.50	132.37
MOVA	27187.53	60.59
SURTRAC	29008.36	72.41
A2C	26382.14	56.07
DDQN	28303.94	50.11
DDDQN	21286.86	49.42

Table 2 - Cumulative Delay and Cumulative Stop Delay in seconds across Controllers on Single Cross Straight.

Because of the simplicity of this 2 actions intersection, there is not a lot of delay difference between adaptive UTCs. As it will be appreciated shortly, these results will change when we consider more complex junctions.

Given the difference in performance between the adaptive and cyclic controllers, which is expected to become greater on more complex intersections, and the increasing difficulty in setting them in large intersections, the cyclic controller will be omitted for the next examples. Given that the A2C agent has been clearly outperformed in this experiment by those based on the DQN architecture, the following experiments will focus on the performance of this last architecture compared with commercial systems.

4.2 Experiment 2: Cross Triple - 4 actions

This junction, as shown in Fig. 9, displays a much higher complexity than the intersection presented in the previous section. It is composed of 4 incoming links of 3 lanes each. In each incoming link, the left lane serves a dedicated nearside turning lane, the central allows for forward travel and the right lane allows for both offside turning and going straight. Due to limitations in how Vissim internally treats the queues, it is not possible to obtain a straightforward measurement of the lane queues in links that have more than one lane. To mitigate this, the first experiment was run with agents that would take 4 queue inputs (one for each incoming link), plus the state of the traffic signal as state input. The action set was consequently limited to 4 different actions, being allowed only those that set to green the 3 traffic lights serving the lanes of the same incoming link. This allows for turning vehicles but prevents more sophisticated stages from happening.

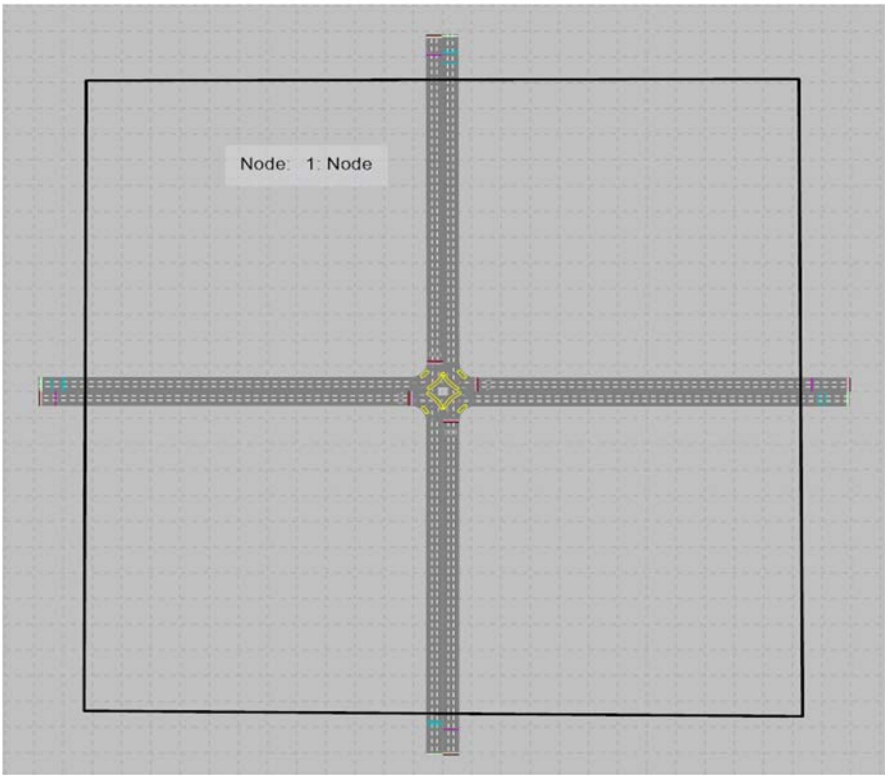

Figure 9 - Cross Triple Map.

The agents were trained on a fixed demand of 400 vehicles per hours on each incoming link. The DQNs were trained for 400 episodes of one hour of simulated time, with ϵ annealed geometrically between 1 and 0.001. A2C agents were trained for 100 episodes until they converged. During the hour of evaluation, the demand profile from the last experiment was used with a scaling factor of 1.5, an average of 3180 vehicles were introduced to the model, with 2 peaks of demand of 4500 vehicles/hour for 6 minutes each, as shown in Table 3.

As it can be seen in Figure 10 and Table 4 the UTC using MOVA performs poorly compared to the DQN-based agents. During this hour of simulation RL agents halve the cumulative delay, saving over 27 hours of travel time for all vehicles involved, an average of over 32 seconds of per vehicle. The length of the queues in those intersections controlled by RL agents during the test scenario were lower than the ones controlled by MOVA. Additionally, it can be seen that the agent using Dueling Q-Learning has a better performance than that Dueling Double Q-Learning.

Time period [min]	North	East	South	West
0-6	300	300	300	300
6-12	600	600	600	600
12-18	1350	750	1350	750
18-24	1500	750	1500	750
24-30	1050	750	1050	750
30-36	750	1050	750	1050
36-42	750	1500	750	1500
42-48	750	1350	500	1350
48-54	600	600	600	600
54-60	300	300	300	300

Table 3 - Demand in vehicles/hour per cardinal direction over the benchmark in Cross Triple.

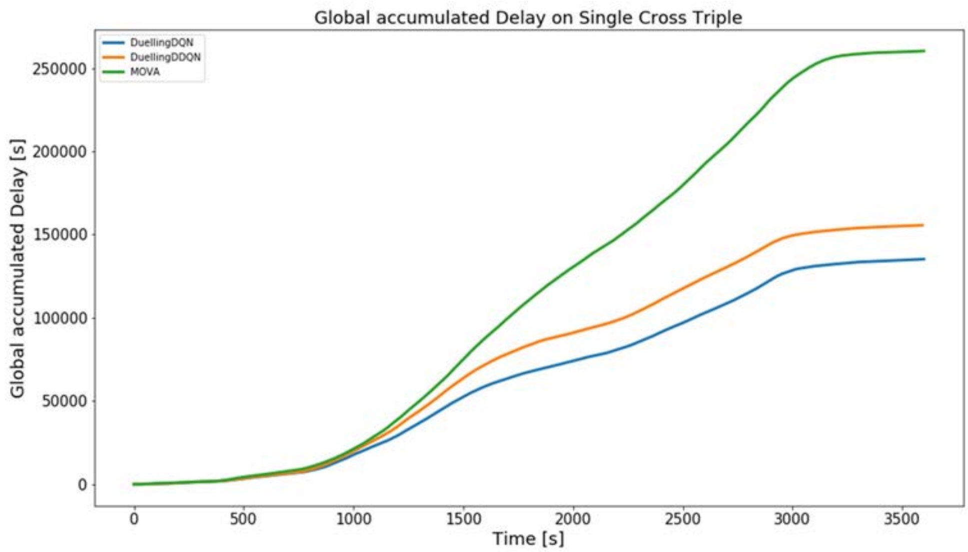

Figure 10 - Global Cumulative Delay in Single Cross Triple - 4 actions.

Controller	Cumulative Delay [s]	Average Max Queue Length [m]
MOVA	260257.65	179.27
DDQN	135220.91	153.58
DDDQN	155563.22	128.20

Table 4 - Cumulative Delay in seconds and Average Sum of Max Queue length in meters on Single Cross Triple - 4 actions.

4.3 Experiment 3: Cross Triple - 8 actions

In order to allow the use of a higher variety of stages in the controllers the map was reworked. All original lanes were partitioned into their own independent links, allowing extra space for lane changes. While these modifications allowed using information from all lanes in an akin manner to what modern sensors would achieve, due the limitations to lane changing, direct comparisons with Experiment 2 must be handled with care. Both models share name and rough geometry, but the layout of lanes is changed and so are the routing possibilities open to the vehicles.

The results presented below, use DQN agents taking 12 queue length inputs plus the state of the signal. Here, 8 different stages are available as represented in Fig. 11. No specific stage order is enforced, and the agents are free to change between any combination of stages.

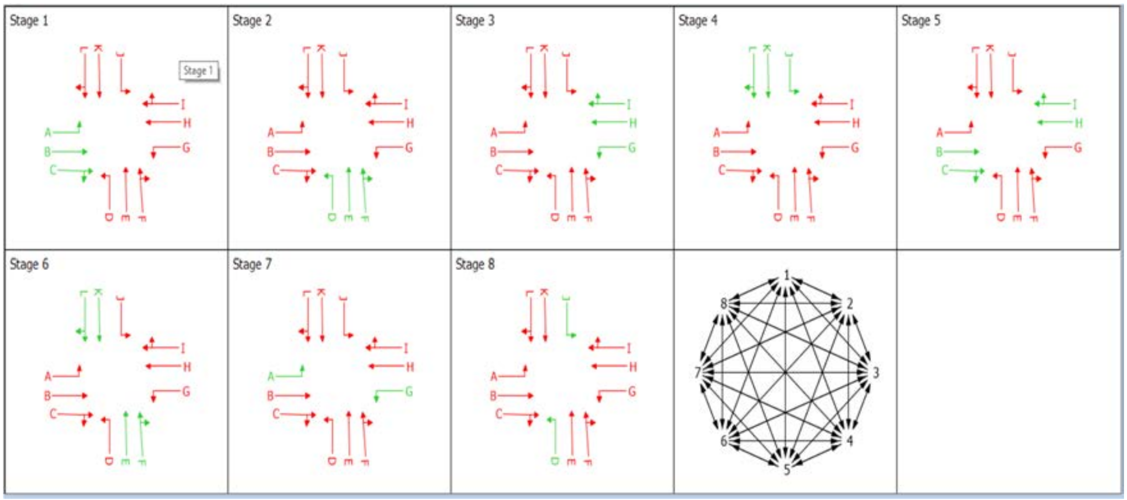

Fig 11 - Allowed stages of the Single Cross Triple model and allowed transitions between stages.

The RL agents display a similar, yet wider gap in performance with MOVA as in the previous experiment, with both classes benefiting from the increased actions pool. RL agents manage to generate about a third of the delay produced by MOVA. While this appears to be a great success, these results must be put into context. MOVA has a lot of internal parameters meant to be fine-tuned by a traffic engineer with site-specific knowledge. Our settings did produce a successful control loop, operating in line with what was expected of the configuration process. None of the RL agents has been fine tuned to the level that would be expected during commercial operation. The layers and neuron distribution weren't optimised, nor were the activation functions, meaning that the RL agents can still be improved upon.

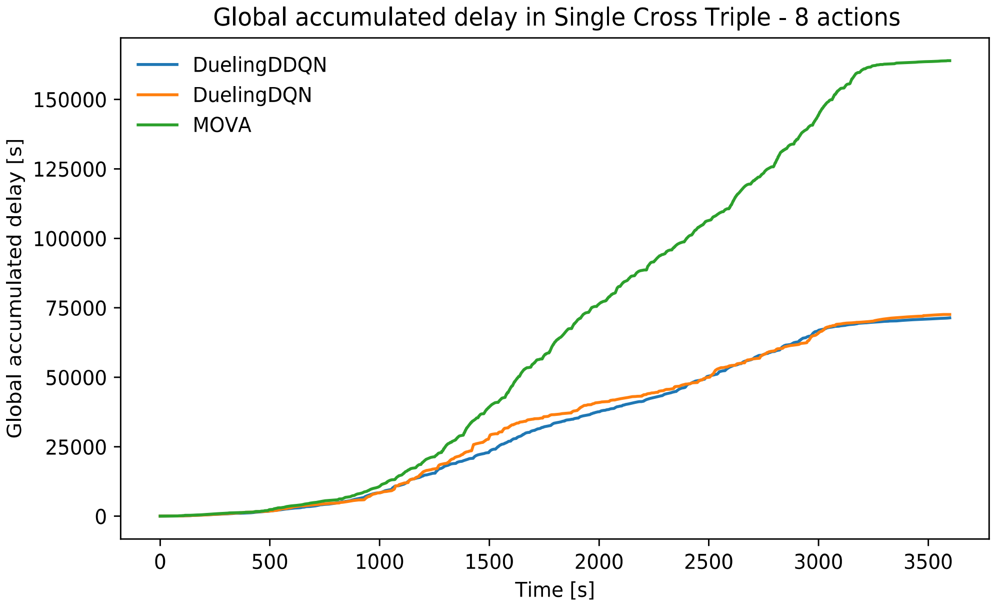

Figure 12 - Global Cumulative Delay in Cross Triple - 8 actions.

When we look at how the performance of the different systems scales as the demand increases, we can observe in Fig. 13 that in the complex intersection where the RL agents have the ability to freely switch between stages, they obtain better performance than MOVA across the board. In the scenarios covering low demand levels, where in simple intersections MOVA was obtaining marginally better performance, now the situation is reversed, mostly due to the previously mentioned ability to switch to the most suitable stages in absence of a predefined order, which was not the case in the intersection with 2 stages.

As the demand increases, the performance gap becomes wider, reaching a very significant advantage for the RL agent at high demand levels. This is consistent with the results presented in Fig.12 and Table 5.

Controller	Cumulative Delay [s]	Average Sum of Queues [m]
MOVA	165456.44	339.41
DDQN	72642.59	123.52
DDDQN	71245.61	119.86

Table 5 Cumulative Delay and Cumulative Stop Delay in seconds across Controllers on Single Cross Triple - 8 actions.

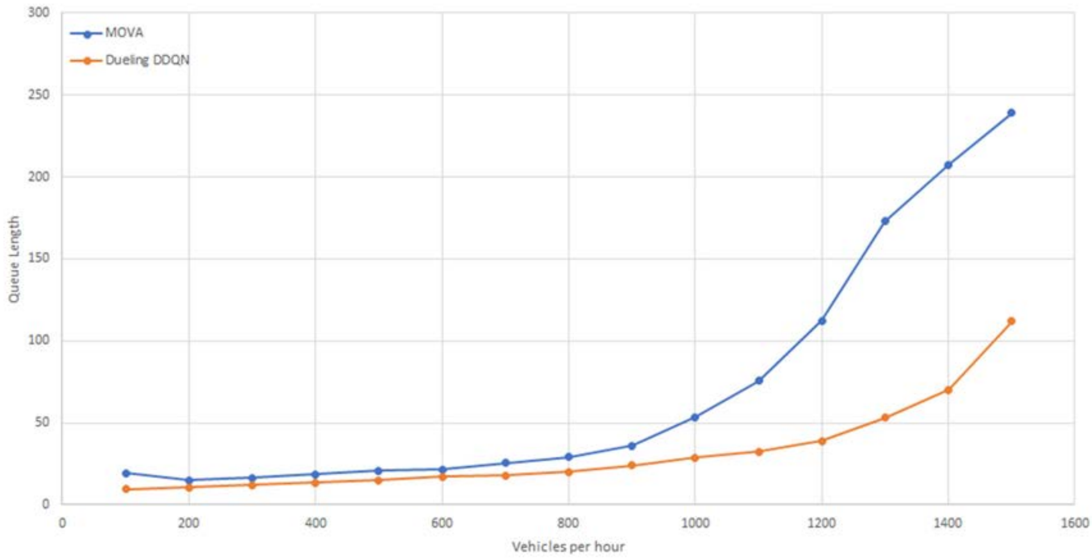

Figure 13 - Queue length by demand level in Cross Triple - 8 actions.

5. DISCUSSION AND FUTURE WORK

Several neural network architectures for RL controllers were tested. The agents did not require extensive or complex configurations to adequately control traffic junctions, outperforming the commercial controllers in terms of average queue length and delay, calculated as deviation from free-flow times. RL agents showed great stability and robustness to control situations within their training envelope as well as outside of it. Additionally, agents trained on relatively low uniform demand showed they can perform better than commercial systems during evaluation tests that included variable demand 5 times higher than anything experienced during training.

Experiment 1 provided evidence that fixed time systems perform worse than adaptive and RL UTCs in simple intersections. In this case, MOVA and the RL agent following a DuelingDDQN architecture obtained very similar results, with a slight advantage for the RL agent.

Experiment 2 provided similar evidence about a smaller number of controllers, in a situation where queues were measured on a per-link basis rather than per-lane. This implies less granularity in the data and makes the control task more challenging. The results followed the same pattern with a DuelingDQN agent obtaining the best performance, despite the lower quality of the input data.

Experiment 3 required modifications of the map in order to obtain said per-lane queues. This model saw the introduction of a much more complex intersection, with a multitude of actions available to the agent, some of them serving the same lanes in different ways, and letting the agent decide on the sequence of actions. Once again RL agents obtained better results than MOVA, with the DuelingDDQN agent obtaining the lowest global delay and average queue length. The gap between the performance of MOVA and RL agents is increased here with respect to the last experiment. Most likely reasons are higher granularity in the data and extra actions being available to the agent, allowing it to display more complex sequences of actions.

Reinforcement Learning applied to UTC keeps demonstrating that it can be a real-life solution to improve traffic conditions in urban environments, even though the sensors required are more sophisticated than simple induction loops. These experiments provide further evidence that Reinforcement Learning based UTCs could be the next generation solution for reducing traffic congestion.

ACKNOWLEDGEMENTS

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PUERTOS
PORTS

CONTAINER SHIP SIZE: WHICH DIMENSIONS CAN BE EXPECTED?

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ABSTRACT

Since the container ship was born, we have seen an impressive increase in order to get advantage of the economies of scale. In the last two decades, the capacity of vessels has been trebled. Currently, vessels of 23,000 TEU (20-foot equivalent unit) sail the seas.

Despite the exponential growth experienced in this sector, individuals question if it is possible to reach a peak capacity, as has occurred with bulk cargo vessels and, recently, aircraft. This paper aims to predict the possible size and dimensions of a new generation of mega container ships. Based on economy of scale, port infrastructure, demand and environmental trends and naval design criteria the limit ship size has been estimated. The results suggest that it is still possible additional increases of the ship size. This paper allow Port Authorities to understand the needs of shipping container industry and to figure out the expansion and investment necessary.

1. INTRODUCTION

Fuelled with the Industrial Revolution in the nineteenth century, globalization and international trade started to take off. After a period of stagnation and decline during the First World War, Great Depression and Second World War, global trade boomed again around the 1950s with the introduction of container boxes. The container shipping market was born, significantly reducing transport costs. In the following decades, container ships became an important part of the global logistics chain. An increase in efficiency and ship size followed. UNCTAD (2018) estimated that 752 million TEUs were moved at container ports worldwide in 2017.

The global trade growth experienced in the last decades has had an impact on container ship size, resulting in six waves of substantial changes, each represented by a new generation of container ships.

The first generation of container ships were primarily modified bulk vessels with a capacity up to 1,000 TEU. Rapid evolution followed. The ships continued to upsize in capacity and size until the Panama Canal limitations came into effect in 1985, with a maximum capacity of around 4,000 TEU. Accordingly, these ships came to be known as the Panama generation. In 1988, a beam of 32.3 meters was first exceeded and the generation of Post-Panama container ships began. This new generation created infrastructure problems for most ports worldwide, as they had to invest in wider gantry cranes and dredge to accommodate those ships.

At the beginning of the 2000s, demand and volume were still growing. From 2001 to 2006, growth in trade volume was, on average, three times higher than the growth of GDP.

Therefore, the top shipping lines, which started to form strategic alliances, saw the need for a new generation of container ships. In 2006, the introduction of Emma Maersk, the first very large container ship (VLCS), marked a new generation. Bigger container ships reduced the cost per TEU even further, which in turn increased demand and therefore incentivized bigger ships. This positive feedback loop ended in 2008 with demand decreasing due to the financial crisis.

However, the market power of alliances and the rise of emerging markets like China stimulated the growth of container ships even further, despite demand not yet catching up.

Therefore, around 10 years later in 2013, ultra large container ships (ULCS) with capacities above 20,000 TEUs were introduced. The current biggest container ship, in terms of capacity, reaches 23,000 TEU, 400 meters of length, 61.5 meters of beam and 16.5 meters of draught. Even though the capacity has noticeably risen, the dimensions of the newest container ships has not changed significantly in recent years. In the last 15 years capacity has been trebled and length increased 20%, beam 43% and draught only 10%.

It is a consensus that both maximum capacity and ship size will increase over the next years (Malchow, 2017; Saxon and Stone, 2017; Park and Suh, 2019). But how long these increases will take remains unclear. In this paper, potential ship dimensions are studied from the point of view of naval design principles and regulations.

The most modern cranes currently available can reach 23/24 rows across the vessel. If this limit is exceeded, then one must either load cargo for another port in the extra rows or take time to turn the vessel around part way through the operation. This is both costly and time-consuming and thus not a practical option if required in every port.

If container ships' capacity increases, some ports will struggle to handle their cargo because of container yards' limitations. Adding extra length to the container yard is often limited by the surrounding infrastructure. According to the International Transport Forum, bridges can become an obstacle if the height of container ships continues to grow. It is important to note that the increase in the capacity of container ships can congest ports that do not have sufficiently fast logistics chain.

By the light of all this, this paper aims to analyse the future evolution of container ship size and dimensions. It is analysed if the exponential growth that the sector has experienced in the last decades is approaching to a peak.

This paper is structured as follows: Section 2 contains a literature review of existing research related to the evolution of the container ship size and influencing factors. Taking into account state-of-the-art technologies, a methodology is proposed in Section 3 to estimate the container ship size of the future, identifying possible limits in growth as viewed through naval design principles. In Sections 4 and 5, we analyze the past evolution of container ship size, according to the Lloyds database, and we define a set of future optimal alternatives according to naval design restrictions and capital costs. In Section 6, we analyze the economies of scale of running bigger ships, considering vessels from the past and a set of alternatives for the future. Finally, we analyze the impact of world economic and demand trends on ship dimensions in Section 7. General results, discussion and conclusions are drawn at the end of the paper in Sections 8 and 9.

2. STATE OF ART

The exponential growth in the last decades of container ship size has motivated several authors to model the industry's evolution and the possible limits for upsizing vessels.

According to Malchow (2017), container ships with a capacity of 30,000 TEU are expected to be launched in 2025, with approximately 20 m draught, which should be the ultimate limit due to the depth constraint of the Malacca Strait. But Malchow questions if we are following this path and compares it with the development in the tanker sector, where a counter movement had happened after hitting a certain tanker ship size. Malchow conclude that container lines will not benefit from further upsizing of container ships, and, moreover, other stakeholders, like ports and terminals, will suffer the consequences of additional investments.

The International Transport Forum (Merk, 2105) points out that the current generation of container ships can be marginally optimized by adding a top layer or an additional container row. Beyond that, however, a new generation of container ships will be needed, with bigger dimensions to generate sufficient cost reduction. This new class could start with a maximum capacity of around 24,000 TEU and require a length of 456 m as well as a beam of 65 m.

The authors (Merk, 2105) question if further ship size increase would be desirable if the potential cost savings to carriers will be outweighed by high infrastructure costs. An introduction of a new generation with 24,000 TEU capacity would require substantial investments for the ports where they will operate first (Far East, North Europe, Mediterranean). In addition, due to the cascading effects, 19,000 TEU ships should be operated in North America and 14,000 TEU ships in South America and Africa, where investments will eventually have to take place.

In a similar way, Tran N.K. (Tran and Haasis, 2015) research concludes that bigger vessels could help container shipping lines to get more revenue, but at a lower ratio than capacity growth. Nevertheless, the paper shows evidences that the scale economies at sea create scale diseconomies at port. A comparison of port’s operating cost shows that serving Post Panamax vessels of 18,000 TEU is 17% more expensive than serving 4,000 TEU vessels (Saanen, 2013). Taking into consideration external costs, S. Veldman (Veldman, Glansdorp, and Kok, 2011) shows that economies of ship size exist for vessels above 15,000 TEU capacity. For existing fleet up to 15,000 TEU the economies are lower than expected.

The upsizing of container ships is mainly restricted by sailing routes. Charchalis and Krefft (2009) point out that the length and beam of a container ship for current mega vessels, from an engineering point of view, are limited by the expected sailing route.

In the long term, Saxon and Stone (2013) conclude that the upsizing of container ships is limited by three main factors: the decline of the return of investment, the physical constraints of the sailing routes and the port infrastructure. However, they hypothesize that container ships with 50,000 TEU are possible for the next half-century. Even though in the next 5 to 10 years the development could slow slightly because of overcapacity, the upsizing could continue when demand catches up.

Gomez Paz et al. (2015) use the Delphi method to determine which factors will slow down the growth of the container ships in the long term. Interviews of experts across the logistics’ chain led them to conclude that the port infrastructure and the canals would be the limiting factors.

The fact that environmental factors will become increasingly important could favour bigger ships. On the one hand, upsizing the ship could reduce the environmental impact by using less energy per TEU (Charchalis and Kreft, 2009). On the other hand, from ports’ point of view, a bigger ship has more air pollution emissions than a smaller ship. If ports are starting to charge container ships based on their emissions, at one point it could become uneconomical to operate those bigger vessels (Helmy and Shrabia, 2016). Therefore, the regulatory framework of ports could also have an impact on further ship size development (Lam and Notteboom 2014).

Tran & Haasis (2015) suggest that because of the interdependencies of stakeholders, we should not make decisions looking from only one side of the problem. Instead, we need a more holistic view when decisions about ship size are taken. For example, besides shipping costs, we should also look at port costs, inventory costs, inland transportation costs, etc.
O. Merk (2018a) concludes that port relocation due to bigger container ships could favour non-urban ports with deep sea access. Nevertheless, a port relocation is consequential for existing ports and inland connections. Thus, these decisions must be carefully considered.

Ports will have to react to the constant upsizing of container ships and to the shipping alliances trends. O. Merk (2016) suggests that ports should coordinate more to build their own alliances in order to balance the power in the container market in their own favour. This could lead to a slower ship size growth.

Related to the container ship size, the relationship between carrying capacity and ship dimensions has been studied in several research projects. Predictions of megaships' dimensions are formulated via regression analysis by Kristensen (2013). The author analyses container ships from the IHS Fairplay database and creates regression formulas, which are used to calculate further length, beam, and draught based on capacity. However, this analysis is based on data from the past and does not consider that, for example, technological disruption or a dramatic ship redesign could change the evolutionary trajectory. Park, Nam K. et al. (2019) and the Korea Maritime Institute (KMI, 2012) construct similar regressions with updated data to predict the tendency toward mega container ships.

Literature suggests that bigger container ships are still possible, with a range capacity size between 30,000 and 50,000 TEUs. Regarding the ship dimensions, authors indicate that, depending on capacity, the length estimated is between 453 and 517 meters; beam between 65 and 72 meters; and draught, between 17 and 20 meters.

3. METHODOLOGICAL APPROACH

In order to study the evolution of container ship size and define the possible limits on growth, various approaches or criteria have been considered at the same time: the evolution of the principal dimensions of container ships; the naval design restrictions and regulations; the geographic and port restrictions; the economies of scale of container shipping lines; the CO2 emissions of vessel; and finally the world economic, demand and global trends.

This paper contributes to the state of art because it defines a methodology to design alternatives of possible bigger container ships according to naval design regulations. Additionally, different criteria are analysed in order to identify the boundary restrictions of growth.

Several studies predict the future ship size dimensions with regressions, based on data of the world existing fleet. Nevertheless, in this paper we predict the container ship capacity and its dimensions by identifying alternatives of possible bigger vessels and selecting the optimal ones. Figure 1 describes the main steps of methodology used.

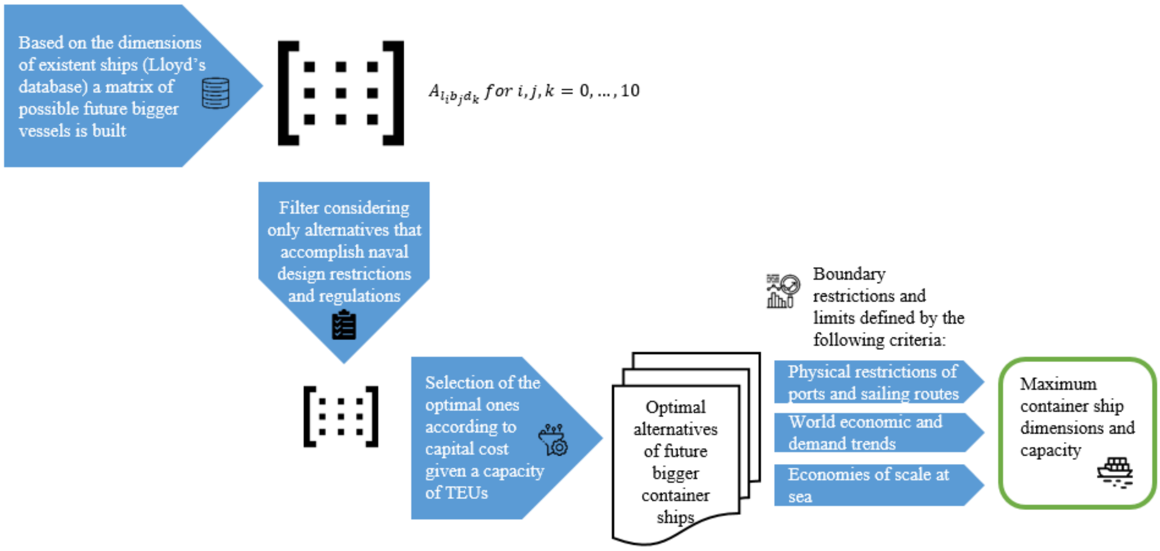

Figure 1. Simplified methodology approach

4. EVOLUTION OF THE DIMENSIONS OF CONTAINER SHIPS

To predict further development, firstly we analysed, based on Lloyd's Database, container ship dimensions from the past. Figures 2, 3 and 4 illustrate the evolution of the length, beam and draught in relation to the capacity of all container ships built since 1944. Analysing the relationships, some comments can be pointed:

- Draught does not significant change once a limit of 12,000 TEU is passed. In fact, draught for these larger ships seems to be stabilized around 16-16.5 meters.
- Length is stabilized around 400 m for vessels bigger than 15,000 TEU.
- Beam is the dimension that experiences the largest proportional growth. Currently, the bigger vessels are 60 meters in length.
- Increase in capacity for VLCS and ULCS is logically related to changes in length, depth and beam, but significantly more so for beam than for the other two. Regarding draught, it is the least-affected dimension for the new mega vessels.

Higher capacities are being achieved without a substantial increase in vessel dimensions. According to the recent vessel developments, the beam is the dimension that best accommodates extra TEU capacity when compared with the other measured dimensions.

5. POSSIBLE ALTERNATIVES FOR BIGGER VESSELS ACCORDING TO NAVAL DESIGN REGULATIONS AND PHYSICAL CONSTRAINTS (PORTS AND SALING ROUTES)

In this section, different scenarios of possible container ship sizes are represented according to different restrictions. Beam (B), length (L), depth (D) and draught (T) intuitively grow by intervals according to the new rows of TEUs added in each direction. For that reason, a matrix of alternative possible larger vessels has been built adding new rows in each direction to the current biggest container ship of 23,000 TEU (L=400, B=61.5, D=33.2, T=16.5). The matrix of alternatives is defined as:

$$A_{l_i b_j d_k} \; for \; i, j, k = 0, \ldots, 10 \quad (1)$$

Where,

$l_i = 400 + i * 5.9$, is the length and increases accordingly to the length of a TEU (5.9 m)
$b_j = 61.5 + j * 2.4$, is the beam and increases accordingly to the wide of a TEU (2.4 m)
$d_k = 33.2 + k * 2.4$, is the depth and increases accordingly to the height of a TEU (2.4 m)

To calculate draught, we assume the same ratio of the current 23,000 TEU, T=0.48*D. For example, the alternative $A_{l_0 b_3 d_1}$ is a container ship with 400 m length, 68.7 m of beam, 35.6 m of depth and 17,08m of draught.

The set of alternatives is calculated following Alvariño formulation (Alvariño et al, 1997). The formulation to define the load capacity considers, aside from the main ship dimensions, the power of the ship, the service speed at 85% of the Maximum Control Rate (MCR) and displacement of different vessels generated. The stability is verified using the assumptions defined by the International Convention for the Safety of Life at Sea (IMO, 2019). To ensure that the alternatives generated are feasible, the initial stability of each of them has been calculated, by making sure that the metacentric height (GM) of the vessel is greater than zero.

$$GM = (KB - BM) - KG \quad (2)$$

Where K is the intersection point between the ship baseline, the creaking plane and the transversal section; B is the center of buoyancy where the thrust is concentered; G is the gravity center of the vessel; and BM the metacentric radius which can be defined as the ratio between the total inertia of and the total volume of the ship.

$$BM = \frac{C_2 * B^2}{12 * C_b * T} \quad (3)$$

KB is the ratio between momentum of the volume in relation to the plane K and the total volume of the ship; $C_b$is the block coefficient which is the ratio of the volume of displacement at that draft to the volume of a rectangular block having the same overall length, breadth, and depth.

$$KB = C_1 * T \quad (4)$$

Where C_1 and C_2 are constants obtained of Riddlesworth's and Normand's expressions (Alvariño et al, 1997). KG depends on the ship's displacement and the distribution of loads. It is estimated using weighted ratios obtained from Alvariño (Alvariño et al, 1997).

The set of alternatives defining future ship sizes was filtered, with selection of the vessel designs that optimize for capital costs of construction given a capacity. This decision is made due to the fact that construction costs represent 42% of major costs associated with running ships, according Stopford (2009).

The capital cost formulation is defined in Section 6. Figures 2, 3 and 4 illustrate the historic dimensions of ships (length, beam and draught) and the set of alternatives selected. The figures show that the alternatives selected follow the historic tendencies for all the dimensions.

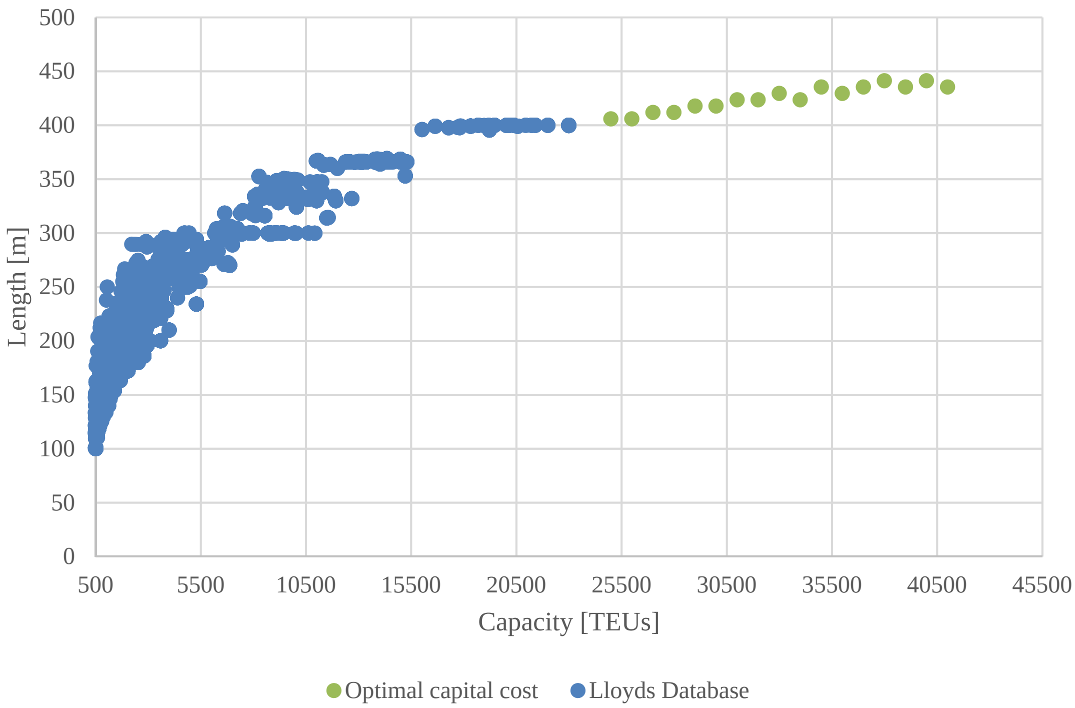

Figure 2. Relationship between the length and capacity of container ships built, with optimal alternatives selected according to capital cost.

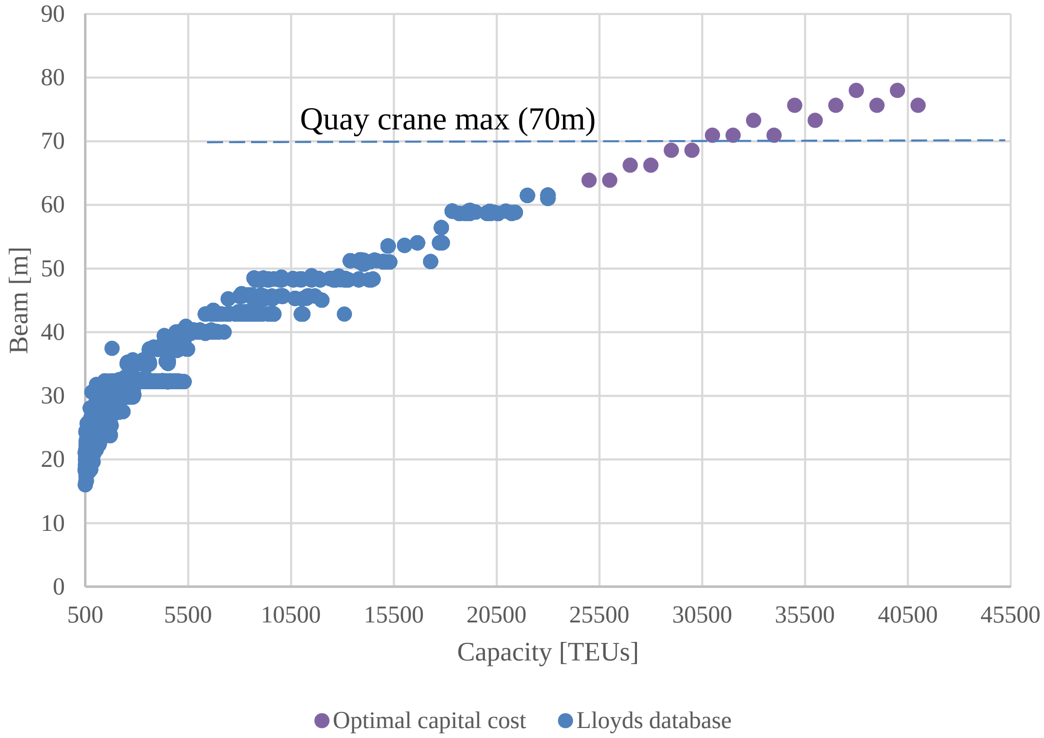

Figure 3. Relationship between the beam and capacity of container ships built, with optimal alternatives selected according to capital cost.

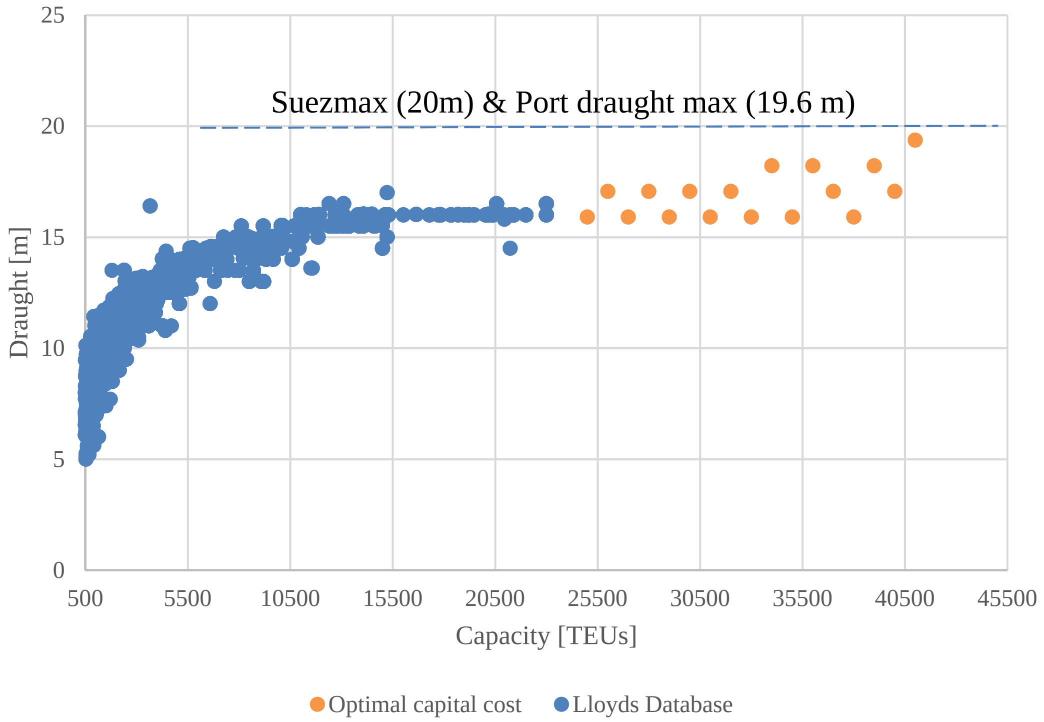

Figure 4. Relationship between the draught and the capacity of container ships, with optimal alternatives selected according to capital cost.

The constraints of the port's infrastructure limit ship size development as well. Draft deepness, the limited arm-length of gantry cranes and the limited space for container yards make it impossible for some ports to handle the ever-growing vessels. The traditional outreach of quay cranes in most container terminals is less than 70.4 m (represented in Figure 3); automatic container terminals opened after 2015 have a length of berth of over than 1.000 m according to Park and Sub (2019). Draft deepness of main ports of the world is contained in Table 1. As shown, the draught port is limited to 20m, and the range is from 16 m to 19.65 m.

Region	Country	Port	Draught [m]
South-Eastern Asia	Singapore	PSA Singapore	18
	Indonesia	New Priork (Jakarta)	16
North-Eastern Asia	China	Dalian	17.8
	South Korea	Busan	17
Middle East & South Asia	India	Bharat Mumbai	16.5
	Saudi Arabia	Saudi Global Port	16
North Europe	Belgium	Antwerp	17
	Hollande	Rotterdam	19.65
	Germany	Hamburg	17.4
Mediterranean Sea	Italy	Savona	17.25
	Portugal	Sines	17.5
	Turkey	Mersin	15.8
	Spain	Algeciras	18.5
	France	Marseille	16
	Morocco	Tanger	18
America	Panama	PSA Panama	16.3
	Colombia	Buenaventura	16.5
	United States	Los Angeles	16.7

Table 1. Draught of the main ports across the world sorted by region and country. Own elaboration based on the ports' website data

Relative height of mega ships or how high containers are stacked could be a limiting factor of growth, especially for maritime routes that need to cross bridges to access to the ports.

The actual relative height is around 17.50 meters for the current biggest container ships, and according to the results shown in Figure 5, it could be stabilized around 20 meters.

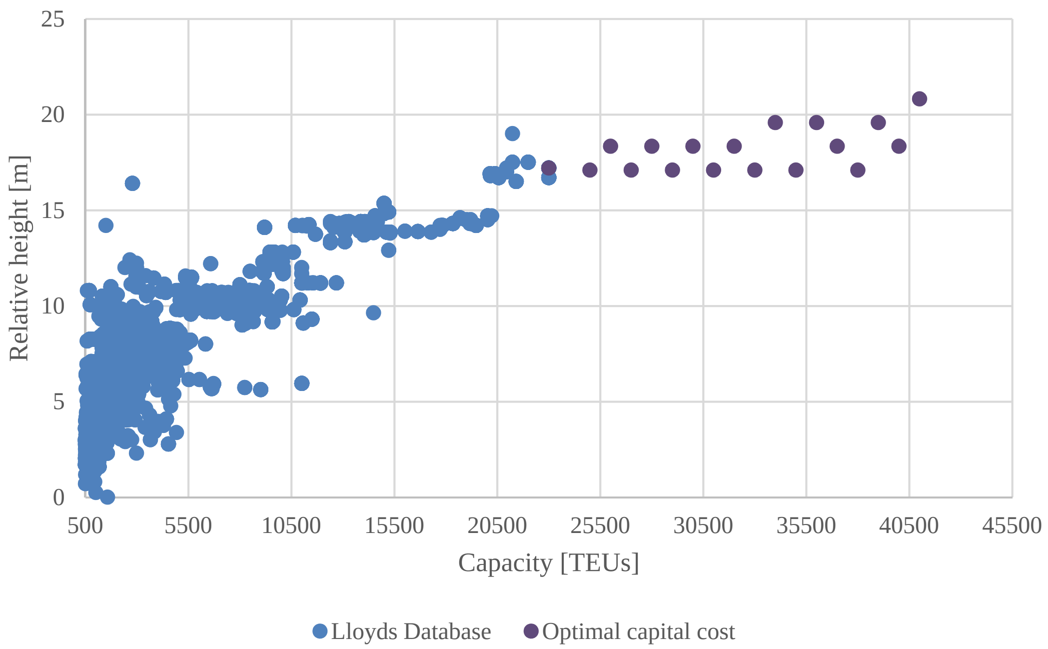

Figure 5. Relationship between the relative height and the capacity of container ships, with optimal alternatives selected according to capital cost.

Ship size development is also limited by the physical constraints of sailing routes. The Panama Canal route is the most restrictive, with a limited length of 366 m, a beam of 49 m and a draught of 15.2 m. For the Asia-Europe route through the Suez Canal, which is the shortest path for this itinerary, there is no limitation of length, a beam limitation of 50m and a draught limitation of 20m or, eventually, 77m of beam and 12.2m of draught (SCA, 2019). It is important to note that, in accordance with the Suez regulations, as we increase the beam, the draft decreases because of the trapezoidal cross section geometry of the canal. For example, for the actual biggest container ship of 23,000 TEU capacity, with a beam of 61.5 meters, the draught restriction is 16.28m. It thus becomes clear that today's container ships should optimize their dimensions to increase capacity according to the Suez Canal's navigation regulations. Nevertheless, this paper aims to study future ship size and accordingly assumes that the cross section of the Suez Canal could be increased, despite the high investment costs required. For the alternate Asia-Europe route, through the Cape of Good Hope, the only limitation is for draught in the Malacca Strait, which is constrained to 25 meters. Finally, due to the global warming, we have considered in a long term the Arctic Route, but according to a study by the Copenhagen Business School (2016) the Northern Sea Route will not be commercially viable until 2040.

Analysing the set of alternative physical and geographic restrictions of sailing routes and ports, we can conclude that:

- According to capital cost optimisation, ship length can grow up to 450 meters, with no boundary restriction on this dimension.
- According to Figure 3 the beam can increase up to 80 meters. This is due to the fact that the beam is the cheapest dimension for increasing capacity. However, the canal and quay crane boundary restrictions could limit this dimension to around 70 meters, which corresponds to a container ship of 30,000 TEUs.
- Finally, draught is the dimension that experiences less increase, growing up to 20 meters for vessels larger than 40,000 TEU. Nevertheless, for vessels with capacity under 35,000 TEUs, draft fluctuates between 16 and 17 meters. Current canal and port restrictions operate at around 20 meters in depth.

In summary, draught or beam limitations could form the natural limit to further ship growth.

6. ECONOMIES OF SCALE AT SEA

One of the main drivers for bigger container ships is the economy of scale. Historically, increased capacity per vessel reduced the cost per TEU, so shipping lines strove over the last decades to enlarge their vessels. However, returns of scale are declining with increasing size. Therefore, it is not clear if the unitary cost will keep declining with the ship size.

Due to the fact that container ship maritime trade is strongly dependent on the economies of scale, in this section we study the main influencing costs of Container Shipping Lines: Capital, Fuel and Operational costs (Stopford, 2016).

6.1 Capital costs

Capital costs are defined as the ship yard building price. To analyse capital costs according to the size of the vessel, we have used the methodology elaborated by Junco O. (2003). The following costs have been taken into account to calculate a ship's total capital cost (CC):

$$CC = CMg + CEq + CMo + CVa \tag{5}$$

The bulk material cost (CMg) considers the materials used and their qualities, as well as the utilization coefficient. Junco O (2003) uses series of coefficients to take into account not only the steel of the ships' hull, but also all the metallic elements included in the structure (superstructure, metallic equipment, etc.)

The ship equipment costs (CEq) have been calculated as a sum of the labour costs of assembling the equipment and facilities, cargo handling equipment, cost of equipment calculated as the cost per power units of propulsion and auxiliary equipment for the total propulsion power. Here we take into account the cost of propulsion equipment, calculated as 350 €/kW for the power installed in the vessel, as well as the cost of crew members' quarters and the price of the remaining equipment calculated by their weight.

General labour costs of the ship (CMo) considers the costs of personnel necessary to carry out the construction in the ship yards, calculated as the hours needed to build the ship by weight of steel.

Other construction costs (CVa) include the costs of the International Association of Classification Societies, insurance, channel tests, etc., where a value of 10% of the total construction cost has been assumed based on Junco O (2003).

Due to the fact that we calculate fuel costs based on the EU-MRV (UE, 2015; EU-MRW,2019) database for 2018 container ships, we analyse only these same vessels' capital costs. We assume the operating life of ships to be 20 years, with an operating time of 365 days per year.

6.2 Fuel costs

To determine fuel costs based on ship dimensions, the Lloyds database has been used in conjunction with the available data from European Union (EU-MRV, 2019) data, which reports ships' fuel consumption of 2018 according to EU Regulation 2015/757. Despite the fact that alternatives fuels are currently emerging, we assume that container ships will continue to use traditional petroleum fuel throughout the next 30 years according to the World Energy Outlook of 2018 (IEA, 2018). We address the impact of new ECA and SECA regulations of the IMO for the next years building three scenarios that consider Marine Diesel Oil and Very Low Sulphur Fuel Oil.

In order to determine daily fuel costs based on the EU-MRV database, we have applied the following formulation:

$$Daily\ Fuel\ Cost_{2018}\ \left[\frac{€}{TEU}\right] = \frac{Total\ fuel\ consumption_{2018}}{Total\ time\ spent\ at\ sea_{2018} * TEU\ capacity} \tag{6}$$

The total fuel consumption cost and the time spent at sea is obtained from the EU-MRV (2019) database.

To estimate the fuel costs of the predicted ships of the future, we use Alvariño's (Alvariño et al, 1997) methodology. The following formulation is used to calculate the ship's fuel consumption:

$$Consumption\ \left[\frac{m3}{hour}\right] = \frac{Power\ (kw) \cdot Specific\ consumption}{Fuel\ density} \qquad (7) \qquad (7)$$

Where, specific consumption is 0,189 $\frac{kg}{kWh}$ and fuel density is 991 $\left(\frac{kg}{m^3}\right)$.

We have assumed a constant cost of $571/tonne of Heavy Fuel Oil, which represents the average cost during the first quarter of 2018 according to Energy prices in selected OECD countries by the International Energy Agency (IEA, 2019). We assume a US dollar to Euro exchange of 1.1534, the 2018 average according the European Central Bank.

It is important to remark that the new generation of Maersk’s Triple E, which practically doubled the capacity of its predecessors, achieved a cost reduction of 40-50%. However, in recent years, it has been found that 60% of the reduction is given more by the efficiency of the engines than by the scale effect (Merk, 2015).

6.3 Operational costs

Operational costs include manning, insurance, stores, spares, lubricating oils, R&M, dry docking, management and administration. They are estimated according to the 2015 regressions of Tran N.K. (Tran, 2015), which are based on Drewry data from 2012. The estimated regression model with respect to TEU capacity is:

$$Daily\ operational\ cost\ \left[\frac{€}{TEU}\right] = \frac{22{,}89 * TEU\ capacity}{r} \tag{8}$$

Where, r is the US dollar to Euro exchange of 1.1534.

Operating cost is the category that presents the least variation for ship size capacity. Doubling vessel capacity increases overall cost by only 32% while decreasing unit operating costs by 34%.

Finally, it is important to point out the inventory cost. Arrival of a mega-ship in a port is associated with higher yard occupancy, more feeder traffic, truck and train movements that could increase the inventory costs due to the delay (Merk, 2015). Tran N.K. (2015) defined the inventory cost as $20 per TEU carried. Inventory costs are excluded from the analysis due to the dependence on the sailing routes and port calls.

6.4 Total costs of running container ships

Given the set of alternatives selected in the previous section, we estimate shipping unitary costs in order to study economies of scale. Figure 6 illustrates the evolution of running costs of all 2018 ships as well as the prospective costs of future vessels.

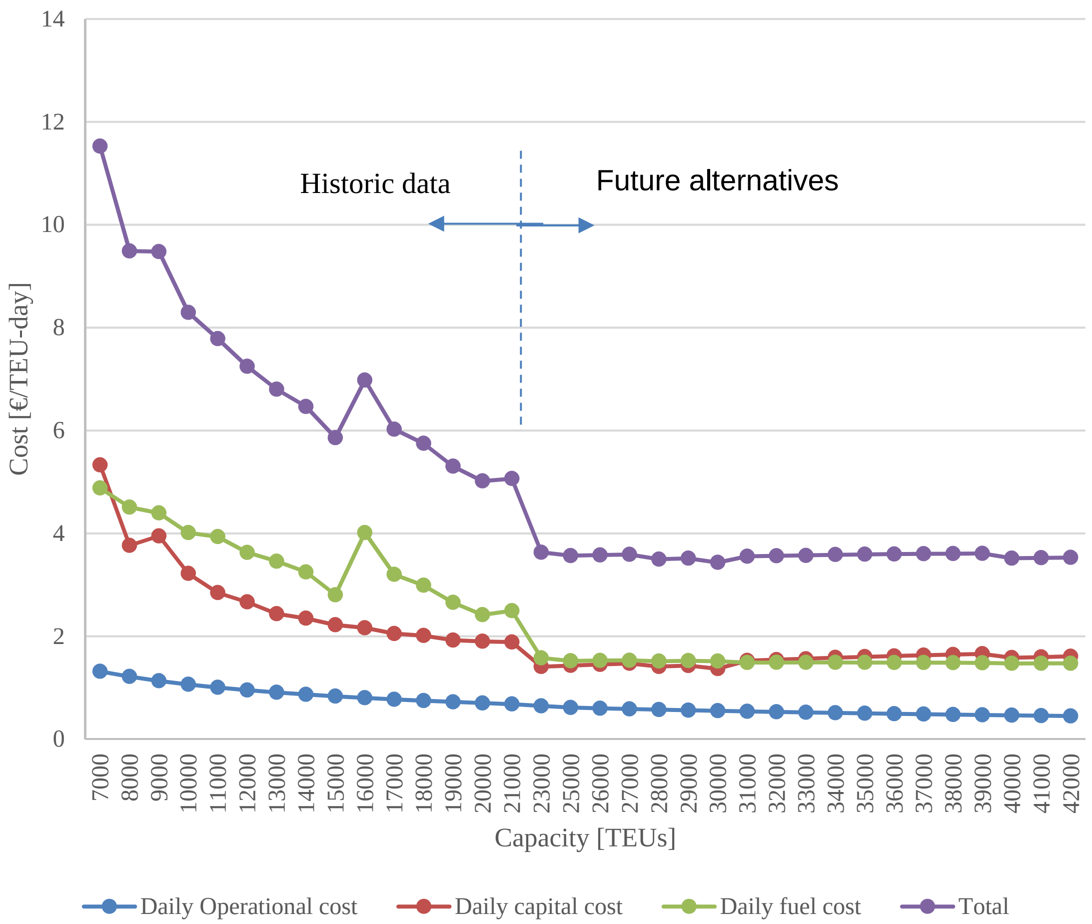

Figure 6. Fuel, capital and operational costs of container ships in 2018 (7,000-21,000 TEU). Prospection for vessels bigger than 23,000 TEU. Own elaboration with Lloyds and EU-MRV databases.

Some comments can be arisen from Figure 6:

- The total unitary cost is stabilized container around 30,000 TEUs. Figure 7 details the relative lifetime costs for a vessel of this capacity.
- For vessels larger than 20,000 TEU, the reduction in operational costs is negligible.
- From the point of view of construction and fuel costs, we observe a stabilization of costs per TEU for vessels over 25,000-30,000 TEU.
- There is a downtick in total costs around 21,000 TEU ships, especially due to the fuel costs. However, if we consider historic ships (2018) up to 15,000 TEU the trend of the historic data follows the one of the future alternatives, drawing a potential stabilization curve.
- The gap detected in the economies of scale that appears in Figure 6 is derived from the EU-MRV database, because 16,000 TEU ships present higher consumptions of fuel.

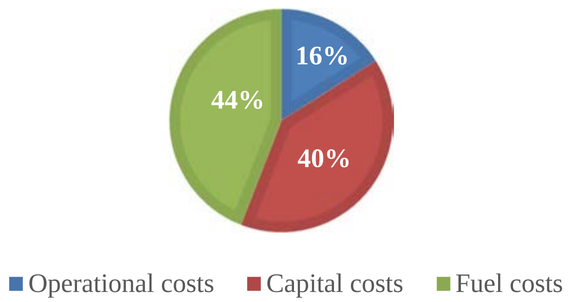

Figure 7. Detailed relative lifetime costs (fuel, operational and capital) of running a container ship of 30,000 TEU

In order to analyse the possible influence of the IMO 2020 regulation, Figure 8 represents the fluctuation of total costs, comparing the High Sulphur Fuel Oil (HSFO) with the Very Low Sulphur Fuel Oil (VLSFO) and the Marine Diesel Oil (MDO), that have respectively +70% and +50% higher cost in relation to the HSFO (Ship & Bunker, 2020). Analysing the results we can assume that in the three scenarios there is a stabilisation of total economies of scale. Costs for running container ships bigger than 25,000 TEU fluctuates between 4 and 6 €/TEU-day.

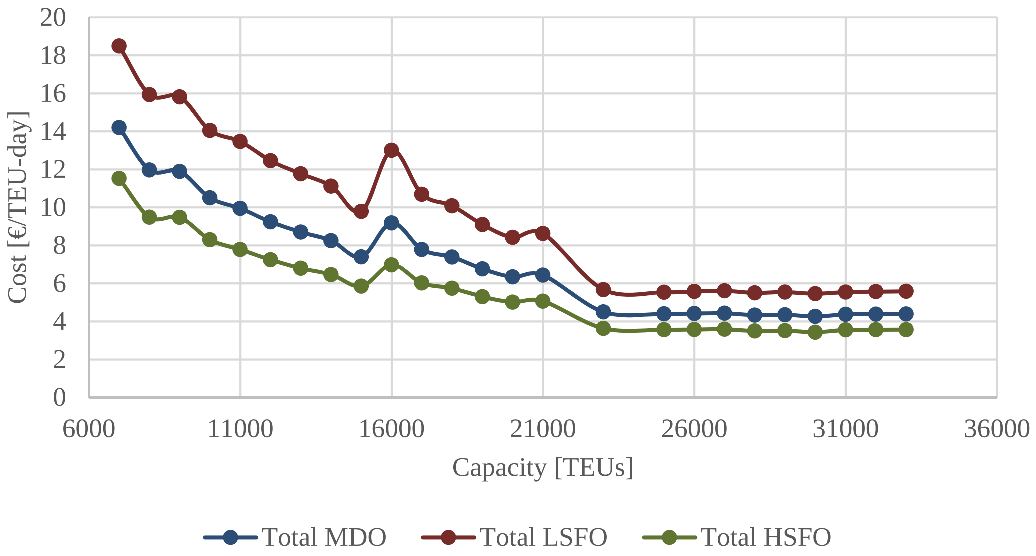

Figure 8. Total costs of container ships in 2018 depending on the type of Fuel Oil used (7,000-21,000 TEU). Prospection for vessels bigger than 23,000 TEU. Own elaboration with Lloyds, EU-MRV databases and Ship&Bunker data prices.

In light of climate change, it is worthwhile to analyse the evolution of CO2 emissions produced by container ships. We have estimated the evolution of CO2 emissions related to container ship capacity.

This is done using Lloyds database as well as data available from the EU-MRV system, which reports ships' CO2 emissions according to EU Regulation 2015/757. Figure 9 illustrates that there is a trend of reducing CO2 emissions as we increase container ship size. Even though there is a small uptick for container ships of 15,000 TEU, it can be assumed that environmental scale economies could favour an increase in ship size.

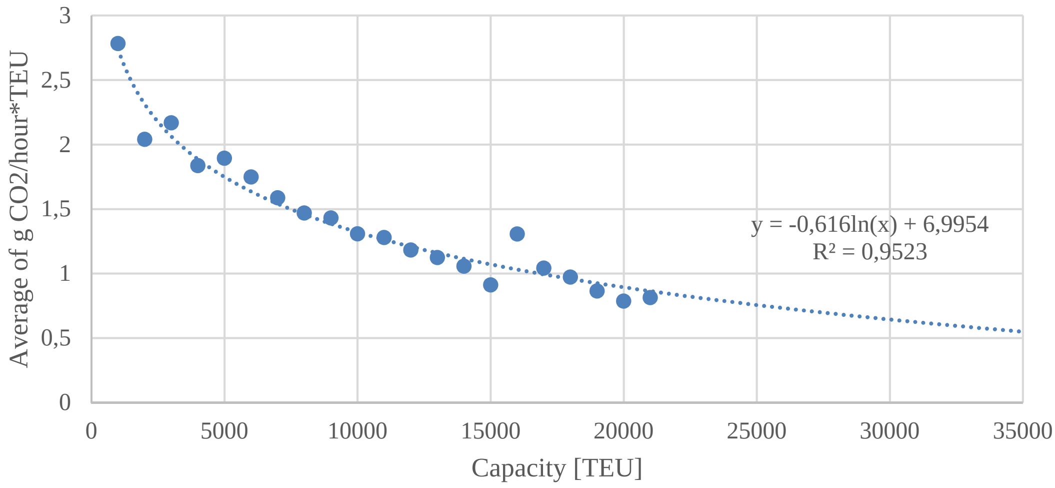

Figure 9. Evolution of CO2 emissions per hour and TEU transported according to ship size. Own elaborations with the EU-MRV database.

7. WORLD ECONOMIC AND DEMAND TRENDS

GDP is usually a valuable indicator to anticipate future trade volume. From 1997 until 2007, the growth of the container trade was almost three times higher than GDP growth. Since the 2008 crisis, the volume of goods traded has increased approximately in line with GDP, with a ratio of TEU growth to GDP of 1.7 (Saxon, 2017). Current estimates show global trade to be growing slightly quicker than GDP but to be on a downward path (Saxon, 2017). Figure 10 illustrates the positive relationship between world container port traffic and the largest ship, in terms of capacity, in each year since 2001.

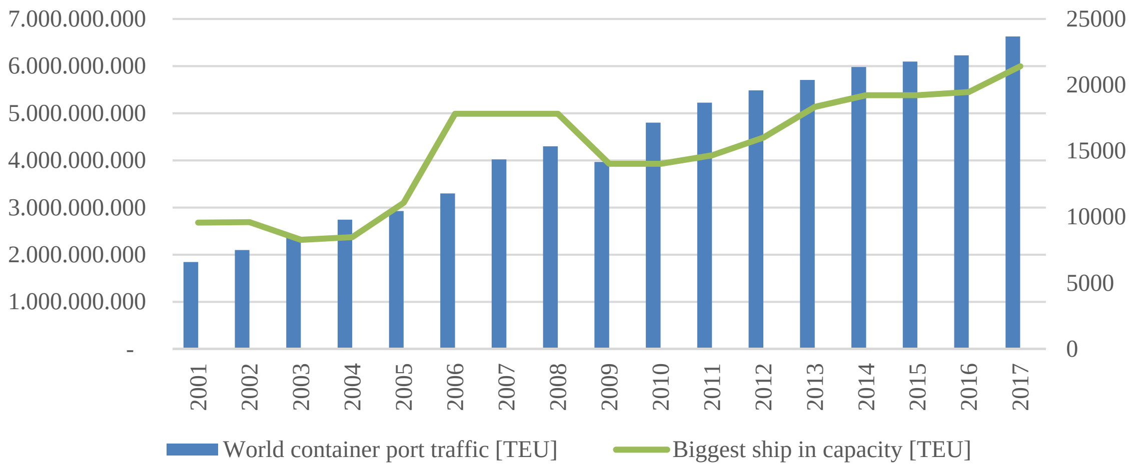

Figure 10. Global TEU trade evolution and biggest current container ship in capacity. Source: Own elaboration based on Lloyds and the World Bank Database.

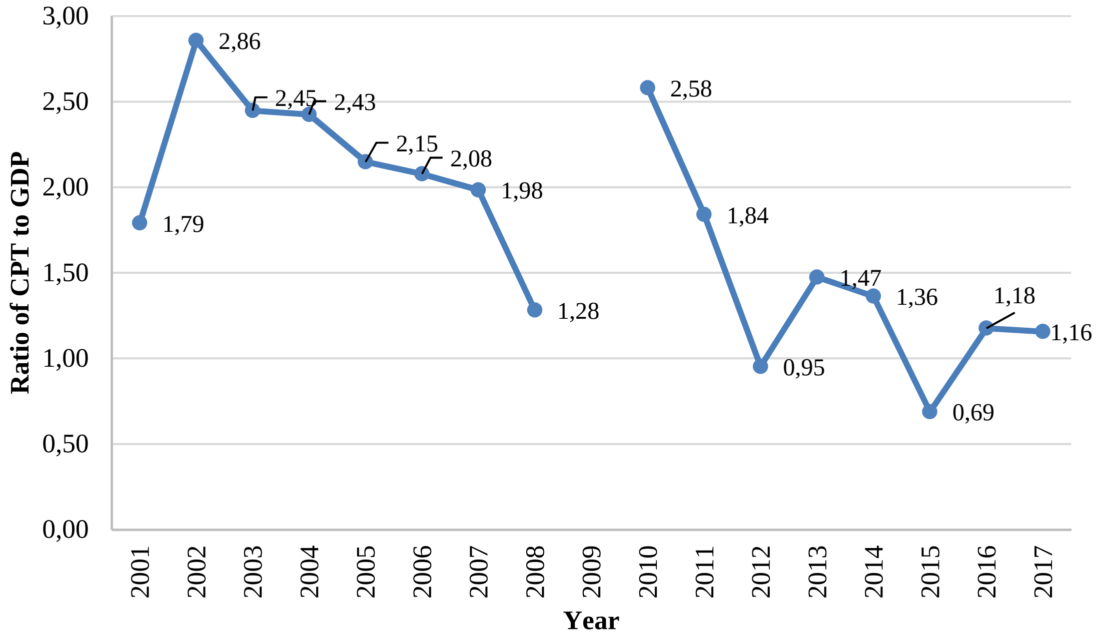

Figure 11. Ratio of annual container port traffic to Annual GDP growth excluding 2009 due to the financial crisis. Source: Own elaboration with World Bank Database.

Figure 11 indicates that the average ratio of Container Port Traffic to GDP is decreasing from two to one. Moreover, in 2012 and 2015, the ratio was under one, which means that world container traffic is growing proportionally less than the global economy.

According to Figure 10, we can assume that, if the global container trade is growing in a similar to GDP (as can be concluded from Figure 11), ship size is going to act in the same proportion. ITF (2019) has estimated that the Compound Annual Growth Rate in the World 2015-2050 is 2.9%. Thus, if the biggest container ship in the world in 2015 was 19,000 TEU, in 2040 we could estimate a container ship of 39,000 TEU, based only on demand forecast and past ship size evolution. In addition to that, the downward trend in TEU growth to GDP growth could be an indicator of stabilization of container ship size.

Another way of favoring bigger container ships and reinforcing a 39,000 TEU capacity ship, is the shipping alliances phenomena. Three global alliances represent the eight largest container carriers of the world. Together, the three alliances represent around 80% of overall container trade and operate around 95% of the total ship capacity on East-West trade lanes (Merk, 2018b). Such alliances have allowed carriers to acquire and operate mega-ships, thereby reducing unit costs.

However, even ever-larger ships are increasing supply, but demand is not catching up. This creates overcapacity in the container market. Although demand has increased since the financial crisis 2007-2009, it is not keeping pace with supply. The supply/demand imbalance will persist, we predict, with revenue and pricing remaining under pressure as container ship sizes increase and global GDP only moderately grows. To take just one example, in 2016, supply total fleet was 23% over the world demand (Saxon, 2017).

In addition to the supply and demand unbalance, some additional trends can slow down the ship size increase. Firstly, 3D printing could decentralize a bigger part of the global production, which would have a negative impact on global trade. At the moment, nonetheless, the impact of new technologies on global trade is expected to be marginal: one analysis, by Irene J. Petrick and Timothy W. Simpson (2013), estimates that TEU volumes will fall less than 1 percent by 2035. Another trend is the slowdown of the Chinese market, which is moving away from a development-based model centered on the export of physical goods and toward a consumption- and services-based model, is negatively affecting world demand and therefore also the evolution of container ship size.

Finally, emerging companies like Amazon and Alibaba could heavily impact the ship size developments by prioritizing time-to-market over cost per TEU. This would result in a push for smaller vessels with more direct port-to-port connections, the opposite trend of that observed in recent years.

8. RESULTS AND DISCUSSION

From the combination of the limiting factors described in the previous sections, it can be concluded that:

- Increases in capacity does not have a large impact on vessel dimensions. Beam is the dimension experiencing proportionally the biggest growth. In the last 15 years capacity has been trebled and beam has increased 43%, while length and draught only a 20% and 10% respectively.

- Draught or beam limitations of ports and sailing routes could form the natural limit to further ship growth. The results suggest that this limit will be reached with a container ship of 30,000 TEU capacity due to the physical restrictions of the sailing routes and port infrastructure (quay crane maximum reach of 70 m).
- From a point of view of the economies of scale, there is possible stagnation, with an eventual increase foreseeable for ships over 30,000 TEUs.
- The overall growth of world GDP and global trade favour the container ship upsizing beyond 30,000 TEU capacity. This is especially true as the container shipping market has become increasingly consolidated, with just a few shipping-line alliances controlling most trading routes. These alliances continue to use their market power to increase container ship size and capacity in order to achieve economies of scale. We predict the possibility of 39,000 TEUs capacity ships in 2040 according to the GDP and traffic trends. However, the decline evidences of the world global trends in relation to the GDP indicates a possible peak of the container ship size. Other global trends like the 3D printing or the overcapacity of the world container fleet could reduce the expectation of a 39,000 TEU capacity ship. In addition to that, according Figures 2, 3 and 4, dimensions of a 39,000 TEU ship are of 435 m of length, 76 m of beam and 18 meters of draught, which will limit the number of feasible port calls and a beam larger than the current quay cranes.

It is necessary to note that from the point of view of CO2 emissions, there is no stagnation of economies of scale as we increase ship size. If environmental scenarios are prioritized by the regulatory frameworks, larger container ships are more sustainable if the transport model is from hub to hub. These findings are consistent compared to Veldman et al. (2011) that estimates that for a 6,000 TEU ship the external costs vary from 5.9% to 29.3%, while for a 25,000 TEU vessel they decrease slightly from 5.2% to 26.2%.

To sum up, the results suggest that there is a stabilization of ship growth around a capacity of 30,000 TEU. Malchow (2017) and Park, Nam K. (2019) predict that 30,000 TEU capacity ships will appear in the shipbuilding market in 2025. However, in the light of the global economic trends analyzed in this paper the findings suggest that the 30,000 TEU ship could appear in 2030. In the long-term Saxon & Stone (2017) hypothesize 50,000 TEU container ships for 2050.

The results of this study are consistent and contribute to the state of art by defining a methodology to predict future optimal vessel dimensions and capacity according to the naval design regulations (1997) and considering different criteria to fix upper and down limits.

Under the assumption of 30,000 TEUs vessel, the results indicate that optimal ship size according the capital costs is of 418 m of length, 69 m of beam, 35 m of depth and 17 m of draught. In order to verify accomplishment of naval design criteria, GM value is calculated. For the alternative selected this value is 3.01 meters and, expressed as percentage of beam, 4.36%. A reasonable value would be between 4-5% (1997), in order to avoid stability problems.

Our predictions are similar to those predicted in 2019 by Park, Nam K: 453 m in length 72 m of beam and 17.3 m of draught. However, they differ from the ones predicted by the Korea Maritime Institute for a ship of 30,000 TEU: 517 m in length, 65 m of breadth, and 19.4 m of draft (KMI, 2012). A similar approach was built by Kristensen (2013) that estimated a hypothetical container ship with a capacity of 30.000 TEU would have 483 m of length, 71.5 m of beam and 18.7 m of draught. Malchow (2017) estimates that a 30,000 TEU ship will have 20 m draught, while our results suggest that this dimension will be around 17 m.

This paper contributes to the state of art of the evolution of container ship size offering some strategic key points in order to evaluate the need investment in new port infrastructures to fit mega ships, considering also the possible unbalanced externalities. Nevertheless, the three existing shipping alliances (2M, Ocean Alliance, The Alliance) represent 80% of all container trade, and they control the driver of ship size optimisation more than ports.

9. CONCLUSIONS

This paper deals with the possible growth path of container ships. A limit on capacity is estimated at around 30,000 TEUs. Analysing historical container ships data, it is apparent that an increase in capacity does not have a large impact on vessel dimensions, with the exception of the beam, which has experienced the biggest growth in the last decades. If no technological disruption drastically changes container-ship design, the results suggest that the world's largest vessel of 30,000 TEUs will have approximately 418m of length, 69m of beam and 17m of draught. It has been assumed that the cost of construction will prevail, to the detriment of fuel costs, as the dominant shaping force, since it is expected that technological development will reduce fuel consumption as a result of increases in engine’s efficiency.

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DEVELOPMENT OF A MULTICRITERIA SCHEME FOR THELOCATION AND SELECTION OF SUSTAINABLE URBAN DRAINAGE SYSTEMS IN PORTS

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RESUMEN

Las infraestructuras de transporte, como los puertos, se enfrentan al desafío de latransición hacia prácticas de gestión sostenible en un contexto de cambio climático. El nexo Energía y Agua es clave para ese propósito como lo señala la Organización Europea de Puertos Marítimos (ESPO) en el informe "*Prioridades de los puertos europeos para 2019-2024*", centrándose en la necesidad de coherencia y coordinación entre la política de transporte y otras políticas a nivel de la Unión Europea (UE) (Medio Ambiente, Aduanas, Competencia, Energía, Asuntos Marítimos, Investigación). En 2019, 94 puertos de 19 distintos países miembros de la ESPO, han tomado iniciativas de sostenibilidad para reducir la contaminación de agua en los puertos y de este modo proteger la calidad del agua y respetar las normas impuestas por la Directiva Marco del Agua. Los SistemasUrbanos de Drenaje Sostenible (SUDS) se han convertido en las técnicas de drenaje másutilizadas para adaptar con éxito las áreas urbanas a los escenarios climáticos presentes yfuturos. Sin embargo, se han realizado pocas investigaciones sobre la aplicación de SUDS en la infraestructura de transporte relacionada con los puertos, lo que representa una brecha clave en el campo de la gestión de la infraestructura de transporte. Algunos trabajos previos sobre pavimentos permeable (PP) mostraron el potencial para implementar SUDS en terminales portuarias, capturando y filtrando la escorrentía superficial, permitiendo el control del volumen y el tratamiento de contaminantes. Esta investigación presenta un nuevo enfoque para la ubicación y selección del drenaje en lospuertos, considerando todos los aspectos del diseño de SUDS dentro de un marco multicriterio (ej.: control de la cantidad de agua, tratamiento de la calidad del agua, biodiversidad y servicios). A su vez, esta investigación demuestra que tipos de SUDS podrían diseñarse y utilizarse en puertos bajo un análisis multicriterio, presentando las principales limitaciones para su implementación.

1. INTRODUCCIÓN

Los puertos son infraestructuras de transporte que, debido a sus características y serviciosque ofrecen, generan una alteración de las condiciones naturales preexistentes a su implantación, tanto en el área donde se ubican como en sus zonas adyacentes. Además, actúan como lugares de punto de encuentro entre el transporte terrestre y marítimo (Bravoet al. 2006). Este último, es el medio más eficaz de transportar mercancías debido a su bajo costo, gran capacidad de transporte masivo de mercancías y movimiento en largas distancias (Bobadilla y Venegas 2018). Actualmente, representa casi el 90% de la gestióndel comercio mundial (Zahed, 2015). De esta manera, los puertos se convierten en un factor indispensable para el comercio y desarrollo económico de un país, siendo puntos nodales en las cadenas de suministro mundiales (Martí et al. 2015). Sin embargo, generan una serie de impactos negativos al medio ambiente como consecuencia de las actividadesinherentes a su función y a una gestión deficiente en esta materia. Además, debido a su ubicación, son susceptibles de recibir la contaminación proveniente del entorno del puerto(Goulielmos, 2018). Muchos puertos en países altamente industrializados están experimentando una grave degradación de sus entornos. En consecuencia, la protección del medio ambiente se está volviendo cada vez más un aspecto importante en la gestióny desarrollo portuario y, en general, para la gestión de zonas costeras (Tubielewicz, 1995).Existen numeras investigaciones que estudian esta problemática, como la realizada por lainiciativa medioambiental EcoPorts, integrada en la Organización Europea de Puertos Marítimos (ESPO), la cual ha identificado y monitorizado aquellos riesgos ambientales que presentan los puertos integrados en la red EcoPorts a lo largo de estos últimos años. Además, han establecido las principales prioridades ambientales de las autoridades portuarias europeas.

Los resultados del "*Informe medioambiental ESPO 2018*", establecen como la primera prioridad medioambiental la calidad de aire (ESPO 2018). Esto se debe a que es el principal riesgo para salud humana en Europa, causante de aproximadamente 400.000 muertes prematuras por año (European Environment Agency,2018). La segunda es el consumo de energía, estrechamente relacionada con las emisionescontaminantes, entre otros factores por la correlación directa entre el consumo de energíay la huella de carbono de los puertos, así como el cambio climático (Raptis, 2019). La contaminación acústica es la tercera prioridad, principalmente la provocada por los motores de los barcos y la maquinaria portuaria (Puig et al. 2015). Es interesante observarque la mitigación y la adaptación al cambio climático se encuentran entre los diez factoresclave, indicando que los puertos ya comenzaron a actuar para adaptarse a los efectos del cambio climático (Raptis, 2019).

La calidad del agua, a pesar de no encontrarse entre las primeras prioridades, se trata del indicador ambiental que ha sufrido un mayor aumento de monitorización desde 2013 (ESPO 2018). Esta circunstancia se ve motivada porque los estados miembros de la UE están realizando esfuerzos para alcanzar los objetivos planteados por la "*Directiva marcosobre la estrategia marina*" (DMEM) (Unión Europea, 2008). Principalmente, los relacionados con alcanzar un buen estado ambiental de las aguas marinas, perseverando en su protección y conservación, así como en evitar su deterioro.

Las autoridades portuarias españolas están actuando en esta materia siguiendo las recomendaciones propuestas en la ROM 5.1-13 (Ministerio de Fomento, 2013). Estas recomendaciones propuestas se basan en el establecimiento de métodos y procedimientos para la tipificación de las unidades de gestión del medio acuático portuario y para la gestión de la contaminación marina accidental. Además, establecen recomendaciones para la evaluación y gestión de riesgos ambientales de las actividades realizadas en el entorno portuario y el análisis de la calidad ambiental de las unidades de gestión del medio acuático portuario.

No obstante, los enfoques actuales para regular los impactos en la calidad del agua no son suficientes (European Environment Agency, 2018).

La gestión de esta problemática en los puertos presenta una gran complejidad dada la diversidad de focos devertido de contaminantes que tienen lugar en las áreas portuarias (Fred Lee y Jones-Lee,2003). La calidad del agua está intrínsecamente relacionada con los factores que influyen en el desarrollo portuario (la ubicación del puerto, su construcción y las operaciones portuarias que se desarrollan en el mismo) (UNESCAP, 1992).

Una de las principales causas de este problema ambiental es que, con demasiada frecuencia, se permite que fluya la escorrentía superficial de las áreas portuarias hacia a la ribera del mar o de las rías, sin ningún tipo de tratamiento (Fred Lee y Jones-Lee, 2003).Las aguas pluviales que precipitan sobre estas áreas no tienen presentes gran cantidad decontaminantes. Sin embargo, cuando estas aguas pluviales arrastran los contaminantes como escorrentía sobre las superficies impermeables del puerto, pueden ir acumulando distintos tipos de contaminantes (depósitos de contaminación del aire, fluidos automotrices, sedimentos, nutrientes, pesticidas y otros tipos de contaminantes) (Bailey et al. 2004). Esta contaminación difusa se ve acentuada a causa de las operaciones de limpieza con baldeo y riego para atenuar emisiones a la atmósfera que se realizan con frecuencia en los puertos (Ministerio de Fomento, 2015). Las escorrentías superficiales que se vierten a la masa de agua de los puertos españoles es, según un gran número de Autoridades Portuarias Españolas (Ministerio de Fomento, 2012), el foco de vertido mássignificativo que repercute sobre la calidad del agua. Numerosos estudios científicos han demostrado repetidamente una correlación directa entre esas superficies impermeables yla contaminación de la escorrentía (Shueler, 1994). Por ejemplo, un aparcamiento de 4.000 m^2 produce 16 veces más de escorrentía que una superficie permeable (Shueler, 2000). Por lo tanto, se puede considerar que en un puerto las superficies impermeables son generadoras de contaminación y consecuentemente de efectos ambientales adversos.

Este estudio tiene el objetivo de reducir esta problemática mediante la implantación de SUDS en áreas portuarias, ya que una de las características de estos sistemas, es su capacidad de disminuir los volúmenes afluentes de pluviales mediante su captación en origen (Lerer et al. 2015). Estas técnicas de drenaje, tienen además la funcionalidad de retener en gran medida los contaminantes arrastrados en la escorrentía superficial, así como otros beneficios de índole social, de biodiversidad y económicos (Stormwater Committe, 2006). Como ya se mencionó, se han realizado pocas investigaciones sobre laaplicación de SUDS en la en los puertos, lo que representa una brecha clave en el campode la gestión de la infraestructura de transporte. Existen estudios y manuales de técnicas específicas, como es el caso de los pavimentos permeables (Sieglen y Langsdorff, 2004), (Knapton y Smith, 1997) y los depósitos de infiltración (Gray et al. 2010). Sin embargo,no existen investigaciones como la realizada en este caso, en la que se presenta un nuevoenfoque para la ubicación y selección eficiente del drenaje en los puertos, teniendo en cuenta todos los aspectos del diseño de los SUDS dentro de un marco multicriterio, comoel que se corresponde con una infraestructura de transporte de tanta complejidad.

2. METODOLOGÍA

La metodología desarrollada para determinar el potencial de implementación de los SUDS en áreas portuarias es el resultado de la recopilación y análisis de metodologías dediferentes artículos, manuales y guías internacionales para la implementación de SUDS en áreas urbanas (CIRIA, 2017), (NCDEQ Stormwater Design Manual, 2017). A consecuencia de las diferencias que presentan las áreas portuarias respecto a las urbanas, también fue necesario estudiar con detalle toda la información disponible relativa a las características que presentan dichas áreas y su legislación correspondiente (Ministerio deFomento, 2011).

2.1 Evaluación del emplazamiento

El primer paso para estudiar la implementación de este tipo de técnicas de drenaje en áreas portuarias es realizar una evaluación del emplazamiento donde se pretende instalar el sistema. Esto se debe, a que la evaluación de la localización en el proceso deplanificación y diseño adquiere importancia para identificar las restricciones que pudieranlimitar o reducir la capacidad de funcionamiento de este tipo de técnicas (Port of Oakland,2015). Llevar a cabo este paso en el proceso de planificación, reduce la posibilidad de tener que rediseñar las medidas adoptadas y/o su ubicación. Por consiguiente, se requiere realizar una revisión exhaustiva de toda la información existente del lugar y recopilar todos los datos específicos que puedan influir en el establecimiento de estas técnicas. Concarácter general, en este tipo de proyectos hay que identificar la siguiente información:

- Ubicación, tipología y tamaño del puerto.
- Condicionantes de la localización (geológicos y tipología del suelo, hidrológicos tanto superficiales como subterráneos, geotécnicos, topográficos y los relativos a la existencia de contaminantes en el suelo y aguas subterráneas).

- Superficie del área portuaria, delimitando los espacios y usos portuarios e indicando la cantidad de superficie impermeable antes de la introducción de las medidas a adoptar.
- Diseño actual del sistema de drenaje de aguas pluviales y residuales del puerto. Señalando con claridad la ubicación de los puntos de descarga de escorrentía de aguas pluviales.
- Las distintas operaciones portuarias que se desarrollen en el puerto, así como, su localización. En concreto, aquellas que sean susceptibles de ser una fuente potencial de contaminantes.
- Indicar la variedad de los potenciales contaminantes que afectan de manera directa o indirecta a la calidad de las aguas litorales en la zona portuaria, determinando su tipología y estimando su cantidad.
- Otras consideraciones y restricciones particulares del sitio.

2.1.1. Geología y geotecnia

El tipo de suelo y las condiciones geológicas y geotécnicas del área portuaria influyen directamente en la elección del tipo de SUDS y su diseño, así como en su ubicación más adecuada. A la hora de analizar la geología de la zona de estudio puede ser de gran utilidad consultar la web del Instituto Geológico y Minero de España (IGME). Uno de los parámetros más importantes en el análisis de la geología y geotecnia es la capacidad de infiltración que posea el terreno, por lo que identificar los principales materiales de los que está compuesto el suelo y su permeabilidad es clave a la hora de alcanzar un funcionamiento óptimo del sistema (Port of Tacoma, 2015). Los suelos pueden tener un comportamiento drenado, no drenado o la posibilidad de ocurrencia de ambas situaciones.Con el objetivo de tener una orientación previa acerca de la capacidad de infiltración de un determinado suelo característico en áreas portuarias, la normativa española en proyectos portuarios recoge los valores típicos de distintas formaciones de suelos y rellenos (Ministerio de Formento, 2005).

En esta primera evaluación de la capacidad de infiltración del terreno, es recomendable revisar toda aquella información existente relativa a la permeabilidad de la zona de estudio, a partir de la literatura existente del lugar y de los ensayos realizados previamente, con el objetivo de obtener unos mejores valores de referencia. Seguidamente, en la fase de proyecto es aconsejable realizar ensayos “in situ” para obtener unos valores más fehacientes sobre la permeabilidad de la zona, así como otros parámetros geotécnicos, especialmente los relativos a la resistencia al corte y compresibilidad. Algunos de los ensayos utilizados con más frecuencia son los de *Lefranc*y *Lugeon*, dependiendo del tipo de suelo, también se realiza con frecuencia el piezocono“CPTU” u otros equipos de ensayo como los permeámetros autoperforadores (Ministeriode Formento, 2005). Además, existen ensayos normalizados para medir la capacidad drenante de algunos sistemas específicos, como es el caso de los pavimentos permeables,en el que es usual utilizar el permeámetro LCS (NLT-327/00).

Con el objetivo de realizar un estudio geotécnico completo, y en concreto de la permeabilidad, los ensayos de laboratorio son muy aconsejables como el realizado a partirde permeámetros de carga constante (UNE 103403:1999) o variable (Ministerio de Formento, 2005). Un ensayo de laboratorio recomendable para evaluar la capacidad de infiltración de los pavimentos permeables es el infiltrómetro CF (Castro-Fresno et al. 2013). Cabe mencionar que, para el almacenamiento y gestión de los datos de la zona deestudio, diseñar una base de datos implementada en un Sistema de Información Geográfica (SIG) puede resultar de gran ayuda.

Coeficiente de permeabilidad (cm/s)	**Viabilidad de infiltración**	**Tipo de suelo**
$k>10^{-2}$	Muy permeable	Gravas
$10^{-2}>k>10^{-4}$	Buena	Arenas y mezclas de arenay grava
$10^{-4}>k>10^{-6}$	Mala	Limos y mezclas de arena, limo y arcillas.
$k<10^{-6}$	Impermeable	Arcillosos

Tabla 1 - Estimación del coeficiente de permeabilidad en función del tipo de suelo. (Fuente: Ministerio de Formento, 2005)

Se puede considerar la viabilidad de infiltración del sistema al terreno a partir de una conductividad hidráulica mayor de 10^{-6} cm/s, pero es necesario tener en cuenta otros factores como son: la proximidad del nivel freático, el grado de contaminantes del suelo y la proximidad a infraestructuras adyacentes (Checa y De Pazos, 2018).

- Como norma general el limitante geométrico del nivel freático hasta la subbase del sistema en el que se desea permitir la infiltración al terreno ha de ser como mínimo de un 1 m (CIRIA, 2017).
- La proximidad a los cimientos de infraestructuras adyacentes varía en función del sistema que se pretenda implantar. Cuando se proponga la infiltración al terreno y esta distancia sea menor de 5 m será necesario estudiar con detalle las especificaciones técnicas del sistema (CIRIA, 2017).
- Si la escorrentía superficial está contaminada, existe el riesgo de que los sistemas de infiltración puedan introducir contaminantes en el suelo y finalmente en el agua subterránea. Se deben realizar verificaciones para confirmar que los suelos debajode cualquier componente de infiltración propuesto sean adecuados para proporcionar una protección adecuada a las aguas subterráneas. El diseño de SUDS también debe garantizar un tratamiento adecuado de la escorrentía antes dela infiltración (NCDEQ Stormwater Design Manual, 2017).

Un aspecto clave también es comprobar que la explanada sobre la que se asentará el SUDS, conste de las condiciones mínimas respecto del índice CBR. Este análisis de la capacidad portante del suelo, así como su clasificación es recomendable hacerlo según lanorma PG-3 (Ministerio de Fomento, 2015).

2.1.2. Topografía

La topografía es un factor muy importante a la hora de analizar los patrones de flujo sobrela zona de estudio y, por consiguiente, para determinar que técnica de SUDS será la más conveniente para el sitio donde se desea implantar. Para realizar este análisis se debe estudiar previamente toda la información cartográfica existente del lugar (Checa y De Pazos, 2018).

Por otro lado, al igual que en el análisis geotécnico de la zona, los SIG permiten el almacenamiento, procesamiento y análisis de toda la información topográfica. Una herramienta muy usual para almacenar y procesar esta información son los modelosdigitales de terreno (MDT), concretamente en formato ráster, es decir, una matriz de celdas en la que cada cuadrícula contiene una información cartográfica que puede ser de gran ayuda para la modelización hidrológica y geomorfológica. A partir de este MDT, se determinan las direcciones de drenaje y seguidamente se obtienen parámetros clave comoel área de drenaje y la pendiente del terreno, las cuales serán de gran ayuda para definir la red de drenaje de la zona estudio y la estimación de variables geomorfológicas (Ramírez, 2002).

2.1.3. Hidrología

El primer paso para el diseño hidráulico e hidrológico es determinar la pluviometría del área de estudio. En este estudio se propone la siguiente metodología, en la que en primerlugar hay que obtener las precipitaciones diarias máximas. Para ello, se puede acudir a los registros de la pluviosidad de la zona en la que se van a implantar, tanto los valores normales como los anómalos. Para la obtención de los datos históricos de dicha variablese van a utilizar los recogidos en la página web de la Agencia Estatal Meteorología (AEMET), concretamente los correspondientes a la estación meteorológica más próximaa la zona de estudio. En caso de que dicha estación no tenga un registro amplio, otra opción es utilizar la monografía “Máximas Lluvias en la España Peninsular” (Ministerio de Fomento, 1999). En este documento se describe un proceso operativo para la obtención de la precipitación diaria máxima para un periodo de retorno seleccionado.

El siguiente paso es calcular el caudal máximo que le va a llegar al sistema correspondiente al periodo de retorno elegido. Si no se dispone de información sobre loscaudales máximos que proporciona la Administración Pública, se debe calcular a través del método racional de la normativa IC-5.2 (Ministerio de Fomento, 2016). En el procesooperativo recogido en esta normativa es muy importante definir y delimitar correctamentela cuenca drenante, así como sus principales parámetros. Un aspecto clave es calcular correctamente el coeficiente de escorrentía, para lo que hay que definir la cantidad de superficie impermeable que hay en el área drenante. Con el objetivo de conseguir unos parámetros característicos fehacientes de la cuenca, es muy recomendable apoyarse en las herramientas SIG comentadas con anterioridad (Checa y De Pazos, 2018).

También es necesario determinar los puntos de descarga de los volúmenes efluentes del sistema. Este proceso de evacuación depende de la modalidad de SUDS que se esté estudiando, así como de la operación portuaria o uso del suelo que se desarrolle en su ubicación y de la permeabilidad del subsuelo (en caso de que se pretenda la infiltración al terreno). Existen recomendaciones sobre cómo realizar la evacuación de aguas pluviales, como las recogidas en la ROM 4.1-94 (Ministerio de Formento, 1994).

Cabe mencionar que, en algunos casos, puede ser recomendable reutilizar este volumen efluente para requerimientos de agua no potable, como la limpieza con baldeo. O en el caso, por ejemplo, de las terminales portuarias de graneles sólidos, reutilizar dicho volumen para el riego con la misión de atenuar las emisiones a la atmósfera (Ministerio de Fomento, 2015).

2.1.4. Principales focos de contaminantes

Como se mencionó anteriormente, las operaciones portuarias y determinados usos de suelo que habitualmente se suelen dar en los puertos, pueden causar daños significativosen la calidad del agua y, consecuentemente, a la vida marina y los ecosistemas, así comoa la salud humana (Herz y Davis, 2002).

Por tanto, es necesario examinar los principales focos de vertidos de contaminantes a la escorrentía superficial que se pueden dar en las áreas portuarias. Para ello, hay que estudiar con detalle las operaciones portuarias y usos del suelo que pueden causar daños significativos en la calidad del agua y, en consecuencia, a la vida marina, los ecosistemasy a la salud humana. Dada la heterogeneidad que presentan los puertos, en especial los deuso de comercial, en función de las actividades que realizan y el tipo de mercancías que manipulan, se realiza un análisis de los usos de suelo de las áreas portuarias. En este estudio, se distinguen las zonas de operación y las de almacenamiento, así como las vías de comunicación y las zonas complementarias.

Una de las instalaciones que se consideran como la razón de ser de los puertos son las terminales portuarias. Se entiende por terminal portuaria aquellas instalaciones que constituyen la interfase entre los diferentes modos de transporte (Ministerio de Fomento, 2005). Los tipos de terminales portuarias que han sido objeto de estudio son las siguientes: contenedores, graneles sólidos (almacenamiento a la intemperie), mercancía general y de buques Ro-Ro. La posible gama de contaminantes que llegan a las aguas de los puertos de este tipo de terminales es muy amplia, destacando los sedimentos, metales, productos químicos, combustibles diésel, gasolina y aceites hidráulicos, siendo estos últimos el mayor contribuyente individual en volúmenes (Gómez et al. 2015). Es posible que las descargas en la costa y ríos no parezcan ser tan graves, pero los vertidos crónicos persistentes reducirían la pesca y los recursos acuáticos, además de disminuir la diversidad de vida vegetal y reducir seriamente la calidad del agua (Davis, 1990). Estos vertidos aumentan la contaminación bacteriana y viral de peces y mariscos comerciales, disminuyen la cantidad de oxígeno en el medio, y generan una bioacumulación de ciertastoxinas en los peces (Herz y Davis, 2002).

Cabe destacar que el principal foco de emisiones en los puertos, según las autoridades portuarias españolas, se da en la manipulación y almacenamiento de gráneles sólidos a la intemperie (Ministerio de Fomento, 2015). En este tipo de terminales portuarias los principales contaminantes son la lixiviación de productos químicos derivados de equipos y productos, vertidos accidentales derivados de las operaciones de mantenimiento y almacenamiento (escorrentía con alta carga de sedimentos y escombros) (Port of Tacoma, 2015).

Existen otros usos de suelo en las áreas portuarias como las zonas complementarias (zonas urbanizadas, de paseo o aparcamiento) o los viales de comunicación, que también son puntos de vertido de contaminantes (principalmente hidrocarburos y metales pesados), así como los derivados de los movimientos de los vehículos (deposiciones atmosféricas, desgaste de neumáticos y frenos) (Port of Oakland, 2015). Pero, dadas sus característicasintrínsecas, se asemejan en gran medida a las áreas urbanizadas donde la viabilidad de implantación de SUDS está contrastada, aunque con algún limitante mayor como son lascargas actuantes sobre el pavimento (Ministerio de Fomento, 1990). Otro uso de suelo que puede ser un potencial foco de contaminantes son las áreas de limpieza y mantenimiento.

Estas áreas conllevan un riesgo de vertidos accidentales de fluidos contaminantes y de aguas contaminadas con hidrocarburos, disolventes y pinturas principalmente (Cedre, 2007).

Por último, también se han considerado como foco de contaminantes las cubiertas de edificios (de más de 45 m^2 (Port of Tacoma, 2015)), ya que estas superficies generan contaminantes, entre los que destacan las deposiciones atmosféricas (CIRIA, 2017).

2.1.5. Normativa

Es necesario revisar y cumplir todas las legislaciones que afecten al ámbito portuario, en especial aquellas que se refieren a su transformación física y que repercutan de manera directa e indirecta en la gestión de las aguas litorales en áreas portuarias. Para ello, se debe conocer quiénes son los organismos con competencias, así como los agentesimplicados en la gestión, la coordinación y el control de eficiencia del sistema portuario (Port of Oakland, 2015). Es necesario conocer todos aquellos Marcos y Directivas legalesrelevantes de la UE (Directiva 2014/89/UE 2014 y 2008/56/CE 2008), así como aquellaspolíticas nacionales y marcos legales para la regulación del estado del agua, tanto los de alcance territorial (Real Decreto Legislativo 1/2001), como los relativos al dominio público hidráulico (Real Decreto 849/1986 y 927/1988), a las demarcaciones hidrográficas (Real Decreto 125/2007 y 126/2007), los planes hidrográficos (Ley 10/2001, Real Decreto 907/2007, 650/1987 y 1/2016) y calidad del agua (Real Decreto 817/2015 y 1341/2007) y otros actos legales relevantes a la hora de estudiar la normativaexistente en el ámbito estatal (Real Decreto 903/2010, 2090/2008, 2/2011, 17/2012 y lasleyes 22/1988, 2/2013 y 1/2018). Algunas de las preceptivas reglamentarias en proyectosdel sistema portuario español de interés general del Estado, también pueden ser de gran ayuda a la hora de implantar estas técnicas de drenaje (ROM 5.1-13, 1.0-09, 2.0-08, 0.5-05, 0.2-90 y 4.1-94). Para la elaboración de este estudio, el equipo investigador también se apoyó en otras normativas y guías (IC-6.1 y IC-5.2).

2.2. Selección de SUDS

A continuación, se describen las distintas técnicas de SUDS que han sido objeto de estudio en esta investigación con el fin de evaluar su posible implementación en áreas portuarias.

Cabe mencionar que hay algunos métodos que, debido a sus características propias y de la ubicación donde se van a implantar, se han descartado desde el inicio. Estos SUDS, se han desechado por la falta de espacio para su instalación, o por motivos de funcionalidad y normativos. Los SUDS seleccionados para lograr reducir y mejorar la calidad del volumen efluente de escorrentías superficiales que se localizan en los puertos de la manera más eficiente posible, se describen a continuación en la Tabla 2.

Nombre del SUDS	Definición	Funcionesprincipales
Depósitos de infiltración (Biorretención)	Se trata de una excavación que es posteriormente rellenada con un materialfiltrante permeable y en cuya superficie suele tener una determinada vegetación. Almacena el agua hasta que se produce su infiltración, para su posterior evacuación mediante un sistema de drenaje subterráneo o su almacenamientoen el propio sistema (Sañudo-Fontaneda,et al. 2012).	Infiltración, detención y almacenamiento.
Pavimentos permeables (Adoquines impermeables en disposición permeable, PICP)	Suelen ser de hormigón y se agrupan de tal manera que dejen ranuras entre cada adoquín. De este modo, se permite la infiltración vertical del agua. Las ranuraspueden ser cubiertas por gravilla o dejarse libres (Sieglen y Von Langsdorff,2004).	Captación, infiltración, detención y almacenamiento.
Cubierta verde (Extensivas)	Elemento constructivo que cubre parcial o totalmente la parte superior de un edificio, mediante un sistema multicapa, en el que la superficie en contacto con el aire está compuesta por una capa delgadade vegetación. Esta vegetación se cultivaen una capa de sustrato de pequeño espesor. La parte inferior debe estar siempre impermeabilizada para de este modo evitar el paso del agua a la estructura (NCDEQ Stormwater Design Manual, 2017).	Captación, infiltración ydetención.
Depósitos de almacenamiento (RHW)	Estructuras cerradas que admiten multitud de diseños y que recogen el agua, para su posterior reutilización enrequerimientos de agua no potable (CIRIA, 2017).	Almacenamiento.
Drenes filtrantes	Son zanjas poco profundas, generalmentelineales, que están compuestas por un material de relleno filtrante granular o sintético(Sañudo-Fontaneda et al. 2012).	Captación y transporte.

Tabla 2 – Técnicas de SUDS para su uso en zonas portuarias. (Fuente: elaboración propia)

Dentro de todas las modalidades de pavimentos permeables se ha seleccionado lamodalidad de adoquines impermeables en disposición permeable (ver Tabla 2), debido principalmente a que, tras realizar un análisis de las categorías tráfico actuantes en las superficies portuarias consideradas, se observa que se obtiene una tipología de A y B paralos distintos usos del suelo (Ministerio de Fomento, 1990). Esta tipología, excederá la capacidad portante de la mayoría de modalidades de este tipo de SUDS, en especial los clasificados como pavimentos permeables de superficie continua (Rodríguez-Hernández et al. 2011). Además, existen estudios y aplicaciones de los adoquines impermeables en disposición permeable en áreas portuarias (Gray et al. 2010), que han demostrado los beneficios que presentan su aplicación. Destacan por su mayor flexibilidad y capacidad portante, menor necesidad de mantenimiento y gran poder de reducción de la carga contaminante.

Por otro lado, también existen modalidades de los depósitos de infiltración y drenes filtrantes que pueden ser muy aconsejables para su implantación en áreas portuarias. Es el caso de los depósitos de infiltración, en los que hay diseños estructurales que se adaptan al espacio disponible y los requerimientos funcionales de las terminales de contenedores(Gray et al. 2010). Además, hay empresas especializadas en el drenaje de puertos como *Polypipe*, que han desarrollado diseños de componentes de estructurales de SUDS(Permavoid system) (Polypipe, 2016), que han sido implantadas en áreas portuarias con éxito (Polypipe, 2017). O la empresa ACO, que también ha implementado modalidades novedosas en áreas portuarias (ACO, 2012).

3. RESULTADOS

Una vez analizadas las características de las zonas portuarias que pueden repercutir en la investigación y las alternativas de SUDS, que por sus propiedades intrínsecas pueden ser viables su implementación, se realiza una tabla multicriterio. Ésta, recibe el nombre de "*Selección de SUDS en función de la operación portuaria o uso del suelo*", la cual puede proporcionar apoyo a los organismos con competencias en infraestructuras portuarias. Igualmente puede servir de guía a su personal técnico para planificar, implementar, diseñar y mantener un control efectivo de este tipo de técnicas de drenaje. Cabe mencionar, que las columnas relativas a los tipos de terminales portuarias que se puedenencontrar en un puerto hacen referencia a sus zonas de almacenamiento (ver Tabla 3). Laszonas de operaciones de este tipo de terminales se han unificado en una única columna, teniendo en cuenta las características específicas de cada una de ellas a la hora de estudiar la viabilidad de implementación de SUDS en ellas. Para los resultados de este análisis, fue necesario tener en cuenta el grado de implementación de cada técnica en función de las limitaciones que pueden presentar los distintos usos portuarios. Las justificaciones generales por las que las técnicas de SUDS no son aplicables o se verían condicionadas en su uso, son las siguientes:

- Cargas: significa que las cargas actuantes derivadas de las actividades que se desarrollan en esos usos de suelo excederán la capacidad portante del método convencional en cada caso.
- Sedimentos: significa que las altas cargas de sedimentos que generalmente están asociadas con esta actividad provocarían que sea incompatible o condicionada su implementación con el funcionamiento normal y el rendimiento efectivo de este método.
- Espacio: significa que este método puede que no sea compatible con la disponibilidad de espacio en el uso del suelo correspondiente.
- Calidad: significa que la calidad del volumen afluente que recibe el sistema debería ser tratada por otro método específico no englobado dentro de los SUDS.

	Terminal de contenedores	**Terminales de graneles sólidos (almacenamiento a la intemperie)**	**Terminales de mercancía general**	**Terminales de graneles líquidos**	**Terminales de buques Ro-Ro**	**Áreas de mantenimiento y limpieza de equipos**	**Vías de comunicación**	**Zonas complementarias**	**Cubiertas de edificios**	**Zonas de operación**
Depósito de infiltración	C (espacio)	P (sedimentos)	PA	C (calidad)	PA	C (calidad)	PA	PA	n/a	C (espacio)
Pavimento permeable	C (cargas)	P (sedimentos)	C (cargas)	C (cargas, calidad)	C (cargas)	C (cargas, calidad)	C (cargas)	PR	n/a	C (cargas)
Depósitos de almacenamiento	C (espacio)	C (sedimentos)	PA	PA	PA	C (calidad)	PA	PA	PR	C (espacio)
Cubiertas verdes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	PR	n/a
Drenes filtrantes	PA	C (sedimentos)	PA	C (calidad)	PA	C (calidad)	PA	PA	n/a	PA

Tabla 2 - Selección de SUDS en función de la operación portuaria o uso del suelo. (Fuente: elaboración propia)

A partir de las limitaciones comentadas, se establece el grado de implementación de las distintas técnicas mediante la siguiente nomenclatura:

- PR (Puerto Requiere): los SUDS en esta categoría deben usarse para las actividades especificadas, siempre que existan condiciones físicas apropiadas.
- PA (Puerto Admite): los SUDS en esta categoría también deben considerarse y es recomendable su uso siempre que sea posible.
- C (Condicionantes): esta categoría es para los métodos SUDS en los que su implementación se vería afectada por las actividades especificadas. Sin embargo, el método puede ser aprobado con alguna variante respecto a su diseño convencional.
- P (Prohibido): el puerto no permitirá el uso de estos SUDS para las actividades especificadas.
- n/a (No aplicable).

Si se analizan las funciones principales de las técnicas de SUDS para su uso en zonas portuarias, mostrados con anterioridad (ver Tabla 3)**, s**e observa que estas difieren en función del sistema. Por esta razón, en ocasiones si los condicionantes del emplazamiento lo permiten será viable combinar algunas de estas técnicas formando un esquema secuencial denominado usualmente tren de drenaje (Ariza et al. 2019). La combinación de SuDS, con el objetivo de alcanzar un sistema de drenaje multifuncional con un rendimiento óptimo, ha sido contrastado con éxito en áreas urbanas (Edmonton, 2014). Las funciones físicas e hidrológicas principales desarrolladas por los SUDS seleccionados son las siguientes: captación (C), infiltración (I), detención (D), transporte (T) y almacenamiento (A). En la siguiente tabla, se propone un esquema secuencial para las distintas técnicas estudiadas, en la que el primer componente indica el proceso relacionado con la fila y el segundo componente el proceso relacionado con la columna (Ariza et al. 2019).

FINAL INICIAL	Depósitos de infiltración	Pavimentos permeables	Cubierta verde	Depósito de almacenamiento	Drenes filtrantes
Depósitos de infiltración					
Pavimentos permeables	C.D.I.A			C.I.D.A	C.I.D.A.T
Cubierta verde	C.I.D.A	C.I.D.A		C.I.D.A	C.I.D.T
Depósitos de almacenamiento					
Drenes filtrantes	C.T.I.D.A	C.T.I.D.A		C.T.A	

Tabla 3 - Esquema secuencial entre los distintos SUDS (tren de drenaje). (Fuente: elaboración propia a partir de Ariza et al. 2019)

Al analizar los resultados de la anterior tabla, se observa el potencial que presentan diversas técnicas SUDS para ser utilizadas como elementos multifuncionales. Es el caso de la combinación de drenes filtrantes en la primera etapa con depósitos de infiltración en la etapa final. Esto se debe a que el objetivo principal de los drenes filtrantes es el de captar y filtrar la escorrentía superficial de áreas impermeables con el fin de transportarlas a otros puntos de tratamiento o de vertido, como en este caso son los depósitos de infiltración (RHW) (NCDEQ Stormwater Design Manual, 2017). En estos depósitos, se logra retener casi en su totalidad la mayoría de la contaminación difusa, mejorar la laminación del volumen afluente y conferir funciones de reutilización del volumen efluente a través de su almacenamiento y posterior bombeo. Si se quiere optimizar esta reutilización de agua, implantar los RHW en la etapa final puede ser muy aconsejable. En especial en aquellas áreas portuarias donde haya una alta carga de sedimentos, ya que, este sistema tiene modalidades en las que se realizan procesos de decantación, como los sistemas bombeados o compuestos (CIRIA, 2017). Si la etapa inicial son las cubiertas verdes o los pavimentos permeables, los RHW también presentan gran potencial como etapa final en un tren de drenaje.

Aunque, si la etapa inicial son cubiertas verdes y la final los RHW, hay que prestar especial atención a los contaminantes que llegan al depósito, debido a que si la escorrentía contiene elementos comocobre, zinc, fungicidas y herbicidas, puede no ser adecuada la reutilización del volumen efluente (dependiendo del propósito para el que se va a utilizar) (CIRIA, 2017).

4 CONCLUSIONES

En base al estudio realizado en la presente investigación sobre la implementación de SUDS en áreas portuarias, se puede concluir que este tipo de técnicas se presentan como un nuevo paradigma y una oportunidad para mejorar la gestión de agua pluvial en los puertos. Es decir, se trata de un conjunto de técnicas que deben complementar, y en algunos casos sustituir, al drenaje convencional en las áreas portuarias. A la par, será ineludible su implantación en los puertos de nueva creación, con la finalidad de evitar todos los indeseables problemas que se generan a consecuencia de mala gestión de la escorrentía superficial.

En relación, a los resultados particulares del estudio realizado, se puede concluir que existen algunas zonas portuarias que presentan una gran idoneidad para la implementación de este tipo de técnicas de drenaje, como es el caso de las zonas complementarias. Son fundamentalmente las zonas urbanizadas, tales como edificios, dependencias administrativas, zonas de paseo y esparcimiento o áreas de estacionamiento, ya que, al compartir características con las áreas urbanas, presentan grandes ventajas desde el punto de vista de funcionalidad de los SUDS que se puedan implantar en ellas.

Por otro lado, en las vías de comunicación también puede ser recomendable su uso, aunque habrá que prestar especial atención en algunos sistemas, como el de los pavimentos permeables, a la hora de seleccionar la modalidad y realizar su diseño para que las cargas actuantes y presiones de contacto con el pavimento no superen la capacidad portante del sistema.

En las zonas de operación, la aplicación de los SUDS estudiados se verá principalmente condicionada por algunos criterios como los normativos, de acumulación de sedimentos o de disponibilidad de espacio, así como por las cargas actuantes en ellos.

En las zonas correspondientes al almacenamiento que se realiza en las distintas terminales portuarias estudiadas, los principales condicionantes se van a dar en las terminales de graneles. Por un lado, en las de graneles líquidos, a consecuencia de su necesidad de tratamientos específicos para la gestión de los vertidos y descargas, y en las de graneles sólidos con almacenamiento en la intemperie, ya que las cargas actuantes en ellos son menores en comparación con otras terminales. Estas terminales presentan la gran desventaja de la cantidad de sedimentos que transporta la escorrentía superficial que se genera en ellos, lo que provocaría una rápida colmatación del sistema. Esto se debe a que uno de los principales inconvenientes de los SUDS es la vulnerabilidad que presentan a ser obstruidos por los sedimentos, por lo que la implantación de las técnicas estudiadas (con la excepción de los depósitos de almacenamiento), conllevaría numerosas tareas de mantenimiento con una periodicidad muy corta y el riesgo de empeorar el funcionamiento correcto del sistema y llegar, incluso, a inutilizarlo.

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PROPUESTA DE UN NUEVO MODELO DE GOBERNANZA PORTUARIA DEL SISTEMA PORTUARIO ESPAÑOL BASADO EN LA EFICIENCIA Y LA COMPETITIVIDAD

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RESUMEN

Esta investigación busca el objetivo de plantear un escenario de gestión portuaria, para el actual Sistema Portuario español, analizándolo y comparándolo con el actual.

Mediante el empleo del Análisis Envolvente de Datos (DEA) y sumándole el análisis de competitividad, se elabora un escenario, en base a criterios técnicos, y bajo la definición de "fachada marítima", sobre la cual analizar la eficiencia operativa y financiera.

La metodología del modelo DEA ha venido evolucionando, ya que actualmente se tienden a modelos orientados en input o en output, lo que favorece el uso de análisis Bootstraping. El cual corrige los sesgos que puedan producirse en el análisis DEA tradicional.

Los resultados del análisis DEA-Bootstrapping muestran una serie de resultados que favorece a este escenario frente a la situación actual, ya que tanto la eficiencia operativa como la financiera mejoran respecto al escenario actual o escenario 0.

1. INTRODUCCIÓN

1.1 El Puerto

En su origen etimológico, la palabra puerto proviene del latín, *portus,* significando puerta o entrada, y, a esta a afección hacen referencia las múltiples definiciones de puerto empleadas en la actualidad. Por citar dos de las más empleadas, Rodrigue et al. (2013) definen los puertos como puntos de convergencia entre dominios geográficos (terrestre y marítimo) de circulación de mercancía y pasajeros. Por otro lado, Martagan et al. (2009) establecen que los puertos son las instalaciones intermodales por excelencia, ya que centralizan múltiples medios de transporte.

El transporte marítimo, ha sido durante toda la historia de la humanidad, el modo de transporte de mercancías por excelencia, siendo los puertos enclaves vitales para el control de dichas mercancías. Tal consideración se ha mantenido en el tiempo incluso tras la revolución industrial y el desarrollo de la automovilística (transporte terrestre) y la aeronáutica (transporte aéreo). Según Rodríguez et al. (2013) los puertos siguen centralizando de forma masiva el tráfico de mercancías debido al elevado coste del transporte aéreo, sólo viable en transacciones urgentes y de productos de tipo tecnológico, cuya relación precio de mercado-peso hace que sea económicamente conveniente. Rodrigue et al. (2013) añade también, que el transporte terrestre no puede competir con el marítimo, en cuanto a la movilización de grandes volúmenes de mercancía, debido a la falta de infraestructura ferroviaria y la rigidez de esta.

La clasificación de los puertos es variable, y depende en gran medida de la perspectiva con la que se analice el mismo. Depende, por ejemplo, de la especialización en cuanto a tipo de tráfico, volumen de tráfico, infraestructura, superficie de ocupación, etc. Además, según López (2018) en numerosas ocasiones es necesario identificar los elementos constituyentes del puerto por separado, pudiendo pertenecer dos terminales de un mismo puerto a clasificaciones diferentes, según el criterio empleado.

1.2 El Sistema Portuario Español: desde sus orígenes hasta hoy

Hasta finales del siglo XIX, los puertos se regían por sistemas más o menos heredados de la Edad Media, tales como los Consulados del Mar y similares, y no es hasta los años 70 de ese siglo cuando se promulga la Ley General de Obras Públicas, por medio de la cual se comienza a ordenar administrativamente las infraestructuras y su explotación. A continuación, se desarrollan las leyes específicas, de aguas, ferrocarriles, etc. que regulan las distintas áreas.

En 1880 se promulgó la primera Ley de Puertos, continuación natural de esa Ley General de Obras Públicas. Prácticamente era más una ley de costas que de puertos, ya que regulaba fundamentalmente el dominio público marítimo terrestre y su aprovechamiento.

De cómo se debían explotar los puertos, no se establecía más norma que la atribución de las operaciones náuticas al Capitán de Puerto, que era el comandante de Marina, y las terrestres al director del Puerto, que era un Ingeniero de Caminos, Canales y Puertos del Estado.

Esta ley estuvo vigente hasta la promulgación de la Ley de Puertos y Marina Mercante de 1992, es decir, 112 años. Naturalmente, si bien no tuvo más que pequeñas correcciones en el año 1928, se fue complementando con otras leyes que regulaban aspectos propios de los puertos, como la ley de Juntas de Obras del Puerto, la ley de Régimen Financiero o la de Juntas de Puertos y Estatutos de Autonomía.

El modelo de 1992 fue modificado por la ley de 1997 que aumentó la participación de las Comunidades Autónomas en el funcionamiento y gestión de los puertos y una mayor liberalización de las tarifas.

La incorporación de las Comunidades Autónomas en la gestión de los puertos de interés general se orientó hacia su participación en el nombramiento de los órganos de gobierno de las Autoridades Portuarias. De este modo, la ley concedió una mayor participación a las Comunidades Autónomas donde estén ubicados los puertos, tanto en su estructura de cargos como en su gestión, a través de la designación de los miembros de sus órganos de gobierno. Se garantizó que en el Consejo de Administración estuvieran también representadas las Administraciones Municipal y Central, la Cámara de Comercio, Industria y Navegación, y las organizaciones empresariales y sindicales de los sectores económicos más relacionados con el comercio marítimo.

Además, con esta reforma legislativa, no sólo aumentó la autonomía las Autoridades Portuarias en relación al Ente Público Puertos del Estado, sino que también el Ente Público Puertos del Estado, ganó autonomía respecto del Ministerio de Fomento (Transportes, Movilidad y Agenda Urbana. Así, por ejemplo, los objetivos generales que aquel fije como guía para los programas de actuación de las Autoridades Portuarias ya no tienen por qué estar de acuerdo con la política de transportes definida por el Ministerio de Fomento (Transportes, Movilidad y Agenda Urbana). Como consecuencia de estas y otras características, es posible afirmar que la Ley 62/1997, crea un nuevo modelo de gestión portuaria: el modelo español.

La Ley 27/1992, de 24 de Noviembre, de Puertos del Estado y de la Marina Mercante (LPEMM), modificada por el Texto Refundido 2/2011, de 5 de septiembre, distingue entre los puertos de titularidad autonómica (básicamente los puertos pesqueros, deportivos y de refugio), que dependen del Gobierno de la Comunidad Autónoma donde están ubicados, y los puertos de titularidad estatal, es decir, los puertos calificados como de interés general.

Figura 1-Mapa de las 28 Autoridades Portuarias del sistema portuario español. Fuente: Puertos del Estado.

2. ESTADO DEL ARTE

2.1 Gobernanza portuaria

La gobernanza portuaria se define, según Comtois y Slack (2003), en función de dos fuerzas: las fuerzas centrípetas y las fuerzas centrífugas. Las fuerzas centrípetas tratan de definir, en términos políticos, los controles de orden jurisdiccional y geográfico de las dinámicas territoriales de un puerto. Es decir, enfatiza sobre los distintos roles de los agentes privados y públicos, profundizando en el ámbito de la gestión y de las operaciones portuarias desde la perspectiva de una economía de mercado. Las autoridades portuarias buscan adoptar aquellas medidas que permitan aumentar la eficacia, como la mayor descentralización administrativa y los mayores campos de libertad para la economía privada, adaptándose a las reglas de mercado. Por tanto, los cambios estructurales en la gobernanza enfatizan hacia una mayor liberalización y desregulación. Producto de esta dinámica es la creación de plataformas multimodales, que buscan captar y atraer tráficos, mejorar el posicionamiento de las infraestructuras portuarias en el mercado mundial y, por tanto, una nueva definición intraportuaria, que supone una ampliación de los servicios logísticos y del desarrollo de redes globales alentadas por las economías locales (Nottebom y Rodrigue, 2005). Los puertos constituyen un elemento más de la cadena multimodal entre productor y consumidor, aumentando los vínculos entre el transporte marítimo y el transporte terrestre. Bajo esta fuerza centrípeta asistimos a un crecimiento de la capacidad de oferta de las terminales; a una adaptación de los flujos y de los sentidos de las rutas de transporte marítimo; a una nueva concepción de los índices de performance y del beneficio empresarial; y a una reducción del riesgo y aumento de la seguridad en el transporte “puerta a puerta”. Las autoridades portuarias combinan las actividades de los transportistas y los operadores de terminales, buscando las mayores economías de escala y el desarrollo de actividades de marketing. Las autoridades portuarias operarán en situaciones de mayor complejidad e interdependencia; con mayor participación en la definición de estrategias marítimas en lo que atañe a acuerdos entre puertos y selección de rutas; y finalmente en lo que concierne a los sistemas de tecnología de información.

Las fuerzas centrífugas, por su parte, hacen referencia a las trayectorias de la gobernanza portuaria. Fuerzan, por lo tanto, a una nueva redefinición de las funciones tradicionales de las autoridades portuaria. Es decir, enfatizan sobre aquellas actividades complementarias de las funciones estrictamente marítimas y portuarias, para reforzar las integraciones verticales y horizontales; en suma, para responder a las nuevas demandas y necesidades de incrementos del comercio. En consecuencia, buscan aprovisionamiento y gestión del espacio; conexiones con otros modos de transporte; y desarrollos logísticos (Laxe, 2008).

2.2 Los nuevos modelos de gobernanza portuaria

El papel del sector privado se ha ampliado considerablemente en muchos sectores económicos importantes en los últimos decenios. Los puertos no han sido inmunes a este avance y muchos puertos de todo el mundo se han beneficiado de la intervención del sector privado. En el documento presentado por Baird (2000) se examinan los objetivos comúnmente asociados a la privatización de las funciones portuarias. Se presenta un marco (Matriz de Privatización Portuaria) que puede utilizarse para ayudar a establecer el alcance de la intervención del sector privado en un puerto determinado. Donde se examinan los principales métodos utilizados para lograr la intervención del sector privado en los puertos, con los ejemplos que procedan. Y, por último, se examina la forma bastante singular de privatización de los puertos (es decir, la transferencia de derechos de propiedad, etc.) adoptada en el Reino Unido. Las pruebas sugieren que el Estado no necesita transferir los derechos de propiedad de los puertos marítimos para beneficiarse de la experiencia del sector privado. De hecho, debido a la naturaleza específica de la inversión portuaria, y teniendo en cuenta el objetivo clave de los puertos de facilitar el comercio, esto puede ser contraproducente.

Cabe destacar que la mayoría de las tendencias a futuro sobre la gobernanza portuaria, enmarcadas en el contexto del libre mercado y la actual teoría económica, pasan por la desaparición de la propiedad pública en favor de la privada. Este hecho vendría reforzado por la idea de que la privatización del sector portuario se daría debido a la incapacidad del sector público de asumir los fuertes requerimientos de capital necesarios en el sistema, de continuar la evolución de volumen de tráfico como hasta ahora, para reforzar la infraestructura, la atracción de embarcaciones y el aumento de superficies destinadas al almacenamiento de mercancías. Por tanto, en la medida que las autoridades e instituciones públicas no sean capaces de afrontar las inversiones serían los agentes privados quienes (a través de adjudicaciones y/o concesiones) llevarían a cabo dichas inversiones en el futuro.

Ante este hecho, aparecen teorías como la de Lavaud-Letilleul (2007) que también afirman que las dinámicas portuarias estarán cada vez más ligadas a las empresas operadoras o propietarias de espacios portuarios y terminales, aunque, añaden que esta trayectoria puede implicar efectos sobre la relación entre los puertos y el territorio.

2.3 Antecedentes del Análisis Envolvente de Datos (DEA)

Farrell (1957) determinó empíricamente un estándar de referencia, la frontera, con el que comparar las empresas para determinar si son eficientes o no. Las medidas de eficiencia calculadas de esa manera definen lo que se conoce como eficiencia relativa, es decir, miden la eficiencia de una empresa comparando su actuación con la de las "mejores" empresas observadas, que son las que definen la frontera eficiente. Este trabajo puede considerarse como el origen de todos los estudios en este campo, si bien, el trabajo de Farrell tiene como antecedentes los de Debreu (1951) y Koopmans (1951).

El Análisis Envolvente de Datos (DEA) usa algoritmos de programación lineal para calcular la frontera. Esta idea fue originalmente propuesta por Hausman (1978) en su discusión del artículo de Farrell. La primera aplicación de la programación lineal al cálculo de la eficiencia se debe a Boles (1966). Posteriormente, Charnes, Cooper y Rhodes (1978) dieron a esta técnica el nombre de Data Envelopment Analysis, cuyo uso se ha popularizado y hoy en día sobrepasa a las aplicaciones basadas en fronteras estocásticas (Førsund y Sarafoglou, 1999).

Es interesante destacar aquí la diferencia fundamental entre el método del Análisis Envolvente de Datos (DEA) y el de Farrell (1957) para el cálculo de la frontera. Farrell no usa programación matemática, sino que calcula la frontera algebraicamente. Sin embargo, los resultados de ambas aproximaciones son equivalentes.

Entre las ventajas de la aproximación no paramétrica hay que mencionar que no hay que suponer una forma funcional concreta para la frontera. Algunos estudios han encontrado que los índices de eficiencia son sensibles a la especificación de la forma funcional. Por otra parte, la aproximación no paramétrica permite el tratamiento sencillo de tecnologías multioutput.

Entre los inconvenientes de esta aproximación cabe citar que es más sensible a los errores de medida que la aproximación econométrica, puesto que no existe un término de error que permita controlar el efecto que tienen los factores no controlables o no observados. Un segundo inconveniente es que no permite realizar inferencia estadística sobre los índices calculados. Este problema se corrige con los métodos Bootstrap, cuyo objetivo es dotar al análisis DEA de una naturaleza estocástica similar a la de los modelos econométricos.

Año	**Autor**	**Alcance del Estudio**	**Input**	**Output**	**Modelo**
2003	Wang, T., Song, D.W. y Cullinane, K.	28 puertos del TOP 30 (2001) mundo y 57 terminales	1) Longitud de muelles 2) Superficie de la terminal 3) Nº Grúas de muelle 4) Nº Grúas de patio 5) Nº Straddle carriers	1) TEUs manipulados	DEA-CCR-I DEA-BCC-I Función Estocástica de Cobb-Douglas
2003	Barros, C.P.	5 puertos portugueses 1999 – 2000	Eficiencia Técnica 1) Nº de empleados/Mano de obra 2) Valor contable de los activos Eficiencia Localizada 1) Coste de la mano de obra – Salarios y beneficios divididos por el número de empleados 2) Coste de la inversión – gasto del equipamiento y de la instalación dividido por el valor teórico de los activos inmovilizados	1) Nº de barcos 2) Movimiento de la carga 3) Toneladas brutas de los barcos 4) Cuota de mercado 5) Toneladas de carga a granel 6) Toneladas de carga contenerizada 7) Toneladas de trafico Ro-Ro 8) Toneladas de carga seca a granel 9) Toneladas de Líquidos 10) Ingresos netos	DEA
2004	Barros, C.P. y Athanassiou, M.	4 puertos portugueses y 2 griegos 1998 – 2000	1) Nº de empleados/Mano de obra 2) Valor contable de los activos	1) Nº de barcos 2) Toneladas movidas de carga 3) Toneladas de carga manipulada 4) Toneladas de contenedores manipulados	DEA-BCC DEA-CCR
2005	Lin, L. y Tseng, L.	27 Puertos internacionales de Contenedores 1999 – 2002	1) Nº Grúas de muelles 2) Longitud de muelles 3) Equipamiento del patio (nº) 4) Superficie de almacenamiento	1) TEUs manipulados	SFA DEA-CCR DEA-BCC
2007	Cullinane, K. y Wang, T.	69 Terminales de contenedores de 24 países europeos 2002	1) Longitud de la terminal 2) Superficie de la Terminal 3) Nº Equipamiento	1) TEUs manipulados	DEA-CCR DEA-BCC

011	Chiu, Y., Huang, Ch. y Ma, Ch.	30 Regiones de China (Costa, Central y Oeste)	1) Fuel consumido 2) Vehículos de pasajeros 3) Vehículos de mercancías 4) Densidad de Autopistas 5) Transporte de pasajeros 6) Transporte de mercancías 7) Accidentes de tráfico 8) Empleos 9) Activos fijos	1) Valor producción 2) Industria contaminante	DEA
2016	Gil Ropero, A.	Puerto de Algeciras y el resto de Autoridades Portuarias (28).	1) Número de grúas. 2) Superficie de la Terminal. 3) Metros lineales de muelle con calado > 14m.	1) TEUs. 2) Número de buques portacontenedores.	DEA-CCR DEA-BCC
2018	Gil Ropero, A., Turias Domínguez, I. y Cerbán Jiménez, M.M.	28 Autoridades Portuarias Españolas y 7 Autoridades Portuarias Portuguesas	a) TEUs.	1) Ships.	DEA-CCR DEA-Bootstrapping

Tabla 1-Revisión bibliográfica de los inputs y outputs utilizados para nuestro DEA-Bootstrapping. Fuente: Elaboración propia.

2.4 Antecedentes de la competencia y la competitividad

Es importante realizar una distinción entre los conceptos de competencia y competitividad. La competencia es la concurrencia de una multitud de vendedores en el mercado libre, de forma que, para conseguir la venta de los bienes y servicios que producen, pugnan entre sí fijando los precios que les permitan sus costes y que estén alineados con los del mercado (Tamames y Gallego, 1996). En cambio, la competitividad se puede entender como la capacidad de competir de la empresa, que no va a depender sólo de sus propias fortalezas, sino también de la capacidad que tenga de hacer frente a sus debilidades y transformar sus amenazas en oportunidades (Winkelmans, 2003).

En definitiva, la competitividad depende de una multitud de factores, y para que una empresa pueda competir en el mercado debe explotar sus ventajas competitivas, principalmente a través de la diferenciación y del liderazgo en costes de los bienes y servicios que produce. En la actualidad, las empresas no sólo compiten con bienes o factores productivos tangibles, sino que, cada vez en mayor medida, la competencia se realiza mediante la provisión de servicios determinados por parte de ella y el desarrollo y aprendizaje de su núcleo específico de competencias específico para la consecución de sus ventajas competitivas (Winkelmans, 2003).

El núcleo de competencias de una empresa puede ser más o menos imitable por el resto; as., si un núcleo de competencias está basado en el desarrollo de complejas tecnolog.as y habilidades, ser. más difícil de imitar por otras empresas y tendrá una mayor probabilidad de desarrollar ventajas competitivas durante un periodo de tiempo más extenso, siendo el mejor núcleo de competencias el que posee un alto grado de durabilidad.

La competencia portuaria se refiere al desarrollo y aplicación de estrategias alternativas para atraer a más clientes o a clientes con un mayor potencial de negocio hacia el puerto (Cerbán Jiménez, 2009). Los puertos analizan continuamente estrategias con el objeto de alejarse de sus competidores. Como consecuencia, los puertos compiten localmente, pero también lo hacen a nivel global, incluso a grandes distancias, sirviendo a las mismas zonas comerciales.

Según Van der Voorde y Winkelmans (2002), la competencia portuaria se extiende a cuatro niveles:

- Competencia entre empresas de un puerto.
- Competencia entre puertos.
- Competencia entre grupos de puertos (por ejemplo, un grupo de puertos con características geográficas comunes compiten entre ellos).
- Competencia entre rangos portuarios (por ejemplo, puertos localizados a lo largo de la misma costa o con un hinterland prácticamente idéntico compiten con los de otro rango por unos tráficos determinados).

Los autores Fleming y Baird (1999) identifican que los principales factores que explican la competitividad portuaria, para todo tipo de tráficos, son:

- La tradición portuaria.
- El rango portuario (puertos que comparten misma costa y mismo transpaís).
- La accesibilidad portuaria.
- La productividad portuaria.
- El apoyo público.
- Las preferencias de los agentes implicados hacia los puertos.
- La localización geográfica.

3. METODOLOGÍA

3.1 Eficiencia

La técnica del Análisis Envolvente de Datos (Data Envelopment Analysis - DEA) es una técnica de programación lineal que facilita la construcción de una superficie envolvente, frontera eficiente o función de producción empírica, a partir de los datos disponibles del conjunto de entidades objeto de estudio, de forma que aquellas que determinan la envolvente son las denominadas entidades eficientes, y permiten la evaluación de la eficiencia relativa de cada una de las entidades.

El análisis basado en DEA, desarrollado por Charnes, Cooper y Rhodes en 1978, es un método extremal y no parámetrico para la estimación de fronteras de producción y evaluación de la eficiencia de una muestra de unidades de producción Decision Making Units (DMU´s), en la terminología científica. La metodología DEA, dado que es una técnica no paramétrica, no supone ninguna forma funcional de la relación entre los inputs y los outputs, ni una distribución de la ineficiencia. Además, es capaz de manejar situaciones de múltiples inputs y outputs, expresados en distintas unidades. Son precisamente estas ventajas de DEA las que han favorecido su eso extensivo.

Dentro de la metodología DEA, se pueden diferenciar varios tipos de eficiencias en función de la unidad de referencia que utilice:

a. Eficiencia Técnica Global (TE): Cuando se escoge como unidad de referencia la de mayor productividad de entre todas las unidades posibles. Se denomina eficiencia CCR, ya que fue desarrollada por Charnes, Cooper y Rhodes en 1978. También es denominada eficiencia CRS, acrónimo de “Constant Returns to Scale”.
b. Eficiencia Técnica Pura (PTE): Cuando se escoge como unidad de referencia la de mayor productividad de entre todas las unidades posibles de su tamaño. Se denomina BCC, por ser desarrollada por Banker, Charnes y Cooper en 1984. También es denominada eficiencia VRS, qye significa “Variable Returns to Sacale”.
c. Eficiencia de Escala (SE): Es el cociente entre la Eficiencia Global (TE) y la Eficiencia Técnica Pura (TE). Para caracterizar el rendimiento productivo de una DMU, no basta con el conocimiento de su eficiencia técnica. Es necesario, además, obtener su Eficiencia de Escala, es decir, conocer si está trabajando en el correspondiente tamaño de escala más productivo (Most Productive Scale Size – MPSS). Cuando una DMU es eficiente tanto en la aplicación del modelo CCR como en el modelo BCC, el valor de su Eficiencia de Escala (SE) es igual a la unidad, y podemos afirmar en ese caso que está trabajando en su tamaño de escala más productivo (MPSS). (Charnes y Cooper, 1989).

Por tanto, de esta expresión se deduce que la Eficiencia Técnica Global (TE), se descompone en Eficiencia Técnica Pura (PTE) y Eficiencia de Escala (SE). TE=PTE x SE.

Modelo	Orientación Input	Orientación Output
CRS	min $\theta = \varphi - \varepsilon\,(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+)$ Sujeto a : $$\sum_{j=1}^{n}(\lambda_j x_{ij}) + S_i^- = \theta x_{io}$$ $i = 1,2,\dots,m;$ $$\sum_{j=1}^{n}(\lambda_j y_{rj}) - S_r^+ = y_{ro}$$ $r = 1,2,\dots,s;$ $\lambda_j \geq 0$ j = 1, 2, …, n. $\sum_{j=1}^{n}\lambda_i = 1$	max $\theta = \varphi + \varepsilon\,(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+)$ Sujeto a : $$\sum_{j=1}^{n}(\lambda_j x_{ij}) + S_i^- = x_{io}$$ $i = 1,2,\dots,m;$ $$\sum_{j=1}^{n}(\lambda_j y_{rj}) - S_r^+ = \theta y_{ro}$$ $r = 1,2,\dots,s;$ $\lambda_j \geq 0$ j = 1, 2, …, n. $\sum_{j=1}^{n}\lambda_i = 1$
VRS	Añadir: $\sum_{j=1}^{n}\lambda_j = 1$	

Tabla 2-Formulación de modelos DEA. Fuente: Gil Ropero (2015).

Donde:

y_{r0} y x_{i0}: los rth outputs y ith inputs para cada DMU_0 evaluada.
λ_j: las variables de decisión que representan los pesos DMU_j que colocaría sobre cada DMU_0 en la construcción de su conjunto de referencia eficiente.
θ: la distancia proporcional en las entradas a la frontera y por tanto, la medición de la eficiencia técnica.
ε: el número real positivo más pequeño.
S_i y S_r: las holguras potenciales o factores de exceso para cada input.

En la siguiente figura (Figura 2) se ha representado ambos modelos.

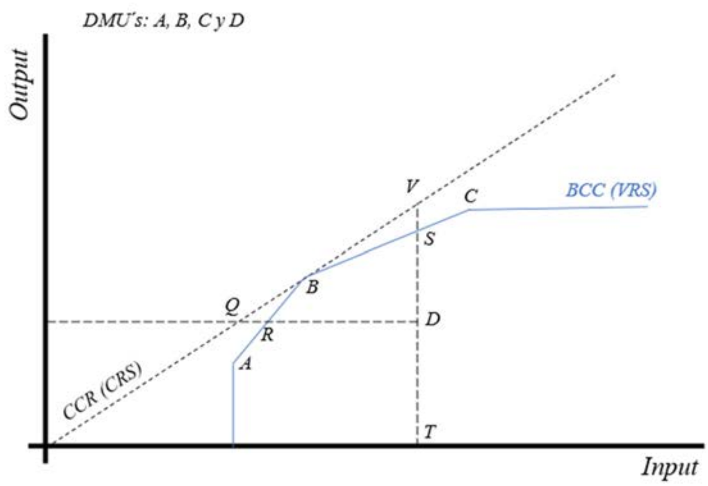

Figura 2-Representaión gráfica de las eficiencias CCR y BCC. Fuente: Elaboración propia, tomado de Gil Ropero (2015).

La técnica *Bootstrap* proporciona estimaciones del error estadístico imponiendo escasas restricciones sobre las variables aleatorias analizadas y estableciéndose como un procedimiento de carácter general, independientemente del estadístico considerado.

El *Boostrap* (Efron, 1979 y 1982) ofrece una aproximación alternativa para la inferencia y el contraste de hipótesis en los modelos DEA. De hecho, en el caso de los modelos DEA con múltiples inputs y outputs, el Bootstrap es la única aproximación existente.

a) Bootstrap orientación input (BCC): $\frac{AD-AC}{AX_0} = \frac{AC-AB}{AX_0}$

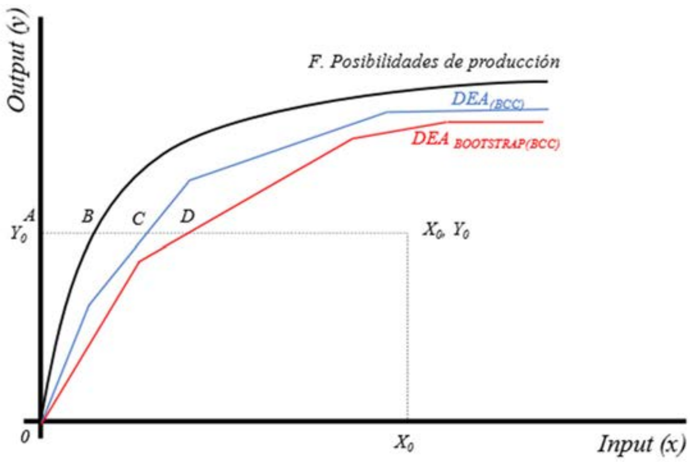

Figura 3-Representación gráfica del Bootstrap consistente Orientación input. Fuente: Elaboración propia, basado en Gil Ropero (2015).

b) Bootstrap orientación output (BCC): $\frac{AD-AC}{AY_0} = \frac{AC-AB}{AY_0}$

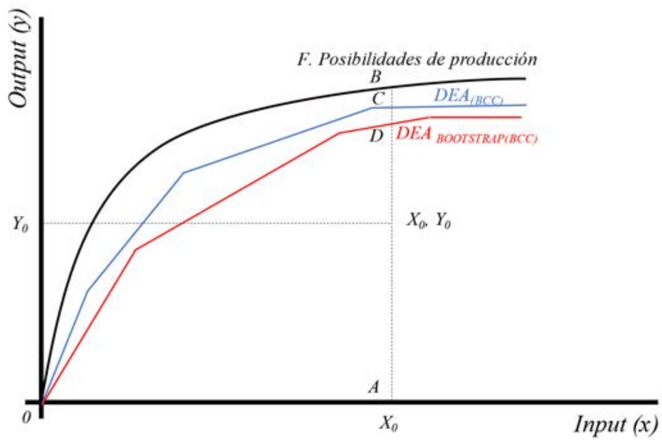

Figura 4-Representación gráfica del Bootstrap consistente Orientación output. Fuente: Elaboración propia, basado en Gil Ropero (2015).

3.2 Análisis de competitividad

La metodología propuesta se caracteriza por la observación de datos anuales y su transformación en forma de indicadores ponderados. La fuente de datos principal ha sido el Anuario Estadístico de Puertos del Estado para el ejercicio del año 2018.

Se observan indicadores pertenecientes a lo que se ha catalogado como tres tipos de "entorno portuario" dependiendo del nivel de escala sobre el que incide el indicador, lo que nos permitirá observar la competitividad de los puertos a distintos niveles, ya que en principio, no resultaría proporcional basar el análisis de competitividad en variables de producción o económicas que aportaría datos sesgados hacia los puertos más importantes, en términos de volumen de tráfico y recaudación, del sistema.

Así, los tres entornos observados y los indicadores que componen cada uno son:

a) El microentorno: se consideran indicadores propios del puerto en sí mismo, es decir, aquellos equipamientos y servicio básicos que proporciona el puerto e inciden en su productividad. Los indicadores estudiados para este entorno, y sus unidades de medida.
b) El mesoentorno: se consideran indicadores relativos al grado de calidad de interacción con otros entornos que presenta el puerto. Así, se consideran las aportaciones científicas y el desarrollo tecnológico o la existencia de sistemas de gestión de residuos y la calidad del agua. Es una forma de valorar la capacidad de los puertos más pequeños de incorporar nuevas funciones al sector portuario, que aportan un valor agrado al mismo más allá de la mera productividad.
c) El macroentorno: mediante este entorno se pretende definir la capacidad del puerto para competir a nivel internacional. Es indicativo del perfil económico del puerto.

4. RESULTADOS Y ANÁLISIS DE RESULTADOS

4.1 Escenario 0 o Situación Actual

Escenario base o de punto de partida, la cual se analiza la situación del actual sistema portuario español, comprendido por 28 Autoridades Portuarias que gobiernan 46 puertos de interés general.

		Operational		Financial	
DMU No.	**DMU Name**	DEA VRS Efficiency	**BOOT Efficiency**	**BOOT Efficiency**	DEA VRS Efficiency
1	**A Coruña**	0,59554	0,54384	0,88003	0,91278
2	**Alicante**	0,33001	0,30120	0,76866	0,78554
3	**Almería**	0,89901	0,82781	0,90960	1,00000
4	**Avilés**	0,32427	0,30330	0,80574	0,81304
5	**Bahía de Algeciras**	1,00000	0,80634	0,89267	1,00000
6	**Bahía de Cádiz**	0,15911	0,14595	0,67890	0,69029
7	**Baleares**	1,00000	0,74393	0,72790	0,75528
8	**Barcelona**	0,63111	0,56540	0,91001	1,00000
9	**Bilbao**	0,39309	0,35768	0,80433	0,82697
10	**Cartagena**	1,00000	0,84712	0,94337	1,00000
11	**Castellón**	0,96024	0,90255	0,90254	1,00000
12	**Ceuta**	1,00000	0,73406	0,27343	0,28549
13	**Ferrol-San Cibrao**	0,37030	0,33667	0,95863	0,98053
14	**Gijón**	0,45462	0,43050	0,93125	0,97022
15	**Huelva**	1,00000	0,89066	0,67290	0,70194
16	**Las Palmas**	0,49661	0,44243	0,93092	1,00000
17	**Málaga**	0,31322	0,27728	0,89166	1,00000
18	**Marín y Ría de Pontevedra**	0,31588	0,29466	0,98084	1,00000
19	**Melilla**	1,00000	0,73050	0,63629	0,64563
20	**Motril**	1,00000	0,74379	0,88501	1,00000
21	**Pasaia**	1,00000	0,73843	0,88491	1,00000
22	**Santa Cruz deTenerife**	0,83316	0,73638	0,84227	0,86895
23	**Santander**	0,22213	0,20396	0,79254	0,79956
24	**Sevilla**	0,23129	0,21368	0,83976	0,84567
25	**Tarragona**	0,75822	0,73655	0,86332	0,89570
26	**Valencia**	0,76594	0,71626	0,90016	1,00000
27	**Vigo**	0,14159	0,12724	0,81681	0,82521
28	**Vilagarcía**	1,00000	0,73447	0,88970	1,00000
Media aritmética		0,64983	0,55117	0,82908	0,87867
Media geométrica		0,55321	0,48033	0,81141	0,85734
Desviación estándar		0,31736	0,24825	0,13739	0,15934
Desviación media		0,29421	0,22763	0,09380	0,12146
Varianza		0,10072	0,06163	0,01887	0,02539

Tabla 3-Resultados del escenario 0 con Índice de Competitividad. Fuente: Elaboración propia.

El mayor valor de Bootstrap operativo lo alcanza la Autoridad Portuaria de Castellón (0,90255), no alcanzando la eficiencia pura en el análisis DEA. Además, para el mayor valor de Bootstrap financiero, la Autoridad Portuaria de Marín y Ría de Pontevedra (0,98084), que además alcanza la eficiencia pura en el análisis DEA.

El menor valor de Bootstrap operativo se atribuye a la Autoridad Portuaria de Vigo, que alcanza los valores más bajos en los dos análisis (0,14159 y 0,12724, respectivamente).

Esto puede deberse a la gran variabilidad de sus ingresos por tasas en función del bajo crecimiento del número de buques. Además, el valor más bajo financieramente hablando se obtiene en Ceuta, tanto en el análisis DEA (0,28426) como en el Bootstrap (0,27573).

Añadir un input más, y además siendo un factor tan determinante como un indicador de competitividad ha resultado salir eficaz, ya que la mayoría de los datos de eficiencia mejoran y se obtienen mayores resultados.

La media del escenario 0 (Sistema Portuario actual), en la aritmética como en la geométrica de la eficiencia operativa es inferior a 0,75 o al 75%, lo que significa que es ineficaz. Sin embargo, en la eficiencia financiera, supera el 0,75 o 75%, lo que puede asimilarse o aceptarse como eficiente, que no es puramente eficiente sino en una escala de eficiente o ineficaz.

4.2 Escenario 1 o Fachadas Marítimas

Escenario en el cual, se agrupan puertos o Autoridades Portuarias de toda una fachada marítima, es decir, todos aquellos puertos o Autoridades Portuarias bañados por el mismo mar u océano, pertenecientes a una misma orientación cardinal, es decir, localizados al este, sur, oeste o norte de la costa española.

		Operational		Financial	
DMU No.	DMU Name	DEA VRS Efficiency	BOOT Efficiency	BOOT Efficiency	DEA VRS Efficiency
1	Bilbao - Pasajes- Santader - Gijón - Avilés	0,52321	0,48415	0,71417	0,74383
2	A Coruña - Ferrol + San Cibrao - Vigo - Marín + Ría de Pontevedra- Vilagarcía	0,65094	0,61001	0,85401	0,88959
3	Huelva - Sevilla - Bahía de Cádiz	0,55014	0,51050	0,74457	0,77207
4	Bahía de Algeciras - Málaga - Motril - Almería	1,00000	0,85412	0,91451	1,00000
5	Baleares	1,00000	0,83860	0,83948	0,87742
6	Alicante - Cartagena - Valencia - Castellón - Tarragona - Barcelona	1,00000	0,88337	0,91337	1,00000
7	Santa Cruz de Tenerife - Las Palmas	0,77114	0,70563	0,91672	1,00000
8	Ceuta - Melilla	1,00000	0,83687	0,91582	1,00000
Media aritmética		0,81193	0,71541	0,85158	0,91036
Media geométrica		0,78519	0,69798	0,84797	0,90457
Desviación estándar		0,20030	0,15168	0,07635	0,10032
Desviación media		0,18807	0,13783	0,06413	0,08964
Varianza		0,04012	0,02301	0,00583	0,01006

Tabla 4-Resultados del escenario 3 con Índice de Competitividad. Fuente: Elaboración propia.

En los resultados obtenidos, en el escenario 1, destacamos que de las 8 autoridades portuarias que se proponen, 4 alcanzan el valor de la frontera DEA igual a 1,0000 en el análisis operacional y otras 4 en el análisis financiero, es decir, el 50% de las autoridades son puramente eficientes operativa y financieramente. En el análisis Bootstrap, los valores mejoran con respecto al escenario 0, ya que 4 de 8 (50%) superan el umbral de 0,75 o 75% de eficiencia operativa, y, en la eficiencia financiera, algo más de la mitad superan el valor de 0,75 o 75%.

El mayor valor de Bootstrap operativo lo alcanza la autoridad portuaria formada por Alicante - Cartagena - Valencia - Castellón - Tarragona - Barcelona en su conjunto (0,88337), alcanzando la eficiencia pura en el análisis DEA. Además, para el mayor valor de Bootstrap financiero, la autoridad portuaria formada por el conjunto de Santa Cruz de Tenerife-Las Palmas (0,91672) alcanza la eficiencia pura en el análisis DEA.

El menor valor de Bootstrap operativo se atribuye a la agrupación de Autoridades Portuarias formada por Bilbao - Pasajes- Santander - Gijón - Avilés en su conjunto (0,48415), coincidiendo con el menor valor en el análisis DEA (0,52321). En el análisis financiero, corresponde al grupo formado por Bilbao - Pasajes- Santander - Gijón - Avilés obtener el valor más bajo en ambos análisis. En el análisis DEA, obtuvieron una eficiencia financiera de 0,74383 y el Bootstrap de 0,71417.

En este escenario, se da el caso de que una misma agrupación obtiene los valores más bajos en las cuatro eficiencias (dos para el operacional y otras dos para el aspecto financiero).

En la media del escenario 1, tanto la aritmética como la geométrica de la eficiencia operativa superan el valor de 0,5 o el 50%, lo que significa que están cerca de ser eficientes. Sin embargo, en la eficiencia financiera, supera el 0,9 o el 90%, lo que se puede asimilar o aceptar como eficiencia pura. En el caso operativo, habría que hacer un análisis más exhaustivo, pero por los resultados obtenidos, se podría decir que no se considera eficiente. Este escenario es el que mejores datos estadísticos alcanza, siendo el escenario con los valores medios más elevados.

5. CONCLUSIONES

Con el análisis del modelo DEA- Bootstrapping se han extraído los resultados a estudiar y se ha llegado a conclusiones satisfactorias. Esta metodología ha permitido analizar el Sistema Portuario español desde ambos puntos de vista: operativo y financiero. Partiendo de una serie de indicadores o KPI´s medibles y valorables, que son analizados por la metodología DEA extrayendo los valores de eficiencia y eficiencia corregida sobre la cual se ha desarrollado esta investigación de una manera muy satisfactoria.

La revisión bibliográfica que se ha realizado en esta investigación ha ayudado a portar gran valor científico a esta tesis doctoral, ya que se han extraído los principales hallazgos relacionados con la gestión portuaria, el Análisis Envolvente de Datos (en materia portuaria) y de la competitividad, y su análisis. Esto ha permitido que la aportación científica que se genera sea de alto valor, aportando conocimiento al ámbito portuario, más concretamente en la medida de la eficiencia del sistema portuario español.

La metodología aportada en esta investigación ha resultado ser novedosa en el ámbito, ya que cruzar el índice de competitividad con el Análisis Envolvente de Datos no lo había realizado ningún otro investigador. Por ello, esta tesis aporta valor en el desarrollo de nuevas metodologías que ayuden a poder medir índices de competitividad y trasladarlos a poder medir eficiencias mediante la metodología DEA.

Centrándose en los resultados obtenidos, la media global de la eficiencia operativa del sistema portuario español es baja, en torno al 0,5, debido en gran medida a la duplicidad en muchos casos de las infraestructuras que componen el sistema. Es cierto que, en muchos casos, los diferentes puertos cuentan con un amplio abanico de las mismas instalaciones a lo largo de nuestro litoral. Por tanto, esta duplicidad de infraestructuras, a veces en distancias cortas, provoca una duplicidad de activos que no se traduce en un aumento del tráfico de mercancías y, más aún, en un mayor atractivo para recibir un mayor número de buques, lo que, a su vez, se traduce en menores ingresos por las diferentes tasas portuarias.

Es decir, los escenarios muestran que una agrupación portuaria, o una reforma del sistema portuario español, favorece la eficiencia financiera y, más aún, la eficiencia operativa de nuestro sistema portuario porque pasan de valores de 0,4 en el análisis BOOT y de 0,5 en el análisis DEA de la eficiencia operativa, a valores superiores a 0,8.

Seguidamente, los puertos con mayor eficiencia financiera son los puertos consolidados del sistema portuario español, con un gran tráfico y con unos activos diseñados para favorecer la captación de nuevos buques y nuevas mercancías, y/o para realizar un gran trabajo operativo en la manipulación de estos casos. Algunos puertos pueden estar desaprovechados, pero esto se debe a los grandes activos que poseen y que no están expresamente dedicados al uso portuario, es decir, su explotación no influye en el rendimiento del trabajo portuario atrayendo más tráfico o influyendo positivamente en la manipulación de las mercancías que entran en el puerto.

Los puertos del norte, en los escenarios mediante agrupaciones, son los que menos eficiencia alcanzan, dado que existe una consecución de una serie de puertos en muy pocos kilómetros, limitando la competitividad intraportuaria. Esto además de sumarle la duplicidad de infraestructuras derivadas de intentar conseguir tráficos de puertos cercanos, no llegando a consolidar el grado de ocupación en el que se tenía esperado en los estudios previos de demanda.

Por último, se observa que la eficiencia mejora al considerar un menor número de DMUs, es decir, la eficiencia global mejora cuanto más se reduce el número de autoridades portuarias.

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SEGURIDAD EN EL TRANSPORTE
SAFETY IN TRANSPORT

INTELLIGENT EMERGENCY MANAGEMENT SYSTEM FOR RAILWAY TRANSPORT

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ABSTRACT

Nowadays, a major safety challenge in rail transport is to manage the incidents and emergencies in the most efficient possible way. The current contingency plans tend to be based on static procedures not taking into account how real-time conditions affect them.

Consequently, the decision-making process may well suffer delays and the possibility of occurrence for human mistakes could raise since the required measures are expected to be carried out under important pressure. In this study, focused on commuter trains, railway safety is enhanced by a new intelligent emergency management system which aims to support the operator tasks in a real-time incident or emergency situation. This cyber-physical system is composed by two main modules: one on board the train, including sensors and GPS, and other integrated in the control centre addressing four computational models. Those models cover (1) the detection of different types of incidents/emergencies using the information received from on board sensors, (2) the calculation of the evacuation process (if necessary), (3) the selection, estimation of routes and communication with emergency services required for each event, and finally (4) a provision of actions to support the operator decisions. Communication between modules is provided by GPRS due to actual technology available in the pilot trains. This system has been implemented in an actual railway line in Cantabria (Santander-Cabezón de la Sal) and three practical demonstrations were defined based on several use cases, which were tested using a pilot facility incorporating all sensors and devices installed in those trains. Results demonstrated the benefits of the new system.

1. INTRODUCTION

According to the last report of 2019 of the National Commission for Railway Accidents only in Spain during 2018 one serious accident (an impact against a landslide), nine events at railroad crossing, two fires and other thirty-one different types of serious incidents took place. This demonstrates the importance of managing such undesirable events in the fastest and safest manner via transportation policies.

Over the last decade, Intelligent Transportation Systems (ITS) have implemented new features, addressing safety and security issues. The importance of enhancing the protection of critical transportation infrastructures, due to the wide range of risks which impact their proper functioning, is shown in studies as Janusova and Ciemancova (2016) through different examples of goals and roles of using ITS in railway transport and its potential benefits for decision-making process of transport operators or emergency responders.

Regarding intelligent systems developments, there is a wide variety of areas and applications. As shown by Qureshi and Abdullah (2013), ITS technology operates in diverse fields of transportation through management systems of freight (e.g. Commercial Vehicle Operations (CVO) or Advanced Fleet Management System (AFMS)), transit (e.g. Automatic Vehicle Location (AVL) or Travel Assistance Device(TAD)), incident (e.g. Critical Incident Management System (CIMS) or Cyber Physical System (CPS)) or emergency (e.g. Emergency Management Information System (EMIS) or Multi-Commodity Stochastic Humanitarian Inventory Management Model (MC-SHIC)), all with the aim of improving safety. Other example of ITS applications is shown in (Shi and Ni, 2015) with the analysis, model and framework of Railway Intelligent Transportation Systems (RTIS) and its applications as the Transportation Management Information Systems (TMIS) or the Automatic Train Identification Systems (ATIS), among others. The application of this technology in urban transport is shown in (Qin, Yuan and Pi, 2016) introducing Urban Rail Intelligent Transportation Systems (URITS) divided into five layers (perception, communication, integration, operation and service) providing communication signals, integrated supervision and operations management.

Moreover, some research works have been done to improve individual components of the system. Developing an online real-time model which represent the normal behaviour of train trajectory, anomalies in train speed during the whole route from the departure location can be detected (Kang, Sristi, Karachiwala and Hu, 2018). Results from the validation of the system through simulations shown a sensitive improvement detection up to 22%. Another example proposes a security incident detection technique based on rough sets theory using a Multilevel Intelligent Control System (MICS) within ITS (Chernov, Butakova, Karpenko and Kartashov, 2016). Network security incidents were defined as a cause-effect chain of events for their classification (e.g. system malfunction incidents, incidents caused by user errors, intentional cyber-attacks). The proposed technique gives rise to a simple and fast calculation. Another important component of transportation is the travel time information, stressing the fact that the longer delay of train arrival means longer waiting time for passengers. To provide better service, researchers from India presented in (Krishna and Yugandhar, 2013) one of the first attempts at real-time short-term prediction of arrival time for ITS applications through the development of three modules (vehicle section module, base station section module and user mobile section module) integrated in a comprehensive system. The arrival time calculation uses the train location and the station location through Global Positioning System (GPS) modules placed on board the train and at each station.

One of the most recently published studies deals the implementation of satellite navigation elements for rail transport (Nedeliakova, Hranicky and Cechovic, 2019). An advantage of the functions is that it can be integrated in current technology systems and with new digital devices.

ITS have been also integrated with other intelligent systems from other type of transport. In (Osipitan, 2016) combining intelligent transportation system for roadways and an intelligent rail system technology developing an Intelligent Grade Crossing System (IGCS) which improves the security of highway-rail intersections.

Based on the importance of ITS, several countries have carried out their own studies to measure the benefits of implementing these technologies to their railway service. In 2012, China analysed the situation of their railway infrastructure, taking into consideration that it is its cheapest means of mass transportation, and how this infrastructure could be affected by the implementation of Rail Intelligent Transportation Systems (RITS) (Jiang, Yang, Yuan and Xu, 2012). This analysis established five sustainable development strategies which offer a transportation solution minimizing environmental impact and contributing to social and economic prosperity. Similarly, Tokody, Schuster and Papp (2015) developed an ITS ensuring the highest reliability implementation, taking into account technical and technological characteristics, probability of system failures and theories of normal accidents, reliability organizations and flexible engineering planning. Also, they paid special attention to safety risks of software and hardware products. Efficiency, safe operation and convenience, as well as the increment of the adaptability of the system were the key aspects considered by the authors for ITS development. In Poland, new concepts and innovative technologies were also implemented as the European Train Control System (ETCS), a subsystem of the ERTMS (Kornaszewski, Chrzan and Olczykowski, 2017). The idea of the ETCS is based on the digital track-vehicle transmission, supplying the engine driver of information concerning locations of trains, allowed speed or the closure of a level crossing. The GSM-R radio communication complete the system.

In essence, the stress produced by emergency events to control centre operators increase the likelihood of making mistakes. Emphasising that responsibility to manage emergency events through a decision-making process it is crucial to minimize risks and emergency consequences. Hence, the application of ITS is certain to provide elements to the operator for decision-making process. In this sense, the purpose of this study is to support the operator during the decision-making process slightly improving its activities.

This paper provides the explanation and characteristics of the four models integrated in SIGNAL system elaborating the corresponding communications protocols and the validation experiments conducted.

2. METHODOLOGY

SIGNAL is a cyber-physical holistic intelligent management system including both on board and control centre modules, see Figure 1. While the former, managed by the train driver, receives information from train devices as smoke and fire sensors, speedometer, accelerometer and GPS, the latter integrated in the control centre hardware aims to support the operator tasks during an incident. The control centre is composed by four independent models.

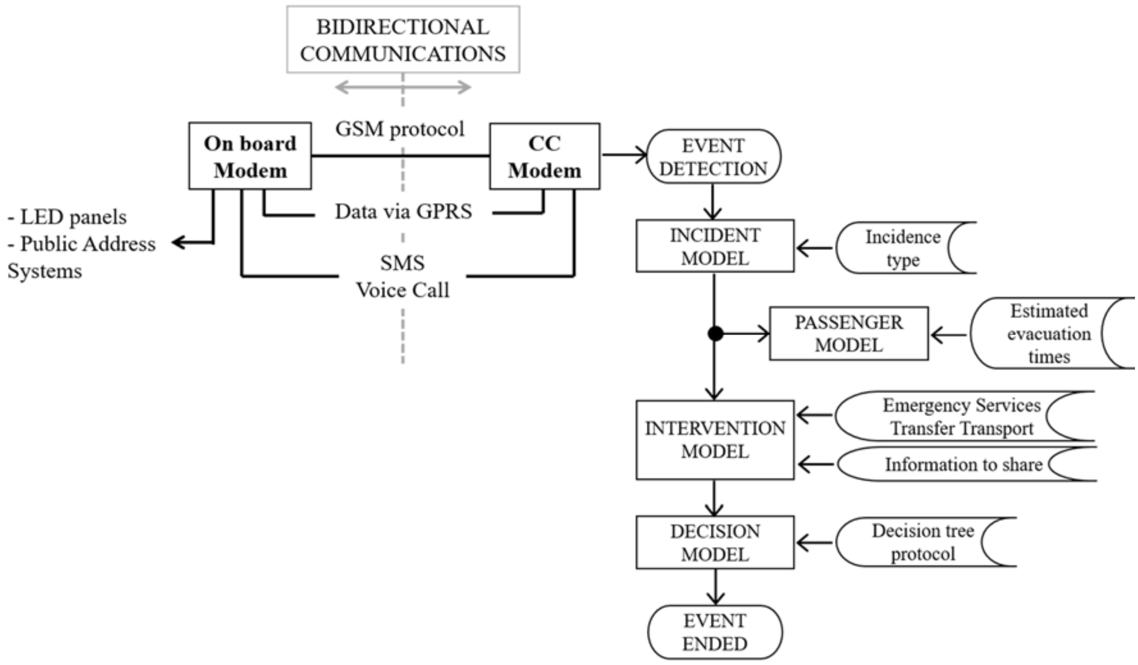


Fig. 1 – Intelligent Emergency Management global scheme

Based on the available technologies installed in the railway vehicles selected for the practical demonstrations, the communication between both modules is provided via General Packet Radio Service (GPRS) using User Datagram Protocol over Internet Protocol (UDP/IP). Likewise, in order to provide Voice Call and messaging services Short Message Service (SMS) and Global System for Mobile (GSM) communication are used. In case of a “dead man” warning from the train driver cabin, the communication between control centre operator and passengers through LED panels and audio system installed in the train is also feasible. The location of the train in both modules is shown through a Global Information System (GIS).

The characteristics of the four models developed are defined as follows:

1) Incident model. Through constant reception of train location via GPS and current status of sensors installed on board, it is able to detect different types of incidents in real-time clustered as can be seen in Table 1. To elaborate this classification an extensive review was conducted founded on previous railway emergency events.

Id.	Incident Code	Incident Designation	Sensors/Devices
1	NOGPS	GPS signal lost	GPS
2	FTEC	Stop due to a breakdown of rolling stock	Speedometer
3	DESC	Derailment	
4	FEVIAJE	Emergency break by passenger	
5	FECOND	Emergency break by engine driver	
6	FEHM	Emergency break for “dead man”	
7	IMPC1	Minor running-over due to the impact against a small object	Accelerometer
8	IMPC2	Major running-over due to the impact against a large object	
9	INCN	Fire in rolling stock	Fire detector

Table 1 – Incidents and its relation with sensors.

Once a sensor achieves threshold values capturing an abnormal behaviour, the model alerts both the driver and control centre. Communication is implemented using the following frame structure to receive and report the current status of the sensors:

UUUU; YYYYMMDDHHMMSSCC;EVENT;LON;LAT,SPD,SPDU

Where UUUU is the train unit identification, YYYYMMDDHHMMSSCC indicates time (Year, Month, Day, Hour, Minute, Second and Second hundredth) noted as DT for simplification, EVENT is the incident code from Table 1, LON is the GPS longitude, LAT is the GPS latitude, SPD is the instant speed (m/s) and finally SPDU is the instant speed-up (m/s^2).

Once an anomalous frame has been detected, the system initiates a voice call between the control centre operator and the engine driver to verify the incident. In case of reception of “dead man” incident code or similar code preventing the establishment of voice call, the operator immediately initiates the protocols for direct communication with the passengers using LED panels through the following frame:

UUUU;DT;MSGD;FMT;’MESSAGE’

Following the above notation, MSGD contains the message to be displayed and FMT controls the display mode being B-normal, R-blink and S-rotary.

Similarly, a Public Address system (PA) could be employed by control centre operator to remotely configure the audio devices installed on board allowing direct voice communication with passengers to provide instructions.

UUUU;DT;AUDIOV;ON/OFF

Where AUDIOV is the corresponding tag of the system and ON/OFF indicates the current status of the devices.

2) Passenger model. In case of remaining inside the train was not a safety alternative for passengers, this model runs stochastic simulations to calculate the total evacuation time under different conditions. The total time (T_{total}) is calculated by two terms: the egress time from the train (T_{egress}) and the movement time of passengers (T_{mov}) towards the access point for the alternative transfer transport (see Equation (1)).

$$T_{total} = T_{egress} + T_{mov} \quad (1)$$

Focus on the first term, trains are characterized as narrow spaces that limits the people movement inside, prevailing the queues discipline. According to (British Standards Institute, 2004; ISO, 2015) the required evacuation time for rail cars comprises two main variables: 1) the time of the first few occupants to reach the exit (movement time) and 2) the flow time of the rest of passengers through the available exits. The chance for passengers to leave the train is determined by the opening of exits, prior notice from the crew. The random flow rate of passengers through exits is expected to be the most decisive variable to calculate egress time. Also, flow rates depend on the operative conditions: the urgency (i.e. evacuation or normal alighting) and the evacuation destination (i.e. high platform, rail tracks). Hence, four egression classes were implemented: evacuation to platform, evacuation to tracks, alighting to platform and alighting to tracks. Data used for flow rates f are based on empirical data provided in (Cuesta, Abreu, Balboa and Alvear, 2017; Capote, Alvear, Abreu, Lázaro and Cuesta, 2008; Nelson, 2002; Norén and Winér, 2003) and its minimum and maximum values are shown in Table 2. The number of passengers (n_{occup}), the number of available exits (n_{doors}) and their width (w_{doors}) are also components of Equation (2). Train occupation is calculated using Equation (3) where n_{max} is the maximum occupation and P_{occup} is the occupation density assumed as 20, 40 and 80 %.

$$T_{egress} = \frac{n_{occup}}{n_{doors} * w_{doors} * f} \quad (2)$$

$$n_{occup} = n_{max} * \frac{P_{occup}}{100} \tag{3}$$

The second term is the movement time of passengers from the train to the transfer transport, which may have two situations, egress to platform or egress to rail level. Both distances are namely d_t. Equation (4) shows the corresponding formula to calculate the movement time.

Finally, walking speeds (v_i) are taken from empirical data (Chandra and Bharti, 2013; Henderson, 1971) (see Table 2). The movement time for each passenger is t_{mov_i}, the number of passengers is denoted as i and the total number of walking speed values is n_p (depending on train occupation load).

	Flow rate (per/s)		Walking speed (m/s)	
	Min.	Max.	Min.	Max.
Evacuation to platform	1.23	3.84	0.5	3
Evacuation to tracks	0.85	1.45	0.3	2.1
Alighting to platform	0.93	0.96	0.4	2.2
Alighting to tracks	0.56	0.69	0.2	1.4

Table 2 – Flow rate through exits and walking speed values.

$$T_{mov} = \max_i \left(t_{mov_i}\right) \qquad 0 < i < n_p \tag{3}$$

$$t_{mov_i} = \frac{d_t}{v_i} \tag{4}$$

Note that flow rates and walking speeds are random variables used to determine the evacuation times through Monte Carlo stochastic simulations, as it is described in (Alvear, Abreu, Cuesta and Alonso, 2014). Moreover, the time calculated from the Passenger model is the 95th percentile of the total evacuation time, resulting of sum up the 95th percentiles of each term (egress time + movement time).

3) <u>Intervention model</u>: this model supports operator and improve time required. The model works under real-time conditions using the information provided by previous models. The conceptual approach is based on defining the emergency services to report the situation and which data should be shared with them (the existence of injuries, access points to the railroad, etc.). To determine that, the model has a decision tree logic which guarantees the optimal information flows to external services. The intervention model also determines the nearest emergency services from the incident location, being essentially the advanced implementation of the geographical coordinates of each service. Finally, the model calculates the estimated arriving times of the corresponding emergency services and transit transport using OpenStreetMaps service (https://www.openstreetmap.org).

Mapping of railroad access points through video recording or GIS must be defined in advance to implement the corresponding information in the system, establishing three levels of access: free (without obstacles), medium (separation systems easy to take off) and no access (impassable areas).

4) Decision model: this model shows a summary of the actions taken during the incident/emergency and helps the operator to verify all those decisions and actions. It is based on a sequence of statements/decisions and is represented as a decision tree.

After each model and the communications between modules were developed, they were integrated in a main software called SIGNAL. The interface of the module on board emulator is shown in Figure 3 and the control centre interface is shown in Figure 4.

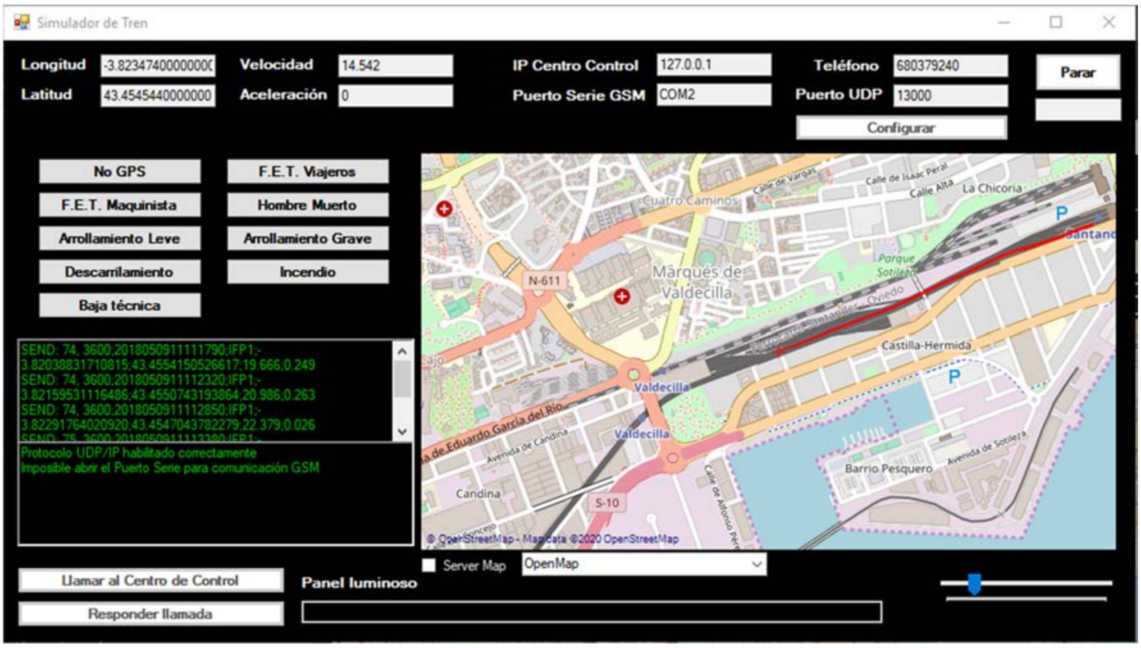


Fig. 3 – On board module interface.

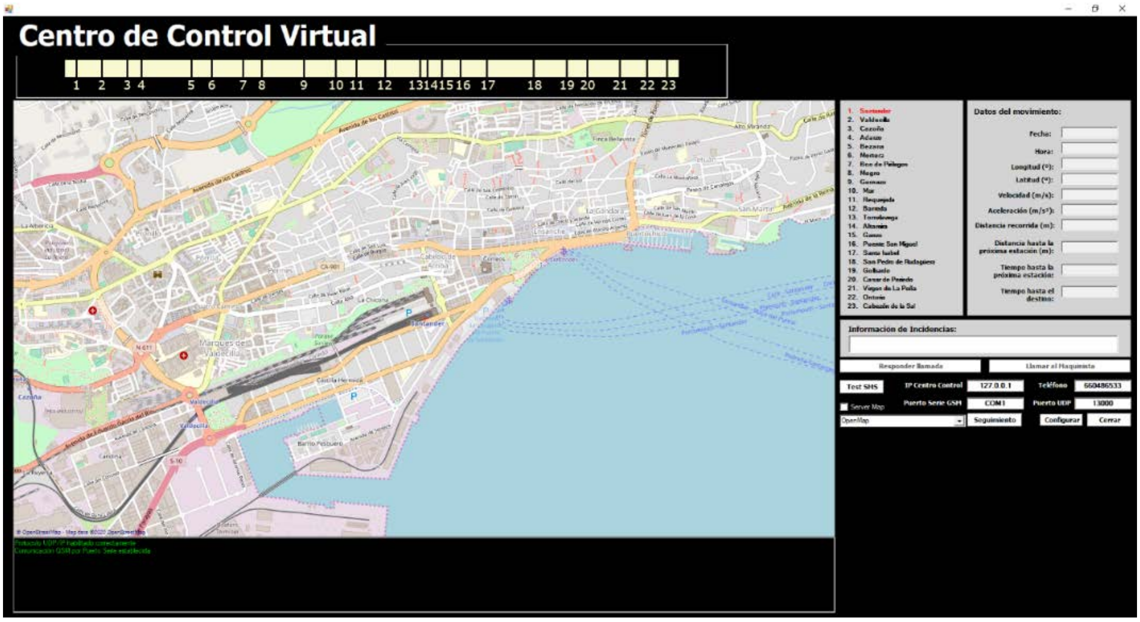


Fig. 4 – Control Centre module interface.

3. SOFTWARE VALIDATION

The evaluation of the proper functioning of SIGNAL was realized through the validation of a set of technical requirements in three use cases. The selected line was Santander-Cabezón de la Sal located in Cantabria (Spain) and operated by Renfe-Feve Railway Company. This line is approximately 48.6 km long and has 23 stations or halts. This line is operated by commuter trains with three coaches of 15.24 m long, 2.35 m width and 4 exits per coach (1.2 m in width each). The maximum speed is 80 km/h due to some operation constraints of the track.

The use cases selected were derailment, emergency brake by engine driver and fire in rolling stock as they cover the validation of all elements of the system. Firstly, a possible scenario was described and executed for each incident with their following descriptions:

Derailment. Partial derailment because of a landslide. Only derails the final coach and it is not overturning any coach. Due to the severity of the situation the presence of injuries is possible. The train occupation is between 20-60%. Passengers can wait for the transfer transport inside the train because the situation is assumed to be safe enough.

Emergency brake by engine driver. The engine driver pushes the emergency brake bottom due to the presence of a car on a railroad crossing. The train can stop before impacting because the engine driver starts the braked-on time. The incident is solved as a false alarm.

Fire in rolling stock. A problem in rolling stock produces a fire that affects the third coach. The train continues operating to reach the next station. They are no injured passengers. The train occupation load is between 20-60%. Evacuation to a platform becomes necessary when the train arrives at the station.

A methodology was defined to conduct the use cases. Each test should start with the constant exchange of frames showing normal operation conditions of the train. At a given time, the on board simulator activates the corresponding incident. The alarm appears at the control centre and the operator calls to the engine driver using a voice communication protocol GSM. For derailment and fire, the driver confirms the incident, but in the emergency break it established a false alarm because the train can continue the route. Then, for the use cases with a verified incident, the Intervention model runs and it allows the operator to implement the corresponding information from the engine driver. The Intervention model provides the course of actions to carry out (i.e. notification to the emergency services and mobilizing transfer transport), if it is necessary.

The operator notifies to the emergency medical services, firefighters and police services for the derailment case and it notifies to firefighters and police services in the fire case.

Also gives the location of the incident, the nearest access points and other relevant information (injuries, overturns,…). Then, the operator calls the engine driver to give him the estimated arriving times of the emergency services. The Passengers model works when it is necessary. Here, it calculates the times for a normal alighting in the derailment case and for an evacuation to platform in the fire case. The operator notifies to the transfer transport of the nearest access point to the railroad and the engine driver of the arrival times. The operator should be alert for possible changes until the incident is over. Its last responsibility is to check the decisions and actions carried out based on the Decision model.

4. RESULTS

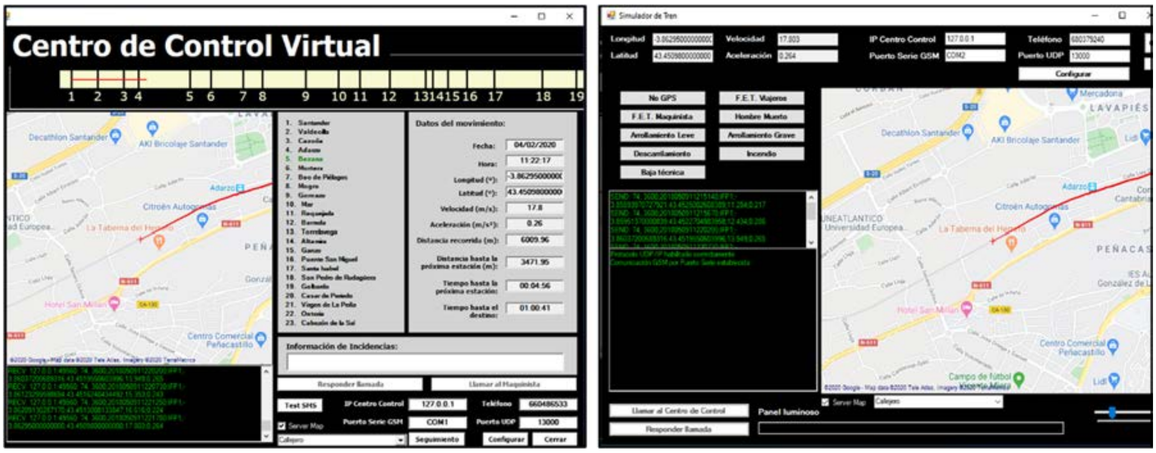
This section includes the validation of each model developed, the verification of operation and autonomy of both interfaces and the entire communications among modules. To limit the number of figures shown in the paper, we decided to include only those corresponding to the complete derailment use case development, since this use case deals all features of SIGNAL.

Table 3 shows a timeline with the corresponding interfaces and description of each moment during the development of the derailment use case. The first element of the temporal sequence X corresponds to the aspect of both interfaces in a normal situation during the train trajectory. When an incident occurs, the software detects it and an alarm is shown on the control centre interface as in the second element of the temporal sequence

X+1. In that moment, the Incident Model interface is activated as an emerging panel (third image of timeline). This panel enables the communication between the operator and the engine driver to confirm the incident and implement the corresponding information. Then, the interface of the Intervention, Passengers and Decision Models appeared (this moment corresponds with the X+3 element of the sequence). Through this screen, the models provide the corresponding results to the operator who can supply them to the engine driver and also notice to the services and transport.

Progress, description and interfaces

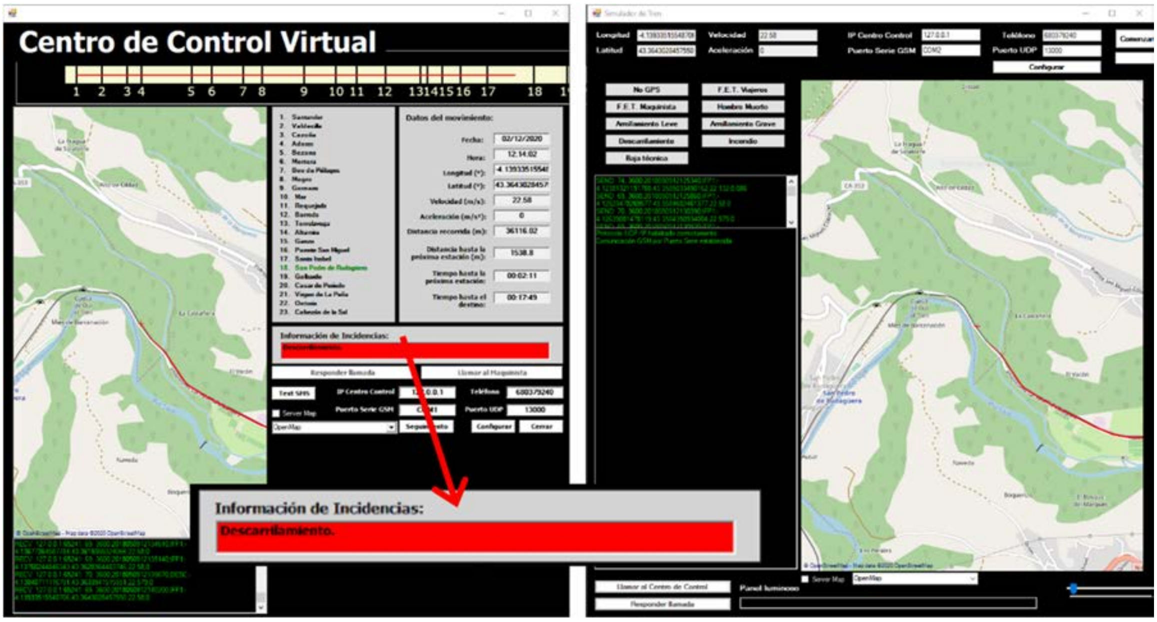
Time: X
Description: Control centre and train software working in a normal situation.
Interfaces:



Time: X+1

Description: Control centre and train software when an incident detection is produced.

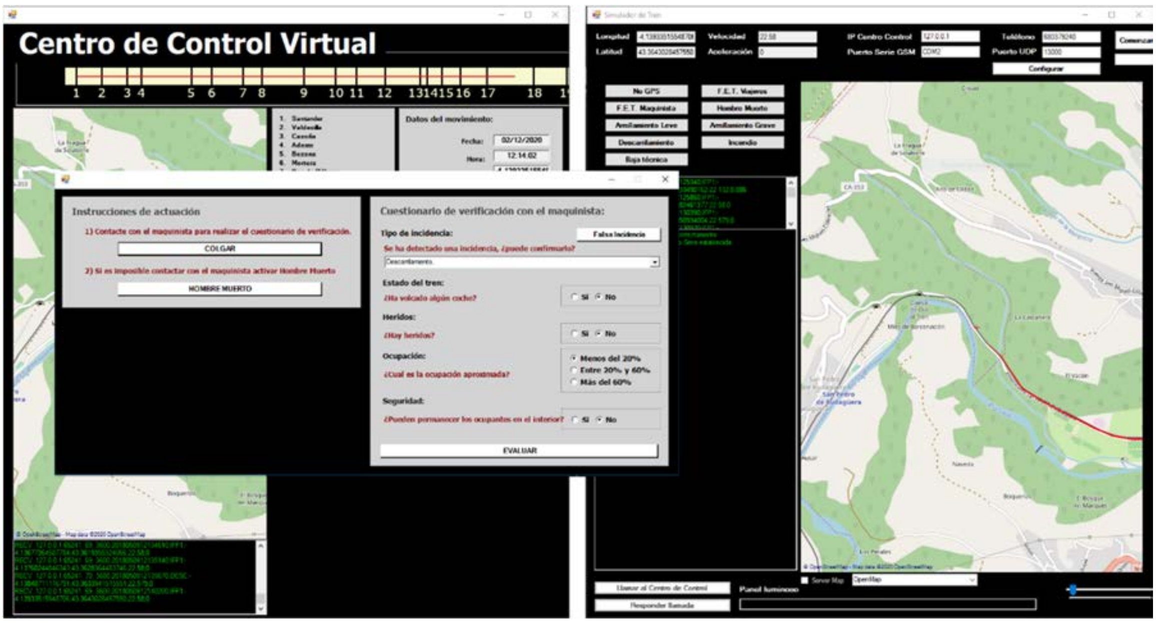
Interfaces:



Time: X+2

Description: Control centre and train software when the Incident Model works. Through a voice call (operator-engine driver) the incidence is confirmed. The first parameters about the event are implemented in an emergent window.

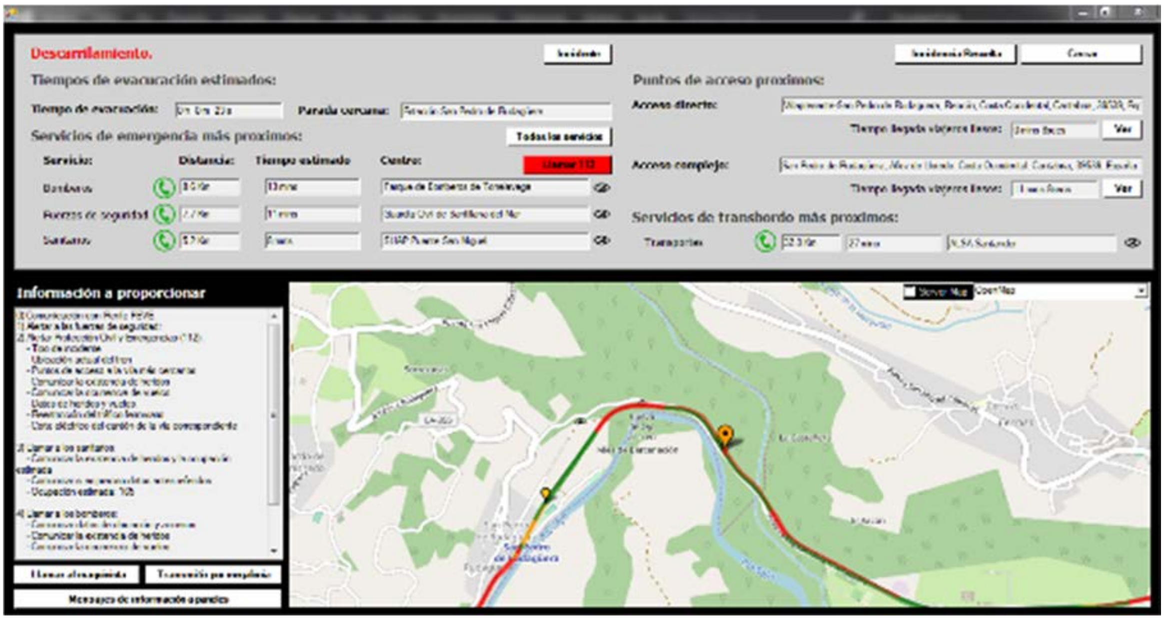
Interfaces:



Time: X+3

Description: Control centre interface meanwhile the Intervention, Passengers and Decision Models are working. Through this interface it is possible notice the emergency services and transit transport and inform the engine driver about the times.

Interfaces:



Time: X+4

Description: Incidence ended.

Table 3 – Development of the derailment use case through a timeline illustrated with images of the process.

5. DISCUSSION AND CONCLUSIONS

Safety and security for passengers of mass rail transportation systems is a major challenge. An incident or an emergency management with people involved is a serious and complicated process. To contribute to the improvement of railway transportation, we developed a prototype of an intelligent emergency management system. The aim is to support the operator tasks of a control centre in the decision-making actions in real-time and reduce the possibility of making mistakes at the minimum. To achieve the objective, we developed a module on board a train that can communicates and shares information from train sensors to the module integrated in the control centre hardware. This module is composed by four models that detect incidents automatically, that calculate evacuation times in a few seconds and that provide emergency management support in real-time.

The case studies have shown that the proposed system does its job opening the field to new application opportunities to emergency management response in rail transport.

First, it is possible to determine the nearest access point to the location of the emergency in a few steps. This is very useful for the emergency services that waste a lot of time defining the best entrance point. Furthermore, the system can be able to provide the type of services (emergencies or transfer transport) to demand their help. This is essential for a better work conditions of the services that are really necessaries. Second, the bidirectional communication among engine driver and control centre operator (or among operator and passengers in case of a dead man of the engine driver), reduces the global anxiety due to the exchange of information in real-time. Finally, the supporting given to the operator is crucial to decrease their responsibility, to reduce its stress and, consequently, to improve the incident management and also passengers safety.

The presented system provides consistent and reasonable results while providing demonstrated benefits. The system would drastically reduce evacuation, intervention and decision times. This paper goes beyond other contributions since it proposes the development and use of a real-time intelligent management system for incidents in rail transport. The next step is to achieve the completely installation and integration of the prototype in a real environment.

ACKNOWLEDGEMENTS

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SAFETY AND ROAD INFRASTRUCTURE: A SPATIAL ANALYSIS IN SUBURBS OF BOGOTÁ

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ABSTRACT

The research was focused in a multiple correspondence analysis. We analyzed the relationships between accident rates and road infrastructure variables in a municipality of Soacha (with more than five hundred thousand inhabitants in the suburbs of Bogota-Colombia). In Colombia, the fatality rate is 13 deaths per 100.000 inhabitants. In Soacha municipality the fatality rate is 10 deaths per 100.000 inhabitants. Soacha reports the highest number of deaths in the region (ANSV, 2020). In this research we performed a spatial analysis using a Kernel density graph to identify the areas with the highest concentration of fatal crashes.

We found that five dimensions explain 70% of the variability of data. We made a cross-dimension analysis by pairs, to obtain information on all possible combinations between that dimensions and used them as an input of a spatial distribution analysis of crashes in the municipality. We also calculated the contour curves for density modeling. We found that higher concentration of fatal crashes is around the highway "Autopista Sur". These crashes were associated whit crash hypothesis variables, immediate cause of the crash, crash class, crash severity and type of vehicle.

1. INTRODUCTION

The Global Report on Road Safety 2018 (World Health Organization – WHO, 2018), highlights that the number of annual deaths from crashes has reached 1.35 million. More than a half of the fatalities and serious injuries in crashes occurs on 10% of the road infrastructure and the most affected actors are pedestrians, cyclists, and motorcyclists. In addition, according to this report, 13% of fatalities occurs in low-income countries.

In order to reduce the rate of accidents, the WHO adopted the road safety factors based on the Haddon Matrix (1968) and proposed to the countries the implementation of programs and the introduction of the main pillars of road safety in their safety plans: safe infrastructure, human behavior, safe vehicles, institutional, environment and victim care. WHO emphasizes in the systematic analysis of accident data and the use of maps to locate accident hotspots in order to focus resources more effectively and efficiently in at-risk road infrastructure (WHO, 2019).

In Colombia (2020) there were 5,458 deaths in crashes, 82% of these fatalities correspond to vulnerable road actors: pedestrians, cyclists and motorcyclists. In the state of Cundinamarca occurred 6% of the total fatalities in the country (327 deaths in crashes), and the municipality of Soacha, located in this department, presented 53 fatalities and 189 injured. This municipality had the highest number of deaths in crashes in this department.

According to information from the *Agencia Nacional de Seguridad Vial* - ANSV, 84% of the fatalities in this municipality occurs on the national road that crosses the urban area of the municipality of Soacha (ANSV, 2020).

Moreover, the annual report of the Transport Ministry (2019) , define that primary roads correspond to 9.3% of the national network, 44% are concessioned roads. The “Via 40 Express”, a road under private concession cross the municipality and it has 144, 8 kilometers long and eight Functional Units – UF, and in the municipality of Soacha is located in UF-8 (Ministerio de Transporte, 2019).

The literature review presents models and techniques for the identification, analysis and assessment of crashes, involved with analysis in Geographic Information Systems (GIS) and spatial statistical methods. In our research, a descriptive statistics process was carried out to define accident patterns, in a second step a multiple correspondence analysis and a GIS analysis were performed. We found that the categories pedestrian, rollover, road, infrastructure, hit-and-run, according with original names of variables in database related to the hypothesis, immediate cause and accident class, that variables have the major contribution in the road accident rate. The multiple correspondence analysis together with the spatial analysis support the evaluation of the variables involved in the accident to generate prevention measures. These results contribute to improve current and future public policies in municipalities, departments and road safety agencies (Forigua, et al., 2020).

The purpose of this paper is to present the methodology based on spatial analysis to identify the areas with the highest concentration of crashes in Soacha and the main variables involved. The databases of crashes in the municipality and secondary information provided by the ANSV and other government organizations for the period 2014-2018 were used. The methodology proposes a multiple correspondence analysis in order to identify the relations between variables, and the variability in the information. We also applied an analysis of the spatial distribution of accident points using a Kernel density graph focused on localization of areas with the highest concentration of fatal crashes for spatial modeling.

2. LITERATURE REVIEW

In general, the models identified in the literature review for the analysis of road infrastructure and its impact on accident rates are from the temporal point of view, such the Accident Prediction Models (APM) that allow to consider road safety problems, identifying safety improvements and estimating the potential effect in terms of reduction of crashes (Kustra 2019, Raheel 2019, Wang 2017, Yannis 2016). Other researches include variables to define geometric and traffic characteristics with statistical analysis such as Loglogistic and Gamma distribution (Negative binominal), the variables of these models are related to traffic volume, distance, type of road, number of crashes, crash costs, crash density and the probability of occurrence according to the severity of the crash (Kustra, Żukowska, Budzyński, & Jamroz, 2019).

Velloso and Prudéncio (2012) in their study on pedestrian fatalities on rural roads passing through urban areas, perform a basic statistical analysis of the risk of crashes, since they have a mixture of the characteristics of a rural road with those of an urban road, where high speeds, wide roadways, high vehicle capacity can be observed and with heavy vehicle traffic, lack of facilities for vulnerable road users, high number of accesses on both sides of the road, cyclists and motorcyclists riding on the road, pedestrians crossing at any point of the road, among others, which is a very common feature in middle and low income countries where the suburbs of the cities are located.

Some authors (Galgamuwa 2019, Liu 2018, Erdogan 2015, Zhou 2015) propose spatial models, these analysis are performed by integrating quantitative methods with a Geographic Information System (GIS), identifying crash hotspots (crash frequency, crash rate and crash severity) with spatial statistical methods such as Moran's I Estimation, GetisOrd G and Kernel Density Estimation to apply actions to reduce the probability of road crash. Spatial road safety models consider crash data, traffic data and road infrastructure design variables. These models are generally developed as a simple regression equation (Safety Performance Function - SPF) where the spatial correlation considers multiple variables at the same location (Yannis, et al., 2016).

Based on this literature review and considering the scope of this research, a multiple correspondence analysis and a spatial analysis using a Kernel density plot are applied to identify the areas with the highest concentration of fatal crashes in the study area.

3. METHOD

According to the official data provided by the ANSV, the information was validated and processed. The road accident rate of the department of Cundinamarca and specifically for the municipality of Soacha for the period 2014-2018 was analyzed. A descriptive statistics analysis was performed with the statistical software RStudio® and we define the variables that have an impact on crashes, making groups to standardize the information. Subsequently, an extensive process of organization and georeferencing of the data was carried out to guarantee the accuracy of the information used for the study, from which the preliminary description of the road accident rate in the municipality was obtained (Forigua, et al., 2020).

The next step continues with the analysis of the points and periods with the highest concentration of crashes in the road network of the municipality, and we apply the multiple correspondence analysis of the variables that affect the response of crashes. After this analysis a Geographic Information System (GIS) was implemented to represent the spatial behavior of road accident rates by creating and designing base maps that illustrate the accident hotspots in different scenarios.

Based on these results, we propose a field inspection in the points with the highest concentration of crashes, followed by a new spatial analysis including variables on traffic, geometric design, signaling and other road infrastructure in order to suggest preventive and corrective recommendations to reduce the number of crashes in these areas and, consequently, contribute to the reduction of accident rates in the municipality.

4. RESULTS

For the development of this research, data from the Police Crash Report - IPAT collected by the National Crash Registry – RNAT, providing 100 attributes associated with each of the crashes presented in the country for 12 years. The distribution of the databases is shown in Table 1.

RNAT	Observations	Variables
RNAT_A	2,451,804	24
RNAT_H	2,692,050	2
RNAT_ML	4,331,376	8
RNAT_S	2,569,877	35
RNAT_V	7,858,013	31
TOTAL	**19,903,120**	**100**

Table 1. Observations and variables of road accident databases.

All the information was rigorously treated and a database was consolidated with the information of 4598 crashes between the years 2015 and 2018 for the municipality of Soacha. The distribution of these crashes according to the year of occurrence and the composition comparisons for 2015 to 2018 is shown in Table 2.

Year	Crashes	Passenger Car Occupants	Small-Truck Occupants	Heavy-Truck, Buses	Motorcyclists
2015	1,427	38%	34%	15%	12%
2016	1,141	39%	34%	11%	16%
2017	1,105	41%	33%	11%	14%
2018	925	41%	30%	14%	15%
TOTAL	4,598	40%	33%	13%	14%

Table 2. Crashes composition per year

According to the analysis of these information the following relevant aspects are identified:

- Regarding the severity of the accident, 65% present only economic damages, 32% injured, and 3% are with fatality.
- According to the type of accident, 81% correspond to collisions between vehicles, 18% to pedestrian collisions and 1% to vehicle rollovers.
- In terms of the type of vehicle responsible for the accident, 40% are trucks, 24% are buses, 13% are motorcycles, 13% are passenger cars, 6% are bicycles and 4% are taxi.
- In terms of the type of road infrastructure where the accidents occurred, 85% occurred on a stretch of road and the remaining 15% at intersections.
- In the area where road accidents occurred, 61% occurred on the "Autopista Sur" corridor and 39% in the urban area.
- In terms of the weather conditions when the accidents occurred, 97% occurred in normal weather and 3% in rainy weather.
- In the time of the week when the crashes occurred, 55% were on weekdays and 45% on weekends.
- In terms of the time of day when the crashes occurred, 32% occurred in the afternoon, 28% at night, 27% in the morning and 13% in the early morning.
- In the age ranges of people involved in road crashes, 36% were young people under 29 years of age, 28% were people between 30 and 39 years of age, 24% were people between 40 and 59 years of age, and 11% were people over 60 years of age.
- In terms of the gender of the people involved in the crashes, 92% were men and 8% were women.
- In terms of the agent that caused the crashes, 89% were caused by drivers, 9% by pedestrians and 2% by road infrastructure.
- In terms of the causes of road crashes, 92% were related to the behavior of people, 4% are related to the consumption of substances, 2% to the infrastructure, and 2% with excessive speed.

With the georeferencing of the crashes, it was possible to establish spatially the points where road accidents are occurring in Soacha, taking into account the severity of the accident. The spatial density of the crashes is shown in Figure 1.

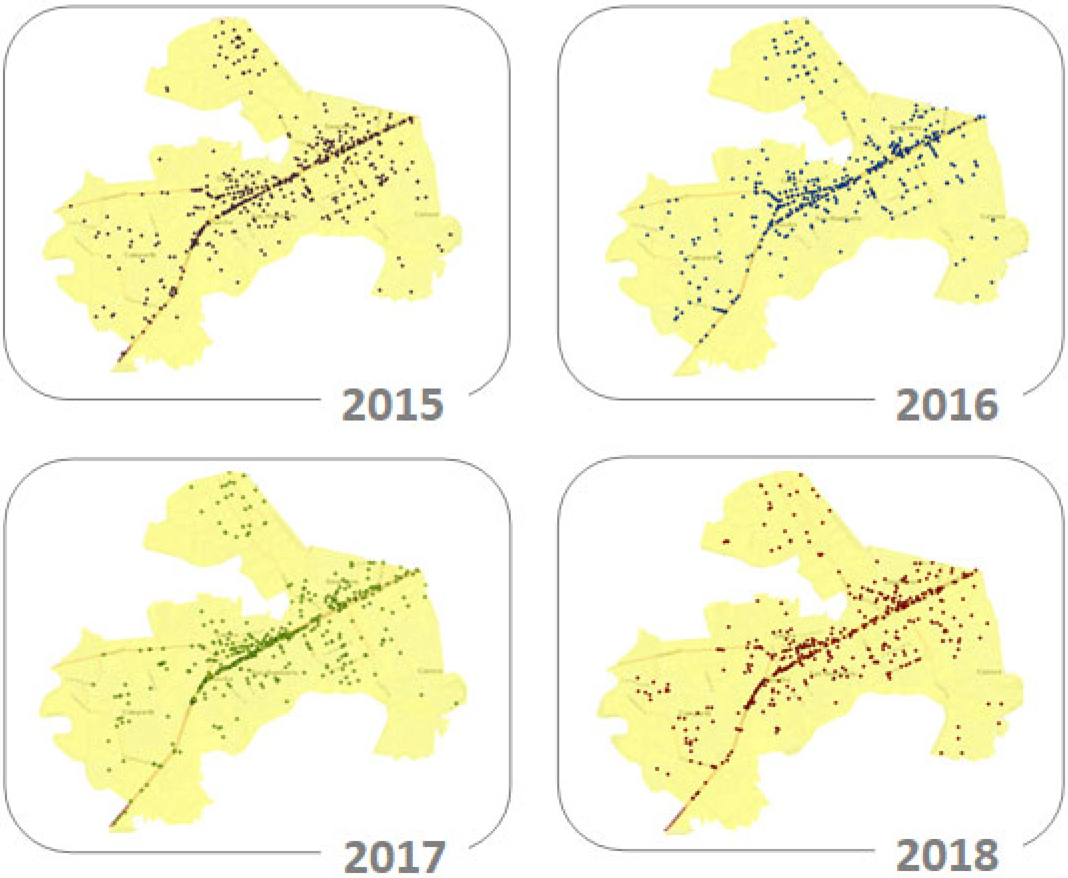

Figure 1. GIS crash localization per year. (Bermudez, Sanchez, Forigua, & Lyons, 2021)

5. ANALYSIS AND DISCUSSION

According with the statistical results, we observed that there are severity features in 35% of the crashes, 40% involves trucks and 61% occurs on the highway, these results confirm that the greatest risk is on the rural roads crossing the urban area particularly for freight vehicles.

We identified in the municipality of Soacha that main crashes do not occur at intersections, 85% of the infrastructure risk is found in continuous segments of roads, which is different from study cases in literature review.

Analyzing the immediate causes defined by the traffic police who report the crash, 98% of the responsibility for the accident corresponds to human factor and 2% to the infrastructure, however, the report does not identify the root cause of the crash.

According to the multiple correspondence analysis, the normal weather variables, throughout the day, during all days of the week do not contribute to the behavior of the accident rate in the municipality of Soacha.

In the spatial analysis of crashes with a GIS, it was possible to identify that the severity of road accidents occurs on the national road that crosses the urban area, confirming the argument of the authors Valenzuela and Burke (2020), where they state that the greatest risk of accidents occurs on this type of roads, because they have characteristics of national roads, but integrating characteristics of urban roads. Figure 2 shows the concentration of fatal crashes on the highway in the municipality of Soacha, while crashes with injuries occur in general throughout the urban area, but with a higher concentration on the national road.

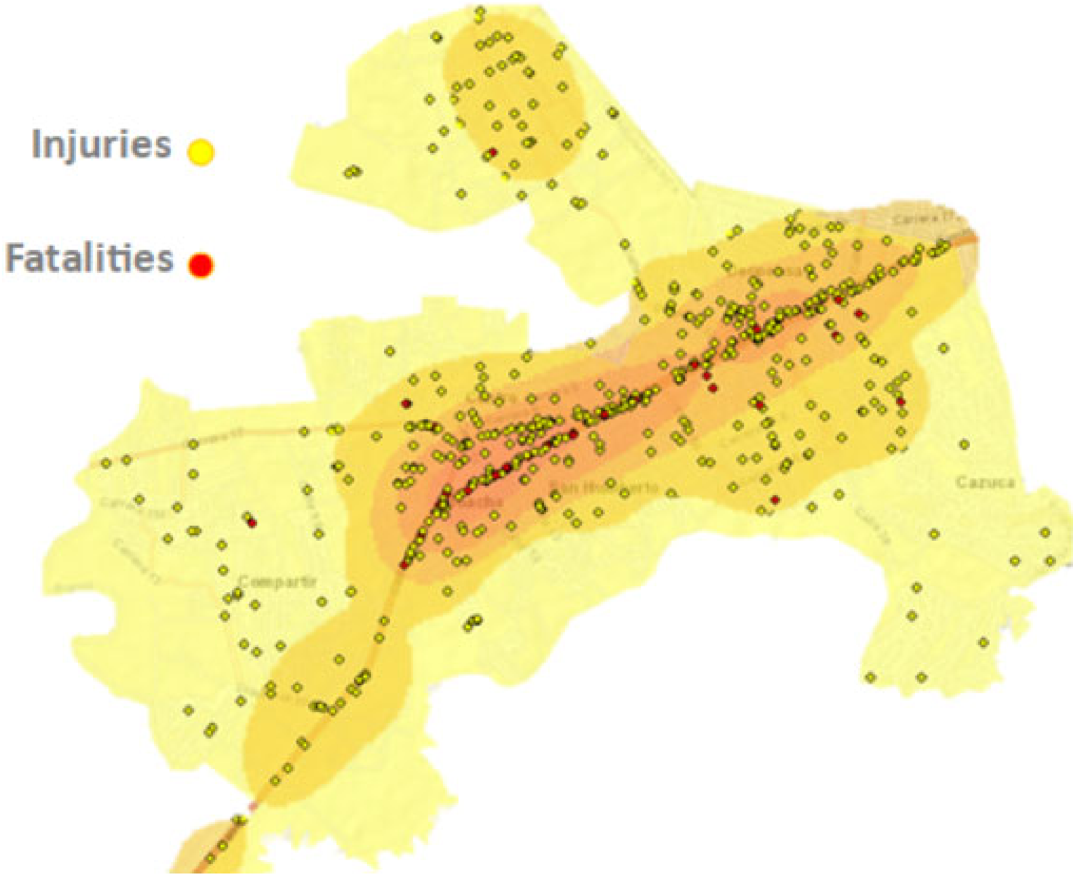

Figure 2. Severity GIS crash localization. (Bermudez, Sanchez, Forigua, & Lyons, 2021)

In the multiple correspondence analysis between the different variables mentioned in the descriptive statistics, it was possible to estimate the behavior of the variables due to the contribution of each one in the road accident problem. The crash hypothesis variables (HIP), immediate cause of the crash (CAU), crash class (CLA), crash severity (GRV) and type of vehicle (VEH), mainly denote a greater contribution to the behavior of the crash rate in the municipality of Soacha, Cundinamarca. The contribution of the variables is shown in Figure 3.

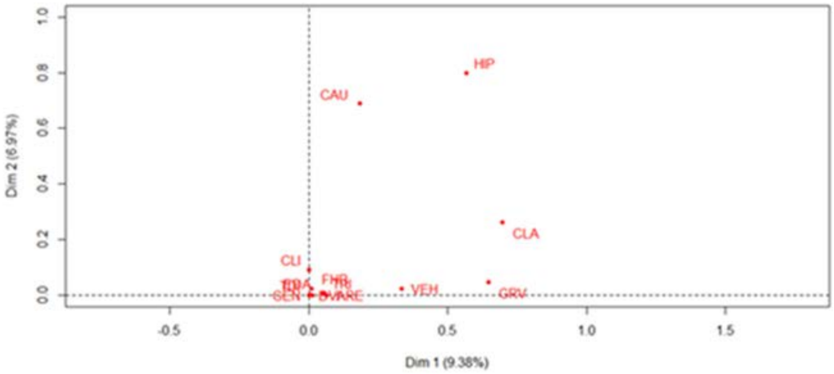

Figure 3. Contribution of variables in the multiple correspondence analysis. (Forigua, et al., 2020)

Variables related to the seasonality of accidents, weather conditions, age and gender characteristics do not contribute to the explanation of road accidents in the municipality of Soacha. Five dimensions explain 70% of the variability of data.

6. CONCLUSIONS

The traffic in rural roads that cross urban areas of conurbation municipalities represent a higher risk of crash severity.

The literature identifies studies that have shown that the use of different hot spot detection models leads to different results. In this research, multiple correspondence analysis together with spatial analysis supports the evaluation of variables involved in crashes.

These research continue with spatial analysis including variables on traffic, geometric design, signaling and other road infrastructure in order to propose preventive and corrective recommendations to reduce the number of crashes in these areas and, consequently, contribute to the reduction of accident rates in the municipality.

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AGENT-BASED SIMULATION MODEL OF BUS EVACUATION EVENTS

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ABSTRACT

The time required for the evacuation of the occupants of buses and coaches, that is, Large-Dimension Passenger Transport Vehicles (V.G.D.T.P.) is a fundamental safety parameter for these vehicles. Starting from the fact that they are a mode of transport with very high levels of security, when events with collision and subsequent fire occur, or in cases of fire exclusively, it is when these events generate injuries or even deaths. Additionally, part of the UN CEPE regulations that affect these vehicles (e.g. R107) are defined in such a way as to reduce this evacuation time. Others, R118, are aimed at reducing the severity of the fire and, therefore, increasing the time available before suffering serious consequences.

Therefore, the need to know which are the fundamental aspects that can improve these two time intervals, evacuation and available, is concluded.

In the present work, a coach is modelled, and simulated by means of an agent-based model, both the boarding process, and the disembarkation or evacuation process. Some relevant characteristics of the model are that it allows to analyse the influence of the mobility of each agent (occupant) as well as that of the vehicle's configuration. Among others, some of the characteristics of the occupants are their average speed of movement and associated with a probability function, their size, the probability of using emergency exits (e.g. jumping through an emergency window), etc. Regarding the vehicle, the fundamental aspects contemplated in the model are those relating to accessibility to the interior of the vehicle and, once inside it in the corridors, access to the seats. Among other parameters, the width of the gangway, the distances between seats, the characteristics of the entrances, stairs, etc.

The model is used to analyse the influence of the variability of each of the occupant and vehicle parameters described, and the probabilities of complete and partial evacuation times are deduced. Based on these results, it is concluded that the exits locations, and the age (mobility) of the passengers are the main parameters influencing the probability of a high evacuation time,

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1. INTRODUCTION

Transportation by bus or coach is a means that has proven to be very safe for its occupants. However, given that they are a means of collective transport, and on many occasions public, the agents involved in the design, approval and use of these vehicles continue to seek to reduce the consequences of their accidents.

One type of accident that occurs with some frequency is fire. These accidents, in which the total or partial fire of the vehicle takes place, normally only have material consequences.

Fundamentally, the vehicle is damaged or partially destroyed. The absence of injuries to the occupants is mainly due to the design of the vehicles that is defined for a fast enough evacuation. The characteristics that buses and coaches must meet to ensure that they are safe in the event of an incident are defined in United Nations Regulation R107. UNECE. WP29. (2018). This regulation defines the maximum and minimum dimensions of each of the parameters that affect safety, including those related to evacuation, dimensions of service doors, emergency exits, etc.

However, and despite the measures ensured in the vehicle type-approval process, from time to time, an incident with fire in a bus, or coach, has as a consequence a significant number of victims. Often these incidents, with fire and serious consequences for the occupants, are the consequence of a collision prior to the fire and a, for different reasons, defective faulty evacuation. This was the case of the accidents that occurred in Bailen Spain (1996) and in Puisseguin, France (2015) with 28 and 43 deaths respectively.

The importance of evacuation, or more specifically of the speed of evacuation of the vehicle, lies in the need to minimize the risk of loss of consciousness due to the inhalation of gases from combustion. There are many studies that analyse the evacuation times of infrastructures, and also some of means of transport including coaches. Some of these studies are carried out by means of evacuation tests, one of the most relevant is the one carried out by JK Poland and SH Markos (2009) where they measure times of passage through different types of emergency exits, service doors, windows, hatches, and used different lighting conditions.

However, all these studies cannot be exhaustive in terms of the profile of the passengers involved in the drill, or the variety of vehicle models based on their interior configuration, entrances and exits. That is why it was decided to approach the study by simulation with a stochastic model that allows to obtain with fidelity an interval of evacuation times associated with a probability of occurrence.

2. OBJECTIVE

Through this WORK, it is intended to carry out an evacuation model for vehicles of class M2 and M3, commonly known as buses or coaches, using the service doors and, also, analysing the probability of using the windows as an emergency exit. This objective has been raised by observing that in certain accidents, in which the vehicle

For this, some partial objectives have been met, which are:

1.- The characterization of the mobility of people, so that the analytical model allows determining the interval of evacuation times of the vehicles, based on the characteristics of the travellers, and the probability associated with each value of evacuation time of the vehicle. model.
2.- The characterization of the vehicle, so that by introducing the plan of the vehicle and the characteristics of the accesses, the evacuation time can be determined.
3.- By using the vehicle model, and the mobility of the agents (passengers), obtain valid results and conclusions on the following factors:

- Evacuation times and uncertainty in their determination.
- Influence of the characteristics of the passengers on the evacuation time.
- Influence of the plant and the distribution of the vehicle.

Finally, the model can be used to obtain an optimal configuration and determine possible improvements to reduce evacuation times, referring to both passenger education and vehicle layout.

3. METHODOLOGY

The model has been developed using the AnyLogic software. This code uses agent-based simulation algorithms and is supported by the Java language. An advantage of this software is that it allows to perform dynamic simulations, discrete events simulations and combined models applying a stateflow to a continuous dynamic model. This type of models allows assigning individual characteristics to each passenger (and vehicle), modify these characteristics during the simulation process, as well as defining the interactions passenger-passenger and passenger vehicle. It is taken the advantage of the fact that AnyLogic already has implemented the internal algorithms for the movement of individuals and the interactions between them.

To analyse the evacuation, the coach layout is modelled based on the requirements reflected in Regulation R107 of the UNECE. In this model, three dimensions are chosen as critical: distance between seats, aisle width and door width. In the standard coach used to determine passenger influence, the aisle is 530 mm wide, the seats are 720 mm apart, and the front and rear doors are 800 and 700 mm wide, respectively. The rear door is located in front of the rear axle, as is common in many M3 Class III vehicle configurations. Stairs are defined as an area in which passengers see their speed reduced to 50%.

The movement of passengers has only been defined by the maximum speed they can reach and by their size. For this, and because the achievable speed is not determined by the size of the vehicle aisle, for values from 40 cm as demonstrated by Huang, S. et al. (2018), various studies on achievable speed according to age are analyzed (Bohnannon 1996 and 1997; Capote 2011; Chiu, 2007; hoogendoom, 2005 and Spearpoint, 2012) and it is decided to use normal speed distributions for each group decreasing with the age, and increasing fixed sizes. This variation is very marked when reaching the third age.

The movement of passengers has been defined considering the maximum speed that they can reach in a corridor (Huang, 2018), and by their size, which determines their mobility. The maximum velocity has been characterized by an approximation to a normal probability distribution assigning the value of the mean and the standard deviation.

To analyse the influence of passengers, simulations are carried out by varying the age distribution within the vehicle. Evacuation is designed as a process in which passengers initially go to the nearest door, since they do not know if it is possible to open that door. Subsequently, and after checking whether it is possible to open the doors, the passengers head towards the available doors following the same principle of proximity. During the entire evacuation time, passengers periodically check if the condition of the doors has changed and after 60 seconds, they begin to consider using the windows as exits (Aparicio, et al 1996).

3.1 Vehicle plant model

This plant of the vehicle is defined by several wall-type elements (Wall). The strange shape of both doors is due to the fact that the entire simulation must take place within a closed wall and because we want to consider that the passenger has left the vehicle once they have managed to cross the line that runs along the side of the coach. Striped areas are areas where passengers cannot enter.

Next, the lines (Target Line) that act as doors are drawn and also another, continuous, on the entire left side that simulates the emergency window. It is decided to simplify the window in this way since it is not used as the main exit in a real evacuation. The hatches are not included and are not used in the case of no overturning.

Lastly, the seats are modelled. The seats are represented by their positions. These positions are fixed by Attractor elements. As the Attractor elements are linked to an area, the area areaAreasSeats is defined and the points are marked on it. The Final model of the vehicle is shown at Fig. 1.

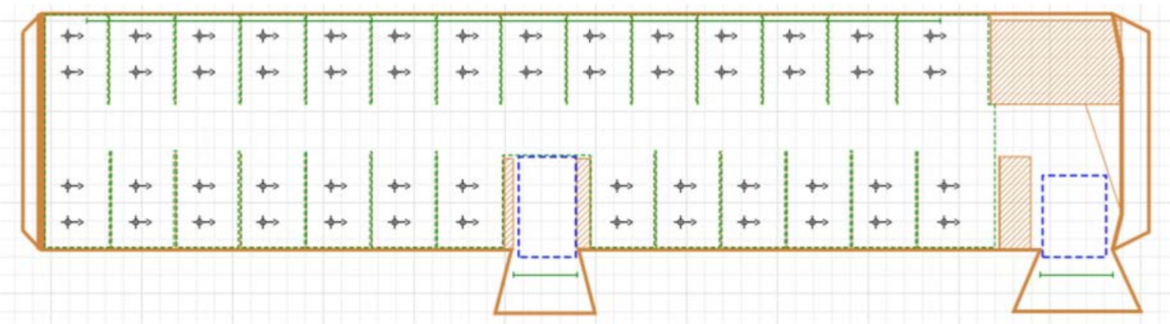

Fig. 1. Complete model of the vehicle plant.

3.2 Passenger model

Before modelling the passengers, it is useful to know the limitations that AnyLogic has when it comes to simulating a Pedestrian-type agent. Passengers are created in a block Ped Source has three mandatory parameters: size, initial speed and maximum speed. The latter, called Comfortable Speed, is the maximum speed at which it travels if there are no obstacles on the road.

Other internal variables of the passengers are also created, which are explained after the three that are indispensable.

3.2.1 Passenger Size

The main limitation in the size of the agents is the size of the coach aisle itself, which is the smallest dimension of the vehicle. Because the agents are represented as circles, it is necessary to check the appropriate size not to create agents that cannot access into the vehicle.

Through test simulations, it has been found that passenger diameters greater than 0.30 meters pose serious problems during evacuation and, therefore, prevent passengers from approaching this size in any evacuation. The lower diameter limit is less critical, but is set at 0.15 meters for very agile passengers or children. This size allows one passenger to outrun another down the aisle.

Therefore, a standard population distribution will contain passengers between 0.15 and 0.25 meters, indicating greater and less mobility and agility, respectively. Each population group will have a fixed size.

3.2.2 Confortable Speed

AnyLogic defines this speed as the speed at which the agent moves in the absence of external factors. In the simulation it will be the maximum speed at which the passengers can move inside the bus. In the simulation, it cannot be considered that there is an absence of external factors.

The backs of the seats act as walls that make the officers stop and they can never move at the speed that is chosen as comfortable. For this reason, the speed values that are finally applied are slightly lower than the movement of a person in an aisle.

The speed of the passengers depends mainly on the age since the gender barely has an influence of between 10 and 15%, which is considered negligible in order to simplify the model. The dependence of speed with respect to age is decreasing, with a more pronounced influence after 60 years of age, and as age increases, the uncertainty in determining said speed also increases.

Group	Reference	Avg speed (m/s)	Standar dev. (m/s)	Size Φ (m)
< 30 yo	G1	2	0,1	0,17
[30 yo: 50 yo]	G2	1,8	0,1	0,2
[50 yo: 65 yo]	G3	1,7	0,2	0,2
[65 yo: 80 yo]	G4	1,3	0,15	0,23
> 80 yo	G5	0,8	0,1	0,25

Table 1 – Passengers study groups

In this way, only the percentage of passengers belonging to each group will have to be established to run the model.

3.2.3 Initial velocity

The initial speed of an agent is the speed with which it is generated in the Ped Source block. It is verified that changes in this value have no influence on the results obtained, since, in the evacuation, the agents start at zero speed from their seats. Therefore, it is set at 0.5 meters per second, the value that AnyLogic assigns by default.

3.4 Validation

Once the construction of the model is finished, four experiments of a thousand test simulations are carried out to analyze if values similar to those found in the literature in simulations and in models are achieved based on the following factors: times used, standard deviations of the times, trends with the variation of passengers and trends when locking the doors.

When carrying out the four experiments and checking the influence of the erroneous simulations, between 1 and 2%, it is decided that the evacuation time taken as a reference will be the time95, since on certain occasions the last two passengers take illogically high times in get out of the vehicle.

When the time95 is excessively high and goes outside the range of times determined by the other simulations, this data is eliminated from the analysis. The loss of 1% of the data is considered acceptable for the statistical analysis.

This is verified by ordering the results from highest to lowest and eliminating those that are 2 seconds or more apart from the next.

The four experiments carried out for the validation, with their results, are shown at table 2:

Run	**Available exits**	**Age**	**AVG (s)**	**Standard Deviation (s)**
1	Front + Rear	100% Young	*53,5*	*5,9*
2	Front + Rear	100% Above 65	*74,4*	*7,5*
3	Front	100% Young	*68,7*	*12,6*
4	Rear	100% Young	*101,0*	*7,1*

Table 2 – Validation Runs

The values obtained, although they differ slightly from other models, are close and follow the same trends as them. So, the model is considered correct as an explanatory method and as a correct estimate of evacuation times for the following reasons:

- Times when evacuating in similar conditions are similar, although slightly higher than in drills. This increase in time is followed by all the models studied and is considered to correct the preparation and learning of the participants in a drill.
- The standard deviation is in the existing values in other models and correctly corresponds to what is expected and found in other stochastic models.
- Locking a door produces time increases of the same order as in drills and models. In this case, the blockage may involve increases between 30 and 90%.

3.5 Evacuation study

Once considered that the model represents the best state of art of evacuation simulations it was used to perform three independent analysis: Analysis of the standard evacuation, Analysis of the influence of the passengers' characteristics and Analysis of the influence of the vehicle configuration

3.5.1 Standard evacuation analysis

The standard evacuation process study employs a population distribution similar to that of aerial evacuation. For the standard evacuation, passengers are chosen from the first four groups, in such a way that it is considered a worse situation than that assumed by the air regulations. G5 passengers, who are very elderly, are not included, because the usual drills do not use people with reduced mobility or who could be injured.

POPULATION GROUP	PERCENTAJE
Jóvenes – G1	30%
Media edad – G2	40%
Mayores de 50 – G3	20%
Mayores de 65 – G4	10%

Table 3 – Vehicle passengers distribution configuration

Regarding standard evacuation, the following parameters are studied:

- Normal development of the evacuation and shape of the time-passengers graph
- Development of evacuation with only one available door
- Door Blocked during the evacuation.

3.5.2 Passengers characteristics influence analysis

To study the influence of passengers, the distribution of speeds and sizes will be varied, separating them from the previously defined as standard distribution. The following experiments are performed with the following distributions:

NÚMERO EXPERIMENTO	JÓVENES	MEDIA EDAD	MAYORE S DE 50	MAYORES DE 65	MUY ANCIANOS
1	100%	-	-	-	-
2	80%	20%	-	-	-
3	-	100%	-	-	-
4	20%	40%	20%	20%	-
5	-	-	100%	-	-
6	-	20%	40%	40%	-
7	-	-	-	100%	-
8	-	-	10%	70%	20%
9	-	-	-	50%	50%

Table 4. – Experiments to study the influence of passengers

The evacuation times and the standard deviations in each case will be analysed, checking how they vary when the distribution of passengers in the coach changes and trying to obtain an estimate of the evacuation time through linear regression.

3.5.3 Vehicle characteristics influence analysis

Considering the standard passenger distribution – defined at para 2.5.1. –, relevant parameters of the coach seat layout are modified to see how they influence the evacuation.

The 54 seats of the coach are maintained at all times. There are three parameters that are analysed to evaluate the coach:

- Width of the doors
- Aisle width
- Rear door position

In this base approach, the two doors are the same width as opposed to the standard evacuation and the corridor is reduced up to 500 mm in its narrowest configuration. The experiments to be performed are shown below.

The increase of the aisle to 600mm is unrealistic and exceeds the legal limit, even taking into account the adaptations of the model, but it is included when considered interesting.

Experiment number	Door width	Aisle Width	Door location
1	700 mm	500 mm	Middle
2	700 mm	500 mm	Rear
3	700 mm	550 mm	Middle
4	700 mm	550 mm	Rear
5	800 mm	500 mm	Middle
6	800 mm	500 mm	Rear
7	800 mm	550 mm	Middle
8	800 mm	550 mm	Rear
9	700 mm	600 mm	Middle
10	700 mm	600 mm	Rear
11	800 mm	600 mm	Middle
12	800 mm	600 mm	Rear

Table 5– Experiments to study the influence of the vehicle

4 EXPERIMENT RESULTS AND DISCUSSION

4.1 Standard evacuation analysis

As it was presented in the paragraph dedicated to the methodology the objective was to characterise de variability of the evacuation process. To perform this characterisation, it the corridor average $\pm\ 2\cdot\sigma$ was represented considering each percentage of the passengers evacuated.

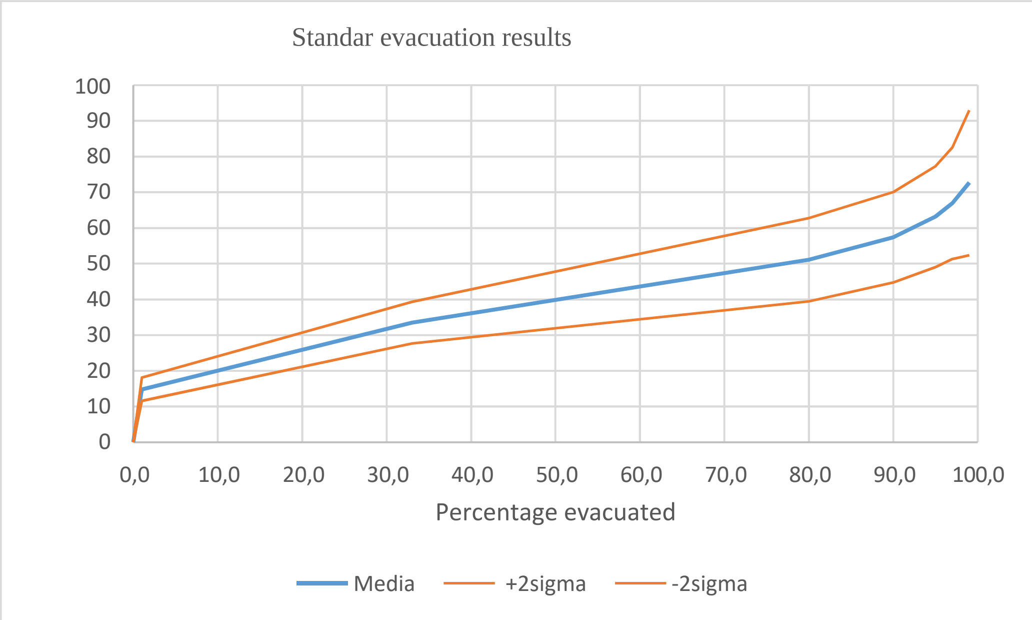

Fig. 2 Standard evacuation Charaterisation

From this standard evacuation and the filtered graphs, the histogram of the value time95 is obtained, the one chosen as the representative time of the evacuation, which is used as a reference to compare other experiments.

The distribution followed by the results of each time has also been studied using the SPC extension for Microsoft Excel. Despite the fact that sometimes follow the Beta4 distribution, it is chosen to define them by means of a log-normal distribution, since this is better adapted to all cases on average.

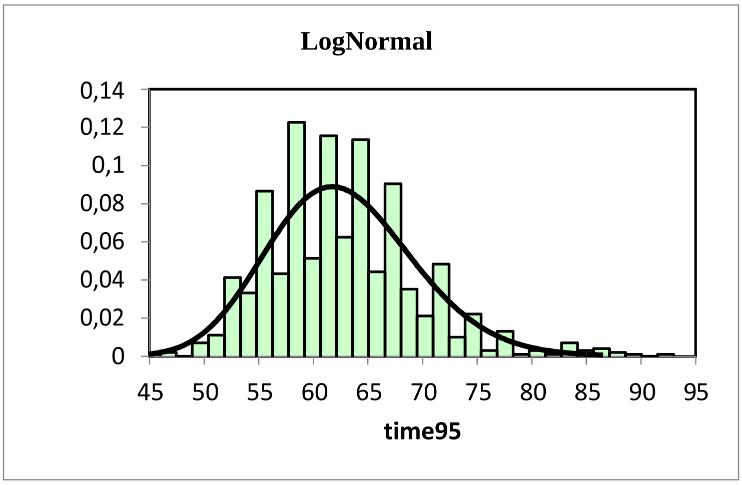

Fig. 3. Time 95 evacuation distribution

4.1.1 Standard evacuation with on door Blocked before the evacuation start

Studies with only one available door are carried out with the standard passenger distribution, obtaining the results shown in the table. During the obtaining of results, it is observed that when evacuating through the rear door there are an average of 12.2

passengers who use the emergency window. For this reason, another experiment is carried out in which the emergency windows are not used. The standard evacuation process through the two doors is included for comparison.

Experiment	Averrage Evacuation Time (s)	Standard deviation (s)
Standard, two exit doors	*62,7*	*6,8*
Front door	*78,4*	*13,6*
Rear door	*109,5*	*10,5*
Rear door and windows	*104,8*	*6,9*

Table 6. – Experiments with only one door available

A clear increase in evacuation times is observed when evacuating with a single door compared to when evacuating through both. This increase is 25% when the door is locked at the back and 75% when the front door is locked. This second case is more common when it comes to frontal crashes or when the fire starts in the front, for example, in the tank or in the front brakes.

The use of the emergency windows in the case of evacuating only from the rear does not significantly affect the times.

The standard deviation also increases with increasing evacuation time: it doubles with the rear locked and 55% more when the front is locked. The fourth experiment shows atypical results, since the standard deviation does not increase with respect to the standard evacuation, something that can only be explained assuming that the people that abandon the vehicle through the windows have less variability and the number of the passengers that exit through the doors is reduced by the same amount.

4.1.2 Standard evacuation with on door Blocked during the evacuation

This experiment considers the situation where some passengers start the evacuation through both available doors, and at some point – e.g. Bailén accident – one of the doors is blocked.

It is decided that the door block occurs when 40% of the passengers have evacuated, in order to observe its influence from time to time50.

Two experiments are performed, the first blocking the front door and the second blocking the back door. In this case, the use of emergency windows is allowed, which are used by a variable number of passengers between 0 and 8, considered reasonable in the face of the panic situation that would be generated.

Below are the evacuation times when the front door is blocked and when the rear door is locked:

% Evacuated	T1 (s)	T25 (s)	T50 (s)	T80 (s)	T95 (s)
Media	*14,3*	*23,6*	*38,0*	*63,9*	*81,5*
Desviación típica	*1,7*	*1,9*	*3,6*	*4,1*	*13,8*

Tabla 7. - Results with blocking the front door during evacuation

% Evacuated	T1 (s)	T25 (s)	T50 (s)	T80 (s)	T95 (s)
Media	*14,3*	*23,6*	*35,3*	*54,7*	*65,7*
Desviación típica	*1,7*	*2,0*	*3,7*	*4,6*	*7,4*

Table 8. - Results with blocking the rear door during evacuation

The development of both evacuations is identical until any of the doors is blocked. From that moment on, all passengers head towards the only one available, or towards the emergency windows if the conditions are met. This difference is observed from time50.

From then on you can consider a situation such as where only one door is available. The same trends are observed as in the previous case: a substantial increase in time when the available door is the rear and this is in an intermediate position of the vehicle.

Rear lockout assumes an average of 16 more seconds of evacuation for the last 30 occupants, or 50% more time since lockout occurs.

The drift of the data also increases with the elapsed time due to the same reasons as in the previous cases: an increase in time implies a greater probability of a blockage in the continuous flow of passengers. This blocking is favoured if two flows mix, as happens when evacuation is through the back door.

4.2 Passengers characteristics influence analysis

As has been performed in the previous analyses, the reference value considered as the evacuation time is the value time95. The results of erroneous simulations are eliminated and the means and standard deviations of the experiments carried out are found.

Finally, a linear regression is carried out in order to estimate the evacuation time of the vehicle as a function of the distribution of passengers. To carry out the study, the results of means and standard deviations of the standard evacuation and the other nine experiments carried out were used.

Young	Mid age	Above 50	Above 65	Above85	avg (s)	SD (s)
1	0	0	0	0	*55,8*	*5,5*
0,8	0,2	0	0	0	*57,3*	*5,6*
0	1	0	0	0	*62,9*	*6,6*
0,2	0,4	0,2	0,2	0	*66,1*	*7,7*
0	0	1	0	0	*65,2*	*7,1*
0	0,2	0,4	0,4	0	*72,4*	*8,8*
0	0	0	1	0	*82,9*	*9,4*
0	0	0,1	0,7	0,2	*101,2*	*16*
0	0	0	0,5	0,5	*128,2*	*18,2*
0,3	0,4	0,2	0,1	0	*62,7*	*6,8*

Table 9 - Percentage of passengers and evacuation results obtained

If a qualitative analysis of the results is carried out, it is observed that, indeed and as expected, the evacuation time grows with the presence of older passengers and therefore slower and less agile.

The big differences in evacuation times occur when dealing with very elderly passengers and with reduced mobility due to age. The presence of these passengers significantly increases the time required to evacuate the vehicle. While the presence of passengers over 65 in good physical condition increases the time by 49% compared to young people, the fact that half of these passengers have mobility problems increases the time by 150% compared to the initial proposals.

In turn, it is observed that the standard deviation increases when the mean evacuation time increases. This indicates that the results of each simulation are more different from each other the slower the entire evacuation process is carried out.

4.3 Vehicle characteristics influence analysis

The results of the experiments defined at paragraph 2.5.3 are collected in the table below:

Experiment number	Door width (mm)	Aisle width (mm)	Door location	Average (s)	SD (s)
1	700	500	Middle	*66,5*	*15,0*
2	700	500	Rear	*53,3*	*6,0*
3	700	550	Middle	*69,3*	*15,0*
4	700	550	Rear	*53,6*	*5,9*
5	800	500	Middle	*66,0*	*12,9*
6	800	500	Rear	*49,9*	*5,0*
7	800	550	Middle	*67,4*	*11,6*
8	800	550	Rear	*51,1*	*5,6*
9	700	600	Middle	*74,6*	*16,5*
10	700	600	Rear	*54,2*	*6,2*
11	800	600	Middle	*71,5*	*12,5*
12	800	600	Rear	*51,0*	*5,0*

Table 10 - Results of the experiments on the influence of the vehicle

In the results it is observed at a glance that the constructive parameter that has the most influence is the position of the rear door. An increase in standard deviations is also observed, linked to the increase in evacuation time. The slower the output, the more difficult it is to predict.

Focusing first the analysis on the average evacuation time a 100 mm increase in the width of the doors causes a minor decrease of 2.4 seconds in the evacuation time. This is due to a greater ease of leaving the vehicle for passengers.

The increase in the width of the corridor causes an increase of 3.9 seconds in said time.

This result is inexplicable and needs further experimentation. If correct, it could be because, with a wider corridor, several people could try to move through it simultaneously, impairing the normal flow of people towards the door.

Placing the rear door at the end of the seats is the factor that most influences the evacuation time. When the door is located in the back of the bus, the passengers are distributed more or less evenly between the two doors and, in addition, the flows towards both doors are unidirectional so that traffic jams are not created either. Placing the door at the back of the coach reduces the estimated evacuation times by 17 seconds and the standard deviation of the simulations by 8.3 seconds.

Broadly speaking, the position of the door has seven times more influence than its width and four times more than the width of the corridor.

5 CONCLUSIONS

It has been developed a bus and coach evacuation model that allows a stochastical analysis of the influence of vehicle and passengers variables.

The model has a good behaviour compared with evacuation drills performed by relevant transport safety institutions as INSIA in SPAIN and RISE in Sweden. The S shape behaviour of the evacuation percentage vs time curve is also coherent with the drill results.

The passengers profile may lead to double the time needed for a full evacuation of the vehicle in case of emergency, this value, even being significantly high is a result that can been used to define the burning behaviour of the materials used for vehicle interiors.

Considering the vehicle design a door blocked can slow down the process by 25-65%. The consequences are much more severe if the blocked door is the front one, which is usually the most common due to a frontal collision. These trends are also observed when the blockage occurs with the evacuation in progress.

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AD HOC MINIMUM SEPARATION: A CHALLENGE FOR AIR TRAFFIC CONTROL (ATC)

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ABSTRACT

The SESAR programme aims at developing the future European air traffic management system. It focuses on four keys areas: capacity, safety, efficiency and environment. In view of the expected growth in air traffic demand in the coming years, the current goal is to increase the airspace capacity, which is already close to saturation in many cases.

Currently, the separation standards applied in a given volume of airspace are fixed, both horizontally and vertically, which means that in many cases this is one of the determining factors of capacity. Separation management is an area where improvement is sought, in particular through the application of new operational concepts (separation modes) which include the redefinition of aircraft separation minima. One of the solutions to be investigated is the variable (Ad Hoc) separation proposal put forward by SESAR.

This future concept implies a change in the application of separation minima from the current fixed standards to a new variable approach. With this new concept, ATCo (Air Traffic Controller) would separate aircraft by applying different separation minima in the same volume of airspace. These separation values are tactically determined for each particular aircraft pair (Ad Hoc) depending on a number of factors: aircraft categories, encounter geometry, atmospheric conditions, etc.

Applying different separation minima in the same volume of airspace implies a substantial change in some of the ATC activities. Also, new functionalities in ATC support tools are needed. This study presents the Ad Hoc separation operational concept and provides the basis for the development of the algorithm for calculating variable separation minima.

1. INTRODUCTION

The SESAR (EUROCONTROL, 2020a) and NextGen (FAA, 2019) programmes in Europe and the United States are aimed at developing the future air traffic management (ATM) system. They are geared towards achieving benefits in four areas: capacity, safety, efficiency, and environment. Both programmes envisage a transition from the current system to the implementation of new operational concepts over the coming decades (BROOKER, 2011).

Since 2014 in Europe there has been a steady growth in air traffic. The year 2018 saw an all-time record of 11 million flights in European Civil Aviation Conference (ECAC) airspace, an increase of 4% over 2017 (EUROCONTROL, 2020a). Last year 2020, as a consequence of the global pandemic resulting from COVID-19, traffic levels dropped drastically (by more than 50% compared to 2019 levels (EUROCONTROL, 2021)). However, a recovery of the sector is expected in the coming years and a return to air traffic growth levels is foreseen. The most reliable traffic forecast scenarios anticipate, by 2040 in ECAC, more than 15 million flights per year (EUROCONTROL, 2020b) . In order to meet this expected growth in demand in the coming years, solutions must be found to increase current airspace capacity in some scenarios already close to saturation.

The separation standards applied in a specific volume of airspace are fixed, both in their horizontal and vertical dimensions (PÉREZ-CASTÁN et al., 2020), which means that in many cases this is one of the determining factors of its capacity. Additionally, the separation minima that are currently applied in a specific volume of en-route airspace were determined decades ago (REYNOLDS & HANSMAN, 2000) when the existing navigation, communication and surveillance systems did not provide the performance of today's systems and when the air traffic controller did not have the advanced support tools available today.

Separation management is therefore an area where improvement is sought, namely through the implementation of new operational concepts (ConOps) which include both the redefinition of the separation minima and the way they are applied. It is therefore necessary to implement a new separation mode, which consists of an approved set of rules, procedures and conditions of application associated with separation minima (ICAO, 2008).

Separation minima studies started with Reich (P.G. REICH, 1964) who developed the first collision risk model (CRM) in order to assess whether a reduction of lateral separation between tracks from 120 NM to 90 NM in the North Atlantic Region (NAT) was safe. Since then several authors have developed this initial CRM in order to extend its application to other scenarios and to overcome certain limitations of the model (MACHOL, 1975), (HSU, 1981), (ANDERSON & LIN, 1996), (BLOM et al., 2003). ICAO adopted the Reich and Hsu models and presented a unified derivation of these (the

Rice formula) based on a general framework (ICAO, 2009). In (BARNETT, 2000) it is proposed a CRM for safety assessment in a free flight scenario while the CRM developed in (SÁEZ NIETO et al., 2010) assesses risk in all three dimensions in an en-route scenario with radar surveillance.

This work develops the operational concept for the application of a minimum variable separation (Ad Hoc) between aircraft, already proposed in a preliminary way as a solution to be studied and developed in some ATM programmes such as SESAR (SESAR EUROCONTROL/EUROPEAN UNION, 2019). This study is organised as follows. Section 2 describes the variable separation operational concept and proposes the basis of the algorithm for the real-time implementation of the concept. Section 3 presents the approach for the reduction of separation minima, the development of which will be presented in future work. This study is concluded in Section 4.

2. VARIABLE SEPARATION (AD HOC) CONOPS

An operational concept (ConOps) is a statement of "what" is envisaged. It asks and answers what results are expected from the future ATM system. It is a vision statement (ICAO, 2005).

2.1 Operational scenario description and CNS requirements

The Ad Hoc separation concept refers to the application of a variable separation value for each aircraft pair within the same volume of airspace, depending on a set of factors (aircraft categories, encounter geometry, atmospheric conditions, etc.). This is therefore a change in the application of separation minima, migrating from the current fixed standards to a new variable approach. Thus, ATCo will separate aircraft, applying different separation minima in the volume of airspace in which the concept is implemented. Implicit in the development of this concept is the research into the reduction of separation minima in order to be able to apply new standards.

The development of this new operating mode will follow a two-step approach, similar to the RECAT project (EUROCONTROL, 2015), where initially static aircraft characteristics are considered, and at future levels a dynamic approach is adopted, considering non-stationary factors such as aircraft weight.

In the initial stage of the concept development, variable separation will be applied in a specific scenario: continental en-route airspace between the upper flight levels (FL 245 - FL 660) where control service is provided. Control sectors of low - medium complexity and traffic density are considered.

In upper airspace the aircraft mix consists mainly of medium, heavy and super heavy aircraft category according to wake turbulence.

In a first step, the airspace structure is assumed to have prefixed routes in which aircraft fly at constant altitudes. Future work will study the implementation of this concept in a free route scenario.

The fundamental factor in the Ad Hoc separation concept is the minimum separation. In this context, this term refers to surveillance minimum radar separation (MRS). However, it is relevant to consider the effects of wake vortex and thus the derived minimum separation (MWS). The variable separation minimum (DS) should always be greater than or equal to the minimum wake separation (MWS).

The main feature of this new operating mode is that there is no single fixed minimum separation value. Instead, there is a set of possible values within a range (3 NM - 5 NM, NM: nautical mile), which extreme values are:

- Upper limit value (5 NM): currently in en-route scenarios with surveillance the defined minimum separation is 5 NM.
- Lower limit value (3 NM): in en-route phase the longitudinal MWS value is considered to be 5 NM for cases where the preceding aircraft belongs to a higher category than the succeeding one. However, when the situation is the opposite, the MWS separation may be smaller (i.e., preceding aircraft of equal or lower category than the succeeding one). There are currently several projects studying the reduction of minimum wake separations and proposing new en-route MWS values: 3 NM, 5 NM (SESAR, 2018). Therefore, it has been decided to take the value of 3 NM as the lower limit of the range of variable separations. Moreover, the reduction of the ATC minimum separation is based, in first instance, on the improvement of the technical systems currently available.

In the initial stage of the development of this concept, the possible Ad Hoc separation values within the defined range will be specific (i.e., 3 NM - 3.5 NM - 4 NM - 4.5 NM - 5 NM). In future work the separation could be specified with a resolution of one tenth (0.1) in NM. These minima will be determined automatically, with a given time horizon, by the Separation Minima Tool. Ad Hoc separation values shall be determined based on a set of conditions:

- Aircraft Category (Super Heavy, Heavy, Medium or Light)
- Navigation Capability
- Surveillance Capability
- Communications Capability
- Encounter geometry
- Aircraft speed
- Wind conditions and ATC procedures.

The implementation of this concept and the consequent reduction of MRS requires aircraft to be capable of ensuring minimum performances from the improved technical systems available. Failure to comply with any of the CNS requirements would reinstate a reference separation value of 5 NM which corresponds to the current applicable standard and the maximum value of the Ad Hoc minima range.

Aircraft operating in these scenarios are required to have PBN (Performance Based Navigation) capability, in particular RNP (Required Navigation Performance). Performance-based navigation requires that for 95% of the flight time, performance related to lateral and longitudinal accuracy, continuity, availability and integrity are guaranteed. Aircraft approved to RNP navigation specifications have an on-board monitoring and alerting system capable of predicting whether the required performance (navigation accuracy) can be met with a probability greater than 10^{-5}. Communications service is available throughout the volume of airspace. Non-urgent communications would be via data link (CPDLC) while urgent communications would be oral in the VHF band.

In scenarios where this concept is implemented the ATC surveillance service shall be based on ADS technology (upgraded with GNSS). The on-board global navigation satellite system (GNSS) receiver provides the ADS-B transmitter with a position accuracy indicator (figure of merit, FOM) and a position integrity indicator (horizontal protection level, HPL) together with other data (ALI et al., 2016). It is a prerequisite that the figure of merit corresponds to the satellite navigation system (FOM 6) and not to other systems (FOM 5 - DME/DME, FOM 3 - Inertial, etc.), otherwise the default separation value (5 NM) would be applied among those aircraft not complying with this requirement. In the event of a regional loss of GNSS positioning capability, radar surveillance would be used as a contingency system and separation management would be provided under current conditions (5 NM fixed separation value).

2.2 Separation Minima Tool

The determination of variable separation minima shall be performed by the Separation Minimum Tool (SMT) integrated in the ground segment. It shall display to ATCo the applicable minimum separation value between two aircraft. While the controller remains the separation agent, the notion in the control exercise will have to change somewhat. Applying different separation minima in the same volume of airspace means that the ATCo is unable to mentally calculate the variable separation value, as opposed to the current fixed value (5 NM). Therefore, controllers need a new tool which presents this separation value for each aircraft pair in the airspace under their responsibility. In this separation mode the supervisory/monitoring role of the controllers become more important and even more complex, so that the operational concept must be defined in order to ensure that the new situation is safe.

In the initial stage, the SMT ground system consists of a single module called 'Separation Proof (SP)'. The function of this tool will be to determine the minimum lateral or longitudinal separation value between two aircraft that meets the required safety threshold (TLS). In order to do so, it requires other systems to provide it with the necessary information.

The trajectory prediction information shall be provided by a predictor tool which will use ADS B data transmitted by the aircraft and the flight plan information (FPL) to perform the 4D prediction. The prediction shall comply with a minimum quality factor in order to achieve a required level of accuracy. The 4D trajectory prediction shall be received by the SMT 20 minutes in advance of the aircraft's planned sector entry time. Information regarding wind conditions and aircraft performance shall be provided to the SMT tool by the aircraft. The FPL information shall be received from the flight data processing system (FDP) (Figure 1).

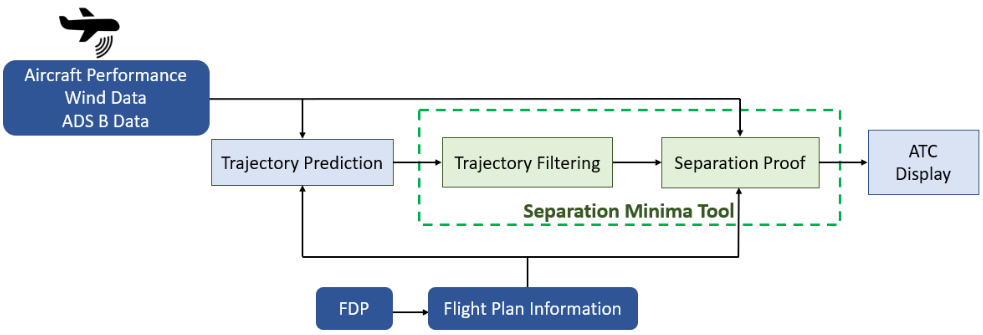

Figure 1. Information flow for Ad Hoc separation determination

Initially the SMT shall filter trajectories by discarding those situations that are not of interest, i.e. aircraft whose trajectories do not intersect, aircraft whose trajectories intersect at a crossing point but with a time difference between them of more than 2 minutes (and therefore separated by a distance of more than 15 NM), aircraft not flying on the same airway and aircraft flying on the same airway but whose time difference at the sector entry time is greater than 6 minutes (and therefore separated by a distance greater than 45 - 50 NM which assumes that differences in aircraft speeds would not give rise to overlap conflicts). After this first filtering, the SP module shall initiate the separation determination between the interest aircraft pairs. This variable separation minimum shall be determined and displayed to the controller 2 minutes in advance of the expected sector entry time of the first aircraft. This time horizon has been selected in order to allow ATCo to have some advance knowledge of the applicable minimum separation value between two aircraft. These initially proposed time values are subject to modification depending on the results obtained in the validation level.

It should be noted that some systems will need to be upgraded in order to be compatible with the proposed concept. In particular, the ATC tool "Conflict Detection" will adopt a more dynamic behaviour by monitoring that there will be no loss of separation between aircraft with the conflict limit distance being the minimum Ad Hoc distance determined.

The same applies to the ACAS system, which operates on time scales that should be analysed to avoid excessive generation of Traffic Advisory (TA) and Resolution (RA) alerts. Also, one of the future challenges to be dealt with in the development of this Ad Hoc separation project is the compatibility with the Trajectory Based Operations (TBO) concept strongly promoted by SESAR. While the former is eminently tactical, the TBO concept has a greater focus on strategic planning. The idea behind this concept is that trajectories are negotiated between all the actors involved before the flight and that the ATM system is aware of them and modifies them, if appropriate, in order to be free of conflicts. The possible discrepancy lies in what minimum separation would be used to make the trajectories strategically conflict-free, as the Ad Hoc separation would be tactically determined. The harmonisation between these two concepts will be explored in future work.

2.3 Separation Proof module

The algorithm for the Ad Hoc separation minima determination implemented in the Separation Proof module aims to determine the smallest safe separation value between two aircraft. Figure 2 shows the flowchart representing the sequence of activities carried out by the algorithm. Four activities are distinguished:

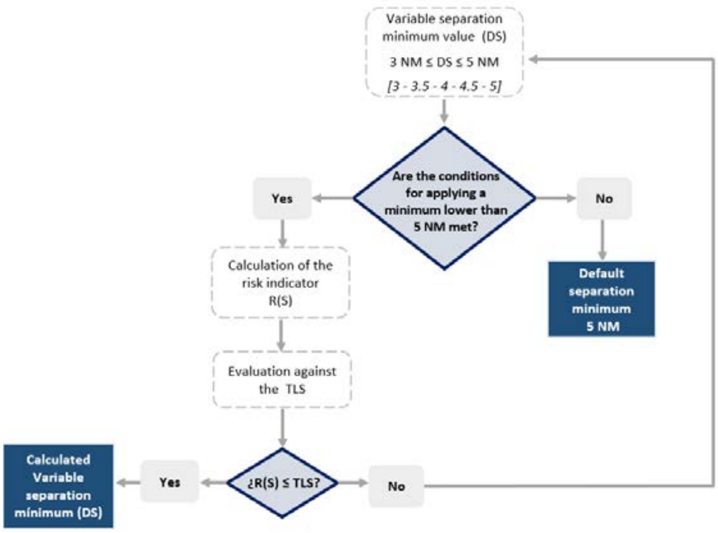

Figure 2. Ad Hoc Separation Determination Algorithm Flowchart

<u>1.- Variable Separation Minimum (DS).</u>

The algorithm has information on the aircraft pairs labelled as "pair of interest" and their specific characteristics (performances, trajectories, etc.). The en-route turbulent wake separation minima between aircraft, depending on the possible sequences (i.e., heavy-medium, medium-super heavy, etc.), are given to the algorithm.

In the initial step of the development of this concept the minimum variable separation (DS) will be determined and not calculated from this information. That is, in the first activity the algorithm will specify in real time for the "pair of interest" the lowest applicable separation value within the range of Ad Hoc separations (3 NM - 3.5 NM - 4 NM - 4.5 NM - 5 NM).

The Ad Hoc value shall always be higher than the corresponding MWS for that situation. If the Ad Hoc value does not meet the requirements of the following activities in the flowchart (target level of safety) the algorithm, following the feedback, would return to the initial step, would take the variable separation (DS') value immediately above the previous one and would repeat the sequence until an Ad Hoc separation value judged as safe is obtained. It is a prerequisite that the required conditions are met in order to be able to apply variable separation. Among those aircraft that do not meet these conditions, the default value of 5 NM shall always be applied.

2.- Calculation of the aircraft pair risk indicator R(S).

After determining the minimum variable separation (DS) the algorithm estimates the risk of collision R(S) of the aircraft pair for which the minimum variable separation (DS) has been calculated. The input variables for the calculation of the risk indicator are:

- Characteristics of the encounter geometry (angle of intersection between trajectories, aircraft speeds, altitudes, etc.).
- Minimum variable separation value determined (DS).
- Aircraft horizontal overlap probability (as a function of DS separation)
- Errors (aircraft position uncertainties, human factor, time windows, etc.)
- Meteorological conditions (wind) affecting aircraft ground speed (GS).
- ATC Intervention Capability

3.- Safety assessment.

After estimating the risk of collision R(S), it is compared with the Target Level of Safety (TLS) whose value is fixed. In making this comparison, the possibilities are:

- If the risk indicator R(S) ≤ TLS, then the minimum variable (DS) is applied.
- If the risk indicator R(S) > TLS, then:

    1. A new variable separation minimum (DS') value is determined that is higher than the previous DS value which did not comply with the TLS threshold.
    2. It is checked whether the new DS' value satisfies with the TLS fixed safety target level. If yes, the applicable separation value is DS'.
    3. If not, the process is iteratively repeated until the value of the minimum variable separation is 5 NM. This value corresponds to the current en-route (with surveillance) separation standard and therefore satisfies with the defined TLS.

4.- Display of the applicable minimum variable separation value to ATCo.
Finally, the minimum variable separation value applicable between the aircraft pair is displayed to the controller with a reasonable amount of time in advance.

3. APPROACH FOR THE ATC SEPARATION MINIMA REDUCTION STUDY.

Separation minima can be described as a function of three factors: navigation performance, risk exposure and intervention capability (Communications, Surveillance and ATC procedures and tools) (ICAO, 2020).

ICAO adopted collision risk models for the purpose of determining minimum separation in airspace with procedural control. However, in scenarios with ATS surveillance services (ATS surveillance systems: radar, ADS-B, etc.), the determination of separation minima appears to lack rigorous formal development. To determine the appropriate radar separation minima the analysis is related to the effect of inaccuracies, in the displayed radar data, so as to estimate the risk of collision and to decide whether the risk, for the implementation of a separation minimum, is acceptably safe (EUROCONTROL, 1998). Some authors have followed this approach and address the determination of the separation in scenarios with surveillance from the uncertainties of the different elements that make it up (REYNOLDS & HANSMAN, 2000). These uncertainties associated with the errors can be approximated by probability density functions (generally Gaussian and Double Exponential distributions).

The separation between aircraft displayed on screen to ATCo (apparent separation) does not correspond to the actual separation between aircraft, due to the associated errors. The actual separation value will depend on the probability density functions of the errors (Figure 3). The limiting case occurs when the apparent separation between aircraft is 5 NM (current separation standard), a value for which the collision risk meets the absolute target level of safety (TLS), but the actual value is less than the standard.

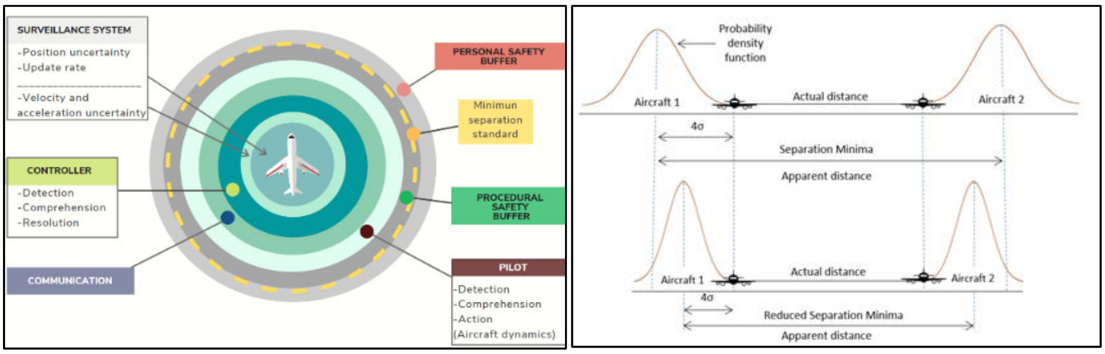

Figure 3. Representation of: left) Separation assurance budget components (REYNOLDS & HANSMAN, 2000) and right) errors probability density functions

The reduction of the ATC separation minimum is based on improvements in the technical systems currently used, in particular in the field of surveillance and navigation. These, not only offer better performance, but also predict whether this performance will be maintained during the flight, as is the case with RNP navigation. In addition, ATC is now equipped with more advanced support tools. The aim is to reduce the uncertainty associated with the various factors influencing separation (modification of the density function). Thus, the actual separation between aircraft would be maintained and, consequently, so would the risk of collision. However, the minimum separation (apparent separation) could be smaller.

In the framework of the minimum separation definition, the navigation and surveillance domains are the ones where most progress has been made. The progress achieved with Performance Based Navigation has been discussed in Section 2. In the surveillance domain, ADS overcomes some of the limitations of radar (positioning accuracy and system update time). In radar, accuracy is dependent, among other factors, on the distance to the target. Furthermore, different separation values are applied depending on the surveillance signal processing mode (5 NM multi-radar, 10 NM mono-radar, etc.). The information captured by the radars is not displayed directly to ATCo but is processed beforehand. This entails a processing time, especially in multi-radar processing, which means that the information displayed on the screen to ATCo corresponds to positions from previous time instants. Likewise, it should be considered that the mode S radar update frequency or information refresh time (speed at which the position of the aircraft is updated to users) is 4 - 15 seconds. In ADS the positioning accuracy is dependent on the aircraft avionics and therefore independent of the sensor range. With the GNSS navigation system (FOM 6) the position accuracy values achieved are less than 0.25 NM. In addition, since the information is received directly from the aircraft, the processing time is shorter than with multi-radar processing, with the update rate in the ADS typically being 1 second.

Research on the reduction of ATC separation minima will be developed in future studies and will be mainly based on the improvements referred above.

4. CONCLUSIONS AND FUTURE WORK

The SESAR and Next Gen macro programmes propose new projects in order to drive the future development of air traffic management (ATM) and ensure benefits in the capacity, safety, efficiency and environment areas. This study has laid the foundations for the development of the concept of variable separation in continental en-route airspace. In particular, the Ad Hoc separation framework or operational concept is defined. Variable separation involves applying different separation minima between aircraft in a specific volume of airspace according to a specific set of characteristics (aircraft category, navigation performance, surveillance, etc.) and external characteristics (conflict geometry, ATC procedures, wind conditions, etc.).

There is no fixed separation value, but a range of possible values that define new standards. For this reason, implicit in the development of this concept, research will be carried out on the reduction of the current separation minima. The approach to be followed to study this reduction lies in maintaining a fixed safety threshold (risk of collision) by reducing the uncertainties associated with the different factors that determine the minimum separation (surveillance, navigation, ATC procedures, etc.) thanks to improvements in the technical equipment currently available. This study also describes the operation of the Separation Minima Tool and the steps carried out by the algorithm in charge of determining the variable separations. Different operational issues are identified that need to be developed in future work to make new concepts proposed by SESAR (Trajectory Based Operations, TBO) compatible with the one proposed in this study. Finally, the implementation of variable separation has the final goal of increasing capacity. This study will be carried out in parallel.

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SEGURIDAD EN PASOS A NIVEL Y FACTOR HUMANO: LA EXPERIENCIA DEL PROYECTO EUROPEO SAFER-LC.

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RESUMEN

Los accidentes en pasos a nivel constituyen un significativo problema de intersección ferrocarril –carretera, pero también conlleva unas consecuencias relevantes sociales a nivel personal, social, de salud pública y de impacto social. Adicionalmente, estos sucesos tienen importantes repercusiones para la operación ferroviaria y por carretera debido a los elevados costes económicos, de tiempo y sanitarios.

Entre 2010 y 2019 fallecieron 2.736 personas en los pasos a nivel localizados en la UE-27. En España, en este período se registraron 74 decesos en los pasos a nivel, a lo que se suman 32 personas que sufrieron heridas graves y 125 con heridas leves.

Los pasos a nivel representan, por tanto, un punto de seguridad crítico en el transporte ferroviario y por carretera que requiere un continuo análisis. Teniendo en cuenta que, el factor humano es la causa del 90% de los accidentes de tráfico, resulta fundamental identificar los errores humanos y los requisitos de los usuarios, para mejorar la seguridad en las infraestructuras de los pasos a nivel.

El artículo aborda el tema del Factor Humano en los Pasos a Nivel con el objetivo de contribuir a la reducción de la siniestralidad. Este estudio se basa en la experiencia adquirida en el proyecto europeo SAFER-LC: Pasos a nivel más seguros mediante la integración y optimización de la gestión y el diseño de infraestructura vial y ferroviaria, (2017-2020), y que se enmarca en la línea de investigación sobre seguridad ferroviaria desarrollada por los grupos de investigación de la FFE.

Los resultados de este análisis permitirán incorporar elementos del comportamiento humano en las soluciones tecnológicas y no tecnológicas de los diseños de pasos a nivel. También tienen como objetivo impulsar la cooperación entre las diferentes partes interesadas de los diferentes modos de transporte implicados en los pasos a nivel.

1. INTRODUCCIÓN

En el año 2014 había 114.580 pasos a nivel en la Unión Europea (UE-28). Sin embargo, se pueden encontrar muchas diferencias entre países en cuanto al número de pasos a nivel. Por ejemplo, Francia, Alemania y Polonia tenían el mayor número de pasos a nivel de Europa (más de 9.000) e Irlanda, Portugal, Eslovenia, Bulgaria, Letonia, Estonia y Luxemburgo el menor número (menos de 1.000) (ERA, 2016) (Figura 1).

En promedio, había 5 pasos a nivel por cada 10 kilómetros de línea en la UE, pero esta proporción variaba considerablemente entre países. Por ejemplo, Suecia, Austria, la República Checa y Hungría tenían la mayor densidad de pasos a nivel en términos de pasos a nivel por línea-kilómetro (más de 75 por cada 100 kilómetros) y, Bulgaria y España la densidad más baja (menos de 25 por cada 100 kilómetros de línea) (ERA, 2016).

Hay que tener en cuenta que, los pasos a nivel son una parte fundamental de la infraestructura ferroviaria. Por ello, a nivel general, las estrategias se han centrado en introducir mejoras técnicas en las infraestructuras y eliminar los pasos a nivel, pero también se han combinado estas medidas con otras que reducen los riesgos para los usuarios (por ejemplo, medidas educativas y de sensibilización).

En Europa, el número de víctimas mortales en accidentes ferroviarios ha disminuido, salvo las relacionados con los accidentes en pasos a nivel. En los últimos años, de media, en Europa todos los días ha muerto una persona y casi una ha resultado gravemente herida (ERA, 2016). En 2014, Alemania y Polonia eran los países de la EU-28 con más muertes de usuarios en los pasos a nivel (41 y 38, respectivamente). Del total de países estudiados, España ocupaba el décimo puesto en mortalidad en pasos a nivel (8 fallecidos).

El objetivo del proyecto europeo SAFER-LC (SAFER Level Crossing by integrating and optimizing road-rail infrastructure management and design; Proyecto de investigación de la Comisión Europea, Programa Horizonte2020 (2017-2020) coordinado por la UIC y en el que participa la FFE en el Consorcio del proyecto.) era mejorar la seguridad y minimizar el riesgo mediante el desarrollo de un conjunto de soluciones innovadoras, y herramientas para la gestión proactiva y el diseño de la infraestructura de los pasos a nivel.

Las herramientas desarrolladas permiten a los agentes encargados de la toma de decisiones de las infraestructuras de carretera y ferrocarril encontrar formas más eficaces de detectar situaciones potencialmente peligrosas, evitando incidentes en el cruce de nivel mediante un diseño innovador y métodos de mantenimiento predictivo.

El proyecto se centró en las soluciones técnicas (como los servicios de detección inteligente y sistemas de comunicación avanzada infraestructura-vehículos), los procesos humanos para adaptar el diseño de la infraestructura a los usuarios finales, y la cooperación entre las diferentes partes interesadas de los distintos modos de transporte implicados en los pasos a nivel.

Con el objetivo de demostrar cómo estos avances tecnológicos y no tecnológicos se podían integrar en soluciones, así como validar su viabilidad y evaluar su desempeño se llevaron a cabo una serie de pruebas piloto en diferentes ciudades europeas.

A partir de los resultados obtenidos en SAFER-LC, en esta comunicación se presenta una propuesta de marco descriptivo útil para el diseño de los pasos a nivel y los sistemas de seguridad teniendo en cuenta la perspectiva de los usuarios de carreteras y ferrocarriles, especialmente de los usuarios vulnerables (El informe completo de esta tarea (Tarea 2.1.) se puede encontrar en la extranet del proyecto: https://safer-lc.eu/)

La comunicación se estructura en tres partes. Con el objetivo de mejorar la comprensión de los indicadores clave de seguridad relacionados con errores humanos e infracciones en los pasos a nivel, en el primer apartado se presentan un marco teórico relacionado con el análisis de los factores humanos en los sistemas de seguridad de los pasos a nivel. A continuación, se describen las fuentes de datos y metodología usada en el desarrollo de los principales indicadores relativos a los requerimientos de los usuarios, errores humanos e infracciones en pasos a nivel. El tercer apartado presenta los resultados del análisis de las variables identificadas en la literatura y los principales indicadores propuestos. Por último, se incluye un apartado que incluye las principales conclusiones extraídas del análisis realizado.

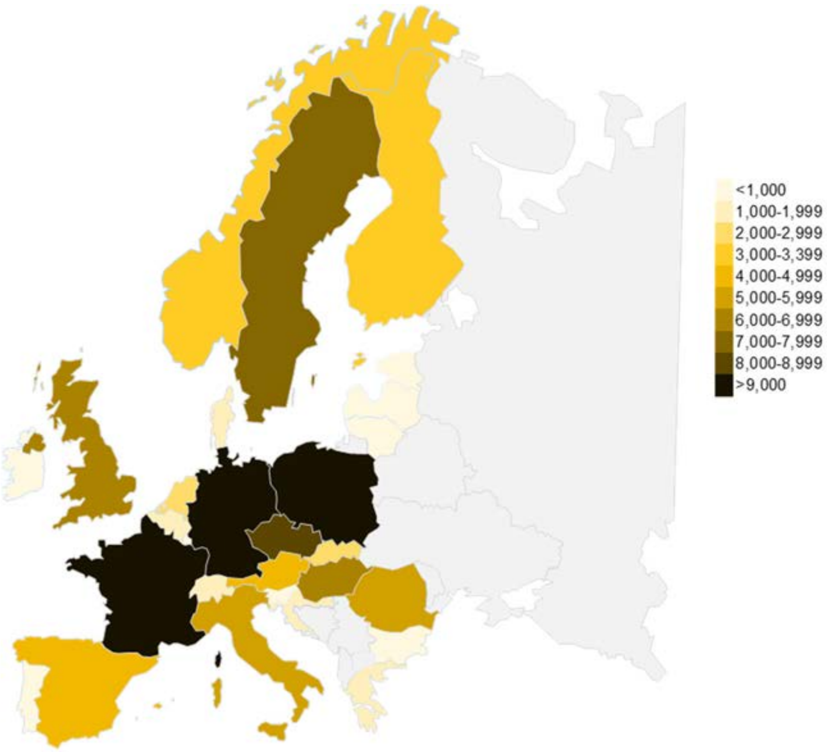

Figura 1. Número total de pasos a nivel en la Unión Europea-28, 2004

2. MARCO TEÓRICO. ANÁLISIS DE LA SEGURIDAD EN LOS PASOS A NIVEL DESDE EL FACTOR HUMANO

Según la Asociación Internacional de Ergonomía, el factor humano es un enfoque teórico relacionado con la comprensión de las interacciones entre personas y otros elementos de un sistema. Este enfoque aplica teoría, principios, datos y métodos al diseño, con el fin de optimizar la seguridad de las personas y el rendimiento general del sistema. De esta manera, el error humano ya no se considera la causa principal de los accidentes, sino una consecuencia de los fallos lógicos del sistema.

De acuerdo con el enfoque de los “sistemas seguros”, los accidentes en los pasos a nivel son el resultado de la interacción compleja entre los usuarios (por ejemplo, peatones, conductores, etc.), vehículos (por ejemplo, vehículos pesados, trenes de alta velocidad, etc.), la infraestructura en el cruce (por ejemplo, distancias de visibilidad, señalización, etc.) y otras condiciones del entorno (por ejemplo, condiciones meteorológicas). De esta manera, la clave para unos pasos a nivel más seguros surge de la responsabilidad compartida entre los peatones, los usuarios de carretera, las operadoras y los administradores de la infraestructura ferroviaria, y los órganos de gobierno. Las contramedidas adoptadas de acuerdo a este enfoque buscan hacer que las características de los pasos a nivel tengan en cuenta la existencia de errores humanos y minimicen su impacto, y reduzcan los comportamientos inseguros de los usuarios (Searle et al., 2012).

El concepto de infraestructura resiliente y autoexplicativa se ha aplicado con mayor frecuencia al contexto de la seguridad vial en carretera. Desde esta perspectiva, una carretera resiliente sería aquella que está diseñada y construida de tal manera que interfiere o bloquea el desarrollo de errores de conducción y, evita o mitiga las consecuencias negativas de los errores de conducción, permitiendo así que el conductor recupere el control, regrese al carril de circulación o pueda detenerse sin lesiones ni daños. Por otro lado, una carretera que se explica por sí misma estaría diseñada y construida para inducir a una conducción adecuada (ya sea por el diseño de su trazado o mediante la señalización existente), reduciendo así la probabilidad de errores del conductor y mejorando la comodidad de conducción (Bekiaris et al., 2011).

Un número creciente de investigaciones abordan el análisis del factor humano en los pasos a nivel, aunque la mayoría de estos estudios se han centrado más en las colisiones de trenes y vehículos que en los arrollamientos de peatones. A continuación, se presentan algunos temas comunes que aparecen en la literatura en relación con la perspectiva del usuario en los pasos a nivel. Debido al enfoque de este estudio, es importante distinguir primero entre dos categorías amplias de incumplimiento en los pasos a nivel: el error humano y la infracción deliberada de las normas.

La mayoría de los usuarios de pasos a nivel tienen comportamientos de riesgo no intencionados (Searle et al. 2012), siendo estos denominados en la literatura como errores humanos. Ejemplos de estos podrían ser, no percibir el acercamiento del tren, o la mala valoración del riesgo ante la proximidad del tren. Factores cognitivos como la falta de atención, distracción, poco conocimiento, mal juicio, distancia de visión limitada, etc. (Freeman et al., 2013) pueden ser los que llevaran a la aparición de este tipo de errores.

Por otro lado, hay usuarios que incumplen voluntariamente las reglas de cruce de los pasos a nivel. Estos hechos se conocen como infracciones deliberadas. En la literatura se citan varios factores que influyen en la tendencia de los usuarios a incumplir las reglas, entre ellos: factores individuales como la edad, el género, la personalidad y las actitudes; factores sociales como normas, cumplimiento y comportamiento de otras personas cercanas; y factores puntuales como el tiempo de espera, el clima, la distracción y el estado de ánimo (Edquist, 2011). Algunas razones más específicas para infringir deliberadamente las reglas de tránsito o de los pasos a nivel incluyen: tener prisa, la conveniencia, la familiaridad, la fatiga o el consumo de alcohol y drogas, entre otros (Freeman et al., 2013).

Según la literatura estudiada, hay menos ejemplos de infracciones deliberadas de pasos a nivel que de errores humanos.

Al analizar los factores humanos en los sistemas de seguridad de pasos a nivel habría que tener en cuenta la tipología (pasivo, activo y peatonal) y el usuario del paso a nivel (usuarios motorizados, no motorizados y vulnerables), ya que estas variables pueden influir en la naturaleza del riesgo y los factores humanos en juego. Por ejemplo, los arrollamientos en pasos a nivel controlados pasivamente que involucran el incumplimiento involuntario del conductor, tienen más probabilidades de estar relacionados con factores humanos que por factores relacionados únicamente con fallos técnicos de los sistemas (Rudin-Brown et al., 2014). Además, ciertos factores humanos pueden ser más prevalentes en un grupo de usuarios de la carretera que en otro (Searle et al., 2012).

Searle et al. (2012) establecieron un conjunto definido de categorías de factores humanos aplicadas a la seguridad de los pasos a nivel (Figura 2):

2.1 Factores humanos relacionados con errores humanos

- Visibilidad de cruces y trenes.

Para cruzar de forma segura un paso a nivel, el usuario debe de tener una visibilidad tal que sea capaz de detectar y percibir con éxito la presencia o proximidad de un tren.

Algunos factores que pueden afectar a la visibilidad de los usuarios/conductores son:

- el contraste visual de los objetos con su entorno más amplio;
- las condiciones climáticas;
- las condiciones de luminosidad: la oscuridad en la noche o el resplandor del sol que pueden cegar temporalmente a los usuarios de la vía (Searle et al., 2012);
- el tamaño percibido;
- el color oscuro de los objetos que se acercan desde la distancia pueden también contribuir a una peor detección y reconocimiento por parte de los conductores (Rudin-Brown et al., 2014).

Las líneas de visión limitadas a lo largo de la vía son otro factor de percepción importante que puede afectar la capacidad del usuario de la vía para detectar un tren que se aproxima en un cruce pasivo. La distancia visual debe permitir a los usuarios de la carretera no sólo darse cuenta de la presencia de un tren, sino también aportar la información suficiente para que se detenga de manera segura antes del cruce. Otros estudios destacan factores como la existencia de vegetación o edificios ubicados a lo largo de la vía, la curvatura en la carretera o vía, o el cruce en ángulo agudo de las vías del camino y del ferrocarril, como elementos que pueden afectar la línea de visión y, por tanto, conducir a una mala visibilidad (Searle et al., 2012).

- Distracción y falta de atención.

La atención de un usuario de la vía puede desviarse de un paso a nivel debido a distracciones externas (por ejemplo, semáforos, señales de ceda el paso, tráfico de peatones, tiendas, etc.). Este problema se experimenta con mayor frecuencia en los cruces activos, dado que se encuentran en entornos urbanos en los que existen muchas distracciones visuales y mentalmente complejas (Searle et al., 2012). Cuando se sobrecarga con otros estímulos, la conciencia de la situación del usuario de la vía puede verse comprometida perdiéndose la atención en el paso a nivel. En esta situación, los estímulos como los propios trenes o luces intermitentes pueden ser completamente visibles pero inadvertidos, un fenómeno conocido como "ceguera atencional", o un "miraron, pero no pudieron ver" (Searle et al., 2012).

Los usuarios también pueden presentar distracciones internas como resultado de realizar tareas secundarias a la conducción o la acción de caminar, como el uso de dispositivos multimedia, conversaciones con pasajeros o con otros peatones, atender a los niños o procesos mentales que distraen, como soñar despierto o abstraerse en pensamientos. Rudin-Brown et al. (2014) argumentan que las distracciones no visuales del conductor que surgen como resultado de estímulos cognitivos (pensamientos) pueden tener un impacto negativo en el comportamiento de exploración visual del conductor o usuario. Este factor podría estar presente entre los usuarios de cruces activos y pasivos, y podría aplicarse tanto a usuarios motorizados como no motorizados.

Otro problema potencial de falta de atención que experimentan los conductores en los cruces pasivos está relacionado con la relajación provocada por la falta de atención al entorno más amplio, debido al aislamiento rural de los cruces pasivos y su bajo tráfico de trenes y carreteras, lo que conlleva que el usuario puede equivocarse en la percepción de la distancia de un paso a nivel o del acercamiento del tren (Searle et al., 2012).

El tema de la presencia (y la conciencia) de un segundo tren que aparece poco después de que el primero ha pasado, está recibiendo cada vez más atención dentro de la literatura (Freeman et al., 2013). Los trenes que se aproximan pueden actuar como una distracción que afecta tanto a los peatones como a los usuarios motorizados. Primero, los peatones pueden concentrarse en intentar coger un tren que llega a una estación de ferrocarril y, al hacerlo, no percibir la llegada de un segundo tren que se aproxima. En segundo lugar, los automovilistas pueden centrar su atención de manera similar en un tren que se acerca, y se detiene en una estación adyacente o que acaba de pasar, y suponer que ya es seguro cruzar, cuando en realidad se acerca un segundo tren que no verán.

- Falta de conocimiento.

Otro factor humano que conduce al uso indebido involuntario de los pasos a nivel es la falta de conocimiento sobre las reglas y normas existentes en los pasos pasivos. Esto suele ir acompañado de una falta general de conciencia sobre los riesgos asociados en los entornos ferroviarios, como las largas distancias de parada de los trenes y la incapacidad para detenerse o reducir la velocidad para evitar una colisión o arrollamiento. Este desconocimiento puede extenderse a que los usuarios desconozcan la ilegalidad de sus comportamientos y la existencia de sanciones.

Existe un problema particular con la comprensión de la forma correcta de actuar en los pasos a nivel pasivos. Varios estudios señalan el hecho de que muchos conductores no esperan el paso de trenes en los cruces pasivos. Se sugiere que esto puede deberse al hecho de que los conductores no distinguen entre cruces activos y pasivos y, por lo tanto, esperan ser informados si se acerca un tren.

En este sentido, varios expertos coinciden en la necesidad de abordar la educación dentro de un programa más amplio de gestión de riesgos para aumentar la seguridad en los entornos ferroviarios y, más concretamente, en los pasos a nivel de peatones y vehículos. Esto implica aumentar la conciencia pública sobre los peligros de los cruces y educar a los peatones, conductores de vehículos de carretera y otros usuarios sobre cómo usarlos correctamente (Metaxatos et al., 2015).

- Percepción de riesgo inexacta.

Algunos usuarios desconocen los riesgos reales que implica el uso indebido de un paso a nivel. Según Searle et al. (2012) hay dos factores clave relacionados con la percepción inexacta del riesgo:

- Familiaridad y expectativa. La familiaridad con los pasos a nivel conduce una baja expectativa de encontrar trenes en los cruces. Los conductores que utilizan los pasos a nivel con regularidad, llegan a desarrollar expectativas sobre la frecuencia de los trenes y la probabilidad de encontrar un tren en ellos. Basándose en su experiencia en esos cruces realizan esquemas o modelos mentales para esos pasos. La familiaridad con un paso a nivel o tipo de paso a nivel en particular, junto con una expectativa reforzada de que no haya trenes, lleva a que se active un esquema de "no trenes" en los enfoques de pasos a nivel futuros (Rudin-Brown et al., 2014). El relacionar la familiaridad y la expectativa de que un tren no esté presente hace que los conductores se sientan satisfechos con los malos hábitos a la hora de usar los pasos a nivel (Caird et al., 2002). La percepción de riesgo inexacta por familiaridad y expectativa se daría en los usuarios frecuentes de cruces pasivos debido a los bajos volúmenes diarios de trenes de este tipo de cruces.

- Juicio erróneo de la velocidad y la distancia del tren. Para los usuarios de la carretera es difícil juzgar la velocidad y la distancia de los trenes que se aproximan y, por lo tanto, el tiempo que tardan los trenes en llegar al cruce. Searle et al. (2012) señalan dos problemas de percepción principales que pueden afectar la capacidad para juzgar con precisión la velocidad del tren, lo que los lleva a subestimar la velocidad del tren y a tener demasiada confianza en su capacidad para "ganarle al tren" y poder cruzar el paso a nivel antes de que este llegue: el efecto Leibowitz que describe el fenómeno en el que los objetos más grandes parecen moverse más lento que los objetos más pequeños, viajando ambos a la misma velocidad; y el efecto amenazante, por el que no se percibe el tamaño real del tren hasta que está a una distancia muy próxima. Esta situación puede agudizarse en los cruces rurales y de noche.

2.2. Factores humanos relacionados con las infracciones en los pasos a nivel

- Comportamiento deliberado en la toma de riesgos.

El comportamiento deliberado que conlleva una asunción de los riesgos puede ser debido o bien a la frustración e impaciencia del usuario que tiene que esperar en el paso a nivel el paso de un tren o trenes que se acercan; o bien también por que el usuario tiene una personalidad que busca riesgos. En el primer caso, el usuario puede decidir infringir las reglas de cruce porque considera que los beneficios de reducir el tiempo de espera superan los riesgos percibidos de infringirlas. Las infracciones tienden a aumentar significativamente cuando el tiempo entre la activación de la alerta y la llegada del tren excede los 20-30 segundos. La impaciencia con los retrasos en los pasos a nivel puede surgir cuando los usuarios de la carretera tienen prisa por llegar a su destino, lo que puede acentuarse en momentos específicos del día, como la hora punta de la mañana. Los usuarios de la carretera también pueden infringir deliberadamente los controles de los cruces si los consideran poco fiables, o si perciben que las consecuencias de sus acciones, en términos de ser sancionados o de que llegue un tren, son poco probables.

Por otro lado, se ha identificado que determinadas personalidades pueden infringir deliberadamente las reglas. En este caso, el desafío del usuario a las reglas de cruce y los controles de seguridad de los pasos a nivel activados puede ser solo un ejemplo de distintos comportamientos de riesgo.

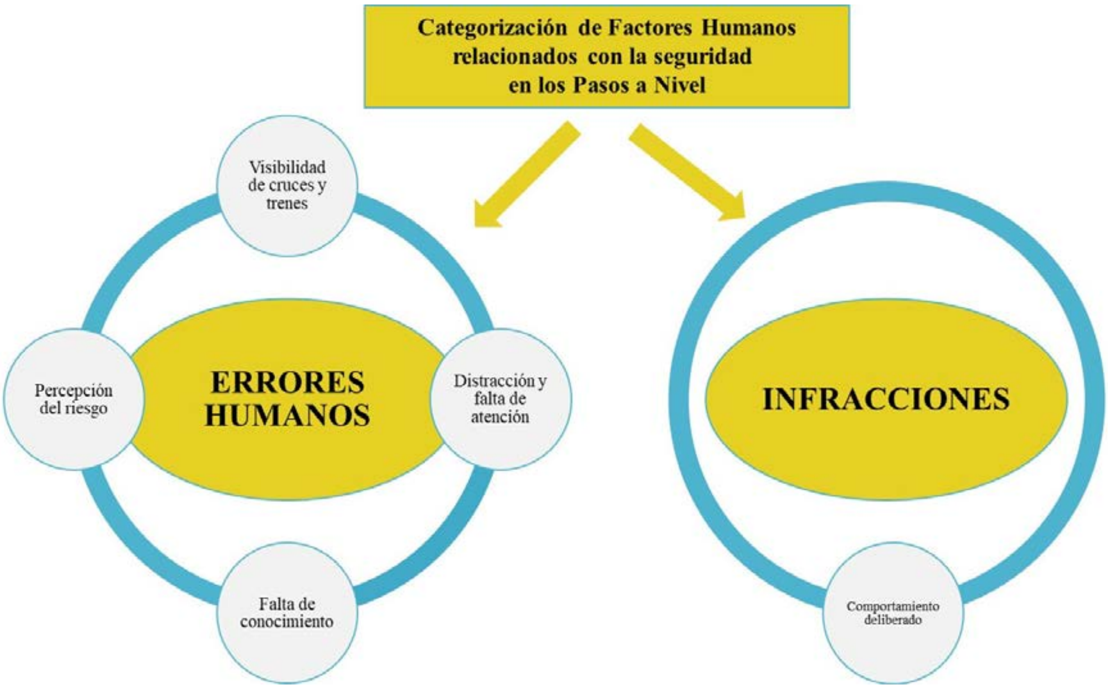

Figura 2. Categorización de Factores Humanos relacionados con la seguridad en los pasos a nivel

3. FUENTES DE DATOS Y METODOLOGÍA

A continuación, se presenta un resumen de la metodología que se utilizó en la Tarea 2.1. (“Estado del arte de la seguridad en los pasos a nivel: identificación de indicadores clave de seguridad relacionados con los errores humanos y las infracciones”) del proyecto SAFER-LC (Figura 3).

Utilizando una metodología que combinaba la revisión de la literatura y la opinión de expertos, se creó una base de datos que identificaba unos indicadores clave de seguridad relacionados con los requisitos de los usuarios y, los errores humanos e infracciones. La creación de la base de datos se realizó en 5 fases:

1. Construcción de una base de datos bibliográfica sobre factores humanos en pasos a nivel y sistemas de seguridad. Los socios de la tarea participaron en la construcción de una base de datos bibliográfica sobre factores humanos en pasos a nivel y sistemas de seguridad. Después de la depuración de la información, la base de datos quedó integrada por 125 documentos: artículos científicos (n = 72); trabajos de investigación (n = 29); otros resultados/informes (n = 22); y otra información (n = 2) (Se puede acceder a la base de datos en la extranet del Proyecto)

2. Revisión de la literatura. Esta fase implicó un análisis de los documentos de la base de datos. Para ello, se desarrolló un formulario de revisión que facilitaba la identificación y el análisis de la información relevante mediante 6 campos de información clave. Con el fin de informar las categorías contenidas en este formulario de revisión, particularmente las relacionadas con el factor humano, se llevó a cabo una revisión preliminar de una muestra de documentos contenidos en la base de datos bibliográfica (Caird et al., 2002; Ngamdung y DaSilva, 2013; Read et al., 2013; Rudin-Brown et al., 2014; Searle et al., 2012). A partir de esta breve revisión, se compiló e incluyó en el formulario una síntesis de las variables relacionadas con el factor humano. El diseño de este formulario se basó en los principios metodológicos del análisis de contenido, una técnica de investigación para hacer inferencias replicables y válidas de los textos (u otra materia significativa) a los contextos de su uso (Bengtsson, 2016).

3. Definición de los indicadores relacionados con los requisitos del usuario. Con el objetivo de definir un conjunto de indicadores relativos a los requisitos del usuario, se diseñó un formulario en el que los socios identificaban las variables sobre factor humano de los documentos de la base de datos. Mediante el programa SPSS se realizó un análisis de frecuencia de las variables identificadas: tipo de paso a nivel, condiciones personales del usuario, tipo de distracción, visibilidad de cruces y trenes, variables relacionadas con el contexto, etc. Las variables más frecuentes (enumeradas en 3 o más documentos) se agruparon en 7 categorías amplias de indicadores de requisitos de los usuarios: condiciones personales; distracción y falta de atención; visibilidad de cruces y trenes; desconocimiento; percepción de riesgo no exacta; conductas de riesgo deliberadas; e información sobre el contexto. Finalmente, se obtuvieron 35 indicadores relacionados con los requisitos de los usuarios . Para explorar posibles asociaciones entre las variables de factor humano de la base de datos y el tipo de paso a nivel y tipo de usuario, se realizó un análisis bivariado de algunas de las variables (prueba de la Chi-cuadrado de Pearson (x2) de $p < 0.05$). (Un pequeño número de indicadores se basa en "nuevas" variables. Se refieren a variables que no se habían incluido en el Formulario de revisión, pero que se detectaron en la literatura revisada. Se consideró de interés incluir todas las variables adicionales con el fin de obtener un análisis más completo de los factores humanos)

4. Validación de los indicadores de requisitos del usuario e identificación de otros nuevos. Para validar los indicadores identificados en la fase anterior y capturar otros no referidos, se desarrolló un formulario de clasificación. Con este formulario cada socio clasificaba la relevancia de medir cada uno de los indicadores en términos de seguridad en los pasos a nivel desde una perspectiva del factor humano. A cada indicador se le asignó una clasificación en una escala Likert de 5 puntos (de "extremadamente importante" a "nada importante").

5. Identificación de indicadores clave de seguridad relacionados con errores humanos e infracciones. Los indicadores de requisitos del usuario creados a partir de las variables identificadas en la revisión de la literatura, se clasificaron como errores humanos e infracciones en los sistemas de seguridad de pasos a nivel utilizando el marco de clasificación de errores humanos del German in Depth Accident Study (GIDAS) (Grippenkoven et al., 2012). GIDAS clasifica los errores humanos y las infracciones en categorías de acuerdo con las diferentes etapas del procesamiento de la información humana: acceso a la información; admisión de información; evaluación de información; planificación y operación. GIDAS fue diseñado originalmente para usuarios de automóviles, aunque también se ha aplicado al estudio de accidentes de pasos a nivel.

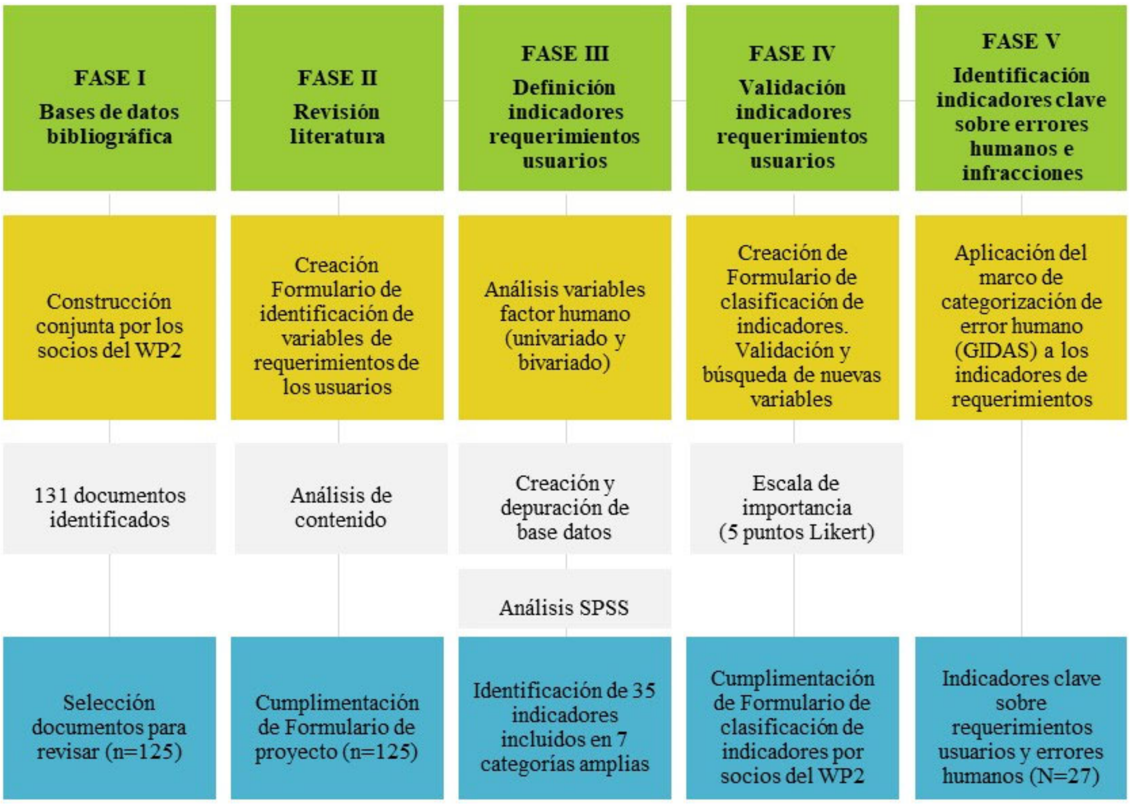

Figura 3 – Resumen del marco metodológico

4. RESULTADOS

La revisión de la literatura reveló que la mayoría de los estudios y proyectos relacionados con los requisitos de los usuarios y, los errores humanos y las infracciones en los pasos a nivel se centran, por un lado, en los pasos a nivel pasivos y los pasos a nivel activos controlados automáticamente y, por otro lado, en usuarios de automóviles y peatones. Casi todos estos estudios, aunque no estuvieran directamente relacionados con los factores humanos, subrayan la relevancia de estas variables y la necesidad de tenerlas en cuenta para comprender mejor la seguridad en los pasos a nivel.

De acuerdo con los documentos revisados, las variables relacionadas con los factores humanos que aparecían con mayor frecuencia eran:

- La distancia visual y las señales.
- Localización de los pasos a nivel.
- Distracciones externas.
- Percepción de la velocidad y distancia del tren.
- Ángulo de cruce.
- Falta de comprensión de la acción correcta que se requiere.
- Personalidades que buscan riesgos.
- Desconocimiento de la señalización en los pasos a nivel.
- Frustración e impaciencia ante la demora en los pasos a nivel.

También se analizaron las variables vinculadas a las condiciones personales de los usuarios para identificar los grupos de riesgo, según la literatura revisada, en los últimos años las investigaciones se han centrado en el análisis de los comportamientos según género y edad.

Como se explicaba en el apartado de Fuentes de datos y Metodología, las variables más frecuentes se agruparon en 7 categorías amplias de indicadores de requisitos de los usuarios

A continuación, se presenta un breve resumen de los principales hallazgos sobre los indicadores relacionados con los errores humanos y las infracciones de acuerdo a las valoraciones realizadas por los socios de la tarea:

- Indicadores relacionados con las condiciones personales. En términos generales, la edad y la discapacidad se consideraron más relevantes que el género en el estudio de las necesidades de los usuarios en los pasos a nivel. El uso de sustancias adictivas también se consideró relevante.

- Indicadores relacionados con las distracciones y la falta de atención. En general, se consideró que todo el conjunto de indicadores relacionados con la distracción y la falta de atención eran relevantes.
- Indicadores relacionados con la visibilidad de los cruces y los trenes. Estos indicadores se consideraron fundamentales, sobre todo, la distancia y el ángulo de las señales visuales.
- Indicadores relacionados con la falta de conocimiento. En términos generales, el conjunto de indicadores relacionados con la falta de conocimiento se valoró como relevantes para el análisis de factores humanos en los pasos a nivel.
- Indicadores relacionados con la percepción inexacta del riesgo. Los resultados apuntaron a que era de particular interés tener en cuenta para el estudio del factor humano la familiaridad del usuario con el paso a nivel.
- Indicadores de comportamiento de riesgos deliberados. Los más relevantes se dividían en 2 categorías principales: los ocasionados por la frustración y la impaciencia del usuario que tiene que esperar en el paso a nivel, y los relacionados con usuarios que tienen una personalidad propensa a la búsqueda de riesgos.
- Indicadores relacionados con la información sobre el contexto. Del conjunto de estos indicadores, el destacado como más importante fue el del entorno del paso a nivel (por ejemplo, si es rural o urbano).

Con el objetivo de examinar los factores humanos que pueden contribuir a los accidentes en los pasos a nivel, estos indicadores se analizaron frente a las categorías de error del marco de clasificación de errores humanos de GIDAS. Teniendo en cuenta el procedimiento secuencial del procesamiento de la información humana, las categorías GIDAS son: acceso a la información, procesamiento de la información, evaluación de la información, planificación y acción (Grippenkoven, Giesemann & Dietsch, 2012).

La Figura 4 incluye una descripción de la influencia y los indicadores identificados y clasificados según las categorías de error del marco de categorización de errores humanos de GIDAS. La Figura 2 se enfoca en las etapas del procesamiento de la información que están más afectadas por cada uno de los factores. Sin embargo, esto no excluye la influencia en otras etapas por los ciclos de retroalimentación de las etapas.

Los indicadores relacionados con las condiciones personales están vinculados a errores de acceso a la información, errores de procesamiento de la información, errores de evaluación y errores de operación. En este caso, pueden producirse errores por no percibir información relevante, experimentar interferencias dentro y fuera del vehículo, realizar una interpretación incorrecta de la información por experiencia previa y conocimiento del lugar, y/o realizar acciones incorrectas.

La visibilidad en los pasos a nivel puede verse reducida debido a condiciones climáticas que reducen la visibilidad, condiciones nocturnas, deslumbramientos del sol, crecimiento excesivo de vegetación, distancia de visión, etc. Estos indicadores están vinculados a errores de información de acceso y de procesamiento de la información.

Los indicadores relativos a la información sobre el contexto están vinculados a errores de acceso a la información, errores de procesamiento de la información, errores de evaluación y errores de operación. En este caso, pueden producirse errores por no percibir información relevante, experimentar interferencias dentro y fuera del vehículo, realizar una interpretación incorrecta de la información recibida por familiaridad con el lugar, y/o realizar acciones incorrectas.

La atención de un usuario de un paso a nivel puede desviarse debido a distracciones externas (por ejemplo, semáforos, señales de ceda el paso, tráfico de peatones, etc.). Los usuarios de la carretera también pueden presentar distracciones internas como resultado de realizar tareas secundarias a la conducción, como el uso de dispositivos multimedia, conversar con pasajeros o con otros peatones, atender a los niños o por distracciones. Estos indicadores están vinculados a errores de procesamiento de la información.

Los indicadores relacionados con la toma de riesgos deliberados están vinculados con situaciones de frustración e impaciencia debido a tiempos de espera en el paso a nivel y con personalidades con inclinación a la búsqueda de riesgos. Estos indicadores están vinculados a conductas voluntarias inseguras o violaciones.

Un factor humano involuntario que conduce al uso indebido de los pasos a nivel es la falta de conocimiento sobre las normas y la falta de conciencia de los riesgos asociados con el entorno ferroviario. Estos indicadores están vinculados a errores de evaluación de la información porque la información se puede interpretar incorrectamente.

En general, la percepción inexacta del riesgo está relacionada con la familiaridad con los pasos a nivel, lo que conduce a una baja expectativa de encontrar trenes en los cruces y a un error de cálculo de la velocidad y la distancia del tren.

Estos indicadores están vinculados a errores de evaluación de la información. La información puede malinterpretarse debido a la experiencia previa y el conocimiento del lugar, y a la falta de conciencia y conocimiento de los ferrocarriles y los riesgos relacionados con las infraestructuras de los pasos a nivel.

Hay que tener en cuenta en el análisis de las medidas de seguridad de acuerdo a los requerimientos del usuario y el factor humano, que existen comportamientos inseguros involuntarios (errores y fallos) y comportamientos inseguros voluntarios (infracciones).

Los indicadores identificados en la literatura revisada relacionados con las conductas de riesgo deliberada y el suicidio, se consideran conductas peligrosas voluntarias o infracciones.

CATEGORÍA DE INDICADORES DE SAFER-LC	DESCRIPCIÓN DE LA INFLUENCIA	CATEGORÍA DE ERROR
INDICADORES RELACIONADOS CON LAS CONDICIONES PERSONALES	La información relevante no se puede percibir. La información de dentro y fuera del automóvil puede interferir e influir. Información interpretada de forma incorrecta Toma voluntaria de decisiones erróneas.	Acceso a la información. Procesamiento de la información. Evaluación de la información. Acción.
INDICADORES RELACIONADOS CON LA VISIBILIDAD DE LOS CRUCES Y LOS TRENES	La información relevante no puede ser percibida. La información de dentro y fuera del automóvil puede interferir e influir.	Acceso a la información. Procesamiento de la información.
INDICADORES RELACIONADOS CON LA INFORMACIÓN SOBRE EL CONTEXTO	La información relevante no se puede percibir. La información de dentro y fuera del automóvil puede interferir e influir. Información interpretada de forma incorrecta. Toma voluntaria de decisiones erróneas.	Acceso a la información. Procesamiento de la información. Evaluación de la información. Acción.
INDICADORES RELACIONADOS CON LA DISTRACCIÓN Y FALTA DE ATENCIÓN	La información de dentro y fuera del automóvil puede interferir e influir.	Procesamiento de la información.
INDICADORES RELACIONADOS CON LA TOMA DE DECISIONES DE RIESGO	La información de dentro y fuera del automóvil puede interferir e influir. Información interpretada de forma incorrecta. Infracción de las reglas debido a la creencia de que no va a suceder nada. Toma voluntaria de decisiones erróneas.	Acceso a la información. Evaluación de la información. Planificación. Acción.
INDICADORES RELACIONADOS CON LA FALTA DE CONOCIMIENTO	Información interpretada de forma incorrecta	Evaluación de la información.
INDICADORES RELACIONADOS CON UNA PERCEPCIÓN DE RIESGO NO EXACTA	Información interpretada de forma incorrecta	Evaluación de la información.

Figura 4 – Categorización de errores GIDAS e indicadores identificados en la literatura revisada

5. CONCLUSIONES

El objetivo de esta comunicación, y de la Tarea 2.1. del proyecto SAFER-LC, es contribuir a la mejora de la seguridad en las infraestructuras de los pasos a nivel desde la perspectiva del factor humano. Mediante una metodología que combinaba la revisión de la literatura y la opinión de expertos, se identificaron indicadores clave de seguridad relacionados con los requisitos del usuario y, los errores humanos y las infracciones.

La introducción de estos indicadores tiene como finalidad apoyar la planificación y evaluación de acciones de seguridad en los pasos a nivel desde la perspectiva del usuario, de modo que las medidas tecnológicas y no tecnológicas puedan adaptarse mejor desde el enfoque del factor humano, haciendo que los pasos a nivel sean más autoexplicativos y resilientes.

Específicamente, la identificación de estos indicadores clave de seguridad favorecerá el desarrollo de un marco del factor humano que, a su vez, permitirá valorar hasta qué punto se tienen en cuenta las variables del factor humano en el diseño y la evaluación de las medidas de seguridad en los pasos a nivel.

Para la construcción de estos indicadores clave de seguridad se utilizaron numerosas fuentes de información cuantitativas y cualitativas (tanto primarias como secundarias), que tenían en cuenta la perspectiva y experiencia del usuario en los pasos a nivel tanto en situaciones de la vida real como en condiciones experimentales.

La literatura revisada constituye, por ende, una rica fuente de información para el desarrollo de los indicadores clave de seguridad relacionados con los errores humanos y las infracciones. No obstante, aunque se incluyó en el análisis una gran variedad de literatura especializada y actual, no representa una revisión exhaustiva de la literatura disponible sobre el tema. Además, la mayoría de los estudios se han realizado en países del ámbito anglosajón, factor a tener en cuenta a la hora de considerar la representatividad de la información recopilada y proponer la extensión de medidas de manera internacional.

Con el objetivo de que los requisitos del usuario sean considerados en el diseño de las infraestructuras ferroviarias, los expertos en factor humano y transporte ferroviario que participaron en la tarea recomiendan realizar definiciones más exhaustivas de los distintos indicadores.

Esto ayudaría a enfocar la discusión sobre qué indicadores clave adoptar en el futuro. Además, estos expertos realizaron algunas propuestas útiles para el diseño de las medidas de seguridad en los pasos a nivel de acuerdo con la perspectiva del usuario:

- En el estudio se destacó la importancia de considerar a todos los usuarios de la vía al diseñar una contramedida (independientemente de su sexo, edad o condición de discapacidad), aunque estimaban fundamental contemplar las necesidades de grupos particulares y realizar las correspondientes modificaciones, por ejemplo, en el caso de los usuarios con problemas de movilidad. Por ejemplo, y dado que los datos evidencian que los hombres son responsables de más accidentes en tránsito que las mujeres, algunos expertos señalaron la importancia de desarrollar medidas específicas (por ejemplo, campañas) que se dirijan a los hombres.
- Dada la importancia de la falta de atención y las distracciones para cometer errores e infracciones, se propuso diseñar medidas de seguridad centradas en evitar distracciones externas y sobrecargas de estímulos en la zona de aproximación al paso a nivel, minimizando la variedad de señales que los usuarios de la carretera deben ver, leer, interpretar y responder antes de llegar al paso a nivel.
- En general, la distancia visual de las señales y el ángulo de cruce se destacan como factores importantes que pueden conducir al incumplimiento en los pasos a nivel. Pero también se propusieron otros elementos que pueden implicar riesgos en la seguridad en los pasos a nivel, como la iluminación del tren, de las calles (por la noche), la orientación de la calle, la dirección de conducción con referencia al sol o el color del material rodante.

- En lo que respecta a la relación entre las infracciones y la personalidad, los expertos señalaron como recomendación para las soluciones tecnológicas y no tecnológicas reflexionar sobre cómo incorporar elementos que eviten las situaciones de riesgo por la frustración o la impaciencia de los usuarios de los pasos a nivel.
- Las multas se consideraron útiles como estrategia disuasoria que reduce los comportamientos de riesgo a corto plazo, pero a medio y largo plazo la conducta persiste, por lo que las recomendaciones deberían centrarse en diseñar programas educativos y de sensibilización para la seguridad en los pasos a nivel.

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SOSTENIBILIDAD
SUSTAINABILITY

CONNECTIONS BETWEEN MOBILITY AND URBAN FABRICS IN THE CITY OF BURGOS (SPAIN)

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RESUMEN

Previous research has studied possible links between different urban environments and induced mobility. The traditional Spanish city patterns have specific features that promote the use of soft modes, mainly favouring pedestrian presence in the streets. Nevertheless the last twenty years development has changed the previous urban reality in many towns, following some sprawl characteristics and occupying much more land than strictly necessary. Accordingly, we have analyzed the morphology of Burgos using the perspective of urban fabric differences. Focusing in some parameters such as density of dwellings, population and compactness, we have tried to understand the underlying correlation between urban environment and private car trip generation.

However, although some of these urban variables can be considered as quantitative and quick indicators for unsustainable modes of transport, the effects of compact or diffuse development cannot be figured without taking into consideration other parallel factors that configure urban vitality. A previous qualitative analysis of urban growth and development may help to grasp this reality, connected with design criteria trends and urban planning policies. Likewise, mobility cannot be completely understood if only quantitative correlation is prosecuted. The retail distribution or concentration, the presence of malls, the excessive streets broadness, the existence and size of open spaces, or the residential building typologies have verifiable impact on the final modal share. Our results show clear correspondence between low dense urban fabrics and higher number of car trips. Hence, future urban development and reform policies must be oriented if sustainable mobility objectives want to be fulfilled. We suggest some final recommendations with this aim.

1. INTRODUCTION

Multiple studies have tried to understand the underlying connection between urban morphology features and mobility, many of them trying to find the best practices to achieve sustainable solutions and policies. Research has used different statistical and modelling tools and approaches to tackle this. An important part of the results have shown that compactness and density are initial indicators of a lower use of car in terms of kilometres travelled (Ewing et al., 2018; De Vos, 2015; Ewing and Cervero, 2010).

However, some others have evinced no significant influence, no direct effect reflected in the analysis, or an increased complexity due to regional differences (Maat et al., 2005; M. G. Boarnet and Sarmiento, 1998; Ewing et al., 1996; M. Boarnet and Crane, 2001; Lin and Yang, 2009). Anyway, we can accept an academic consensus about the convenience of the so called 5D-variables explained by Ewing and Cervero (2010) in terms of sustainable urban development: density, diversity, design, distance to transit, and destination accessibility.

Critically reviewed, we can argue that in many of previously referenced works there is a strictly statistic use of data. Neighbourhoods, districts, towns, suburban areas, travelled kilometres, shopping areas, citizens, and number of trips are numerically adopted by a more simple or complex model to study the possible correlations. Nevertheless, spatial differences are usually forgotten, even when important variances can be observed in very near zones or neighbours. We find here a gap in this kind of studies that must be accordingly revised and which plays a special role in small and medium cities (SMCs) due to the reduced trip distances.

Moreover, density and compactness cannot be analyzed as isolated variables. Counterbalance effects were identified in large cities when high congestion may be provoked by origin-destination concentration, where increased investment on highways is consequently required (Ewing et al., 2018). A carefully design of land use distribution added to parking control measures were identified as requirements to reduce car dependence, seeking for polycentric distributions and adequate mix of uses (Choi, 2018).

On the other hand, low density and compactness have been previously identified as key factors in many other negative factors: health problems (Hamidi et al., 2018); local urban service and facilities costs (Sole-Olle and Hortas-Rico, 2008); and ecological or pollution drawbacks (Cárdenas Rodríguez et al., 2016; Chen et al., 2019). The important impact that transport and urban planning policies has on climate change mitigation strategies has been also recognized by the Intergovernmental Panel on Climate Change (Sims et al., 2014), which suggested a reduction in private cars use as a major contribution to achieve these objectives.

In summary, research has shown the potential of urban planning decisions on mobility, and their implication on health and other important issues. However, we consider that the particular urban morphology of each city plays an essential role in the understanding of this connections and possible effects. Therefore, we introduce here a novel path to perform a locally oriented study of theses links, as an alternative o complement to mere statistical or numerical approaches that forget the city singularities. For this aim, we suggest an urban pattern and tissue analysis to find out possible expected differences when similar values of density or compactness are compared.

2. URBAN TISSUES ANALYSIS

For the purpose of this work, we have selected the city of Burgos as an example of Spanish SMC. Due to its population of 175821 inhabitants (Spanish Statistical Office, 2019) we can consider it as a representative MC according to European statistics. Burgos, placed in the north of Spain between Madrid and Bilbao, experienced a quick increase in number of inhabitants between 1996 and 2012, and after a slight reduction is now in a plateau situation (fig. 1). Burgos has an important heritage ensemble and is crossed by Arlanzón River in the east-west axis. Current local land-use regulation was planned in 2008 and reviewed in 2013, including a set of developable zones denoted as sectors by regional laws.

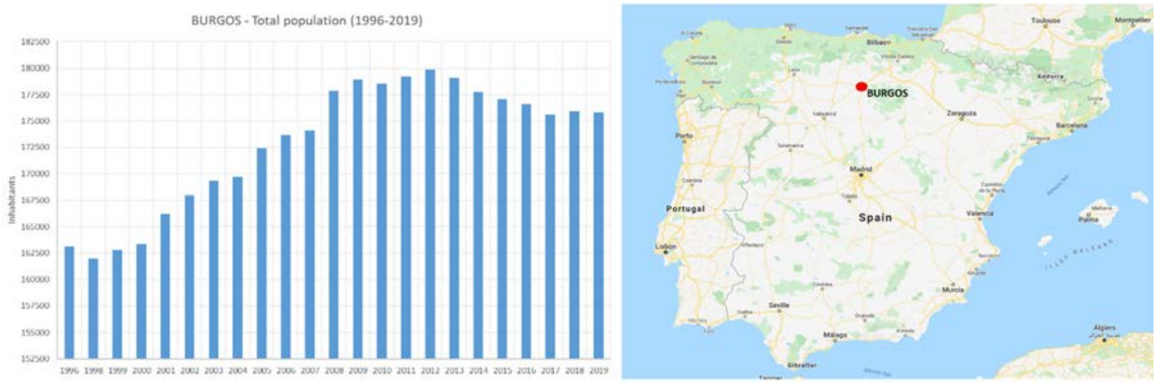

Fig. 1 – Population and location of Burgos (Spain). Source: Google Maps

Fig. 2 – A selection examples for the different urban tissues identified in the city of Burgos. A: historic centre; b: the garden city concept; c: traditional popular area (type 1); d: traditional popular area (type 2); e: first extension; f: second extension, compact; g: second extension, ultra-compact; h: second extension, open type; i: third extension. Source: Google Maps.

Regarding to the already built land, the growth of the city has experienced different phases. This growing mode is very linked with the urban tissue distribution and contrasts. In fact, we can distinguish the following fabrics in parallel to the historical spread of the residential uses. We here generally agree with previous selection criteria by other authors (Andrés López, 2013), but grouping part of them in homogenous sets: Historic centre and near surroundings, Garden city, Traditional popular areas, First extension (1930-1964), Second extension (1960-1980), Third extension (1980-nowadays). Performing a brief analysis of planning features of each of them is an unavoidable step to understand the daily movements of neighbours.

2.1 Historic centre and near surroundings

Although the city was founded around 884 A.D., many buildings in this area were erected between the endings of 19^{th} century and the fifties of 20^{th} century (Andrés López, 2004), and an important part of them have been internally refurbished or adapted in the near past (Fig. 2a). However, the singularities of this district and tissue are intrinsically connected to its origin: a medieval urban pattern with narrow and irregular streets, very compact small-buildings distribution, outdated services, and lack of parking lots. Burgos centre is, since many years ago, partially pedestrian. Nowadays the district is focused on tertiary sector, attracting a vast part of city population to its restaurants and bars, and very connected to the tourism due to the heritage richness.

2.2 Garden city

This special tissue is not a follower of the original Garden City movement spirit, but nearer from the Garden Suburb concept (Andrés López, 2000). Like in other Spanish cities, mainly during the twenties of 20th century, the emergent bourgeoisie was offered to live in specially designed areas for high-income families. These types were commonly placed in the periphery, and the use of vegetation played an important role in the concept. Initially disconnected from the urban core and designed with very low density of detached single-family houses, the growth of Burgos has engulfed this neighbourhood (Fig. 2b).

2.3 Traditional popular areas

Inside this tissue we want to distinguish two different types or groups of popular areas. The first (type 1 in Fig. 2c) are related with the so called Low-income houses law (*Ley de casas baratas*), which were built in Burgos during different phases between 1911 and 1936 (Delgado Viñas, 1992). The main characteristic is the typology: semi-detached or attached single-family houses, with small gross floor area, a little garden included, and reduced budget. Most of these have been already demolished to build multifamily buildings during the 20^{th} century. However, some of them continue in the same position and configuration, although many have been refurbished to be adapted to current building and isolation standards.

The second group (type 2 in Fig. 2d) consists of three low density small popular neighbourhoods built around the thirties of 20th century. Generally speaking they have with very similar features than the first group, but the number of houses is bigger forming each one a sort of core, like a very small village. The size of dwellings is usually bigger in this case. Even though they were initially built far away from urban core, the growth of the city has reached them.

2.4 First extension (1930-1964)

A reduced residential multifamily development was produced during the post Civil War period. The closed block is the used typology (Fig. 2e), with a very compact distribution of dwellings and relatively high population density. A not fully regular gridiron plan was used for the street pattern. Commerce is placed in the ground level.

2.5 Second extension (1960-1980)

An important growth occurred in this period, affecting to several zones of the city. We can distinguish here differences depending on the year of design. First, a compact (Fig. 2f) or ultra-compact (Fig. 2g) closed block solution was extensively used, reaching an exceptionally high population density. Here a lack of parking lots and open spaces is often found, but the compactness promote on foot daily trips. On the other hand, open types like blocks and towers were built (Fig. 2h), with open spaces or parking areas around them.

Sometimes the buildings are distanced each other, extending pedestrian distance. This tissue was also affected by the intersection of big mono-functional zones (mainly sports and schools). Although buildings by itself are densely populated, the distances and interspaces reduce global values for this variable. The ground floor includes space for tertiary sector.

2.6 Third extension (1980-nowadays)

The latest developments are usually featured by oversized carriageways, commonly using a grid pattern (Fig. 2i). Regarding to typologies, a mix of possibilities is found. The open block is revisited, and the closed block has been erected sometimes with a bigger horizontal dimension. Internal block areas include occasionally private services (sport yards, green zones, swimming pools…). Open spaces are often underused due to size, design or placement. Although a mix of used is promoted by regulations, it is usually formalized using detached buildings, while ground floors are sometimes devoted to residential uses. In some cases the planned density has been not reached due to incomplete development, or the presence of half-empty buildings.

2.7 Tissues summary

Table 1 qualitatively summarizes the basic characteristics of Burgos urban tissues.

	Tissue	Density	Open spaces	Commerce
a	Historic centre	M	M	H
b	Garden city	VL	L	VL
c	Traditional popular area (type 1)	L	VL	VL
d	Traditional popular area (type 2)	L	L	VL
e	First extension	M - H	L	H – VH
f	Second extension (compact)	H	L – M	H - VH
g	Second extension (ultra-compact)	H -VH	L – VL	VH
h	Second extension (open type)	M - H	H – VH	L- M
i	Third extension	M	M - H	L - M

Table 1 – Tissues features as a glance (VL= Very Low, L=Low; M=Medium; H=High; VH= Very High).

3. URBAN PARAMETERS AND GENERATED CAR MOBILITY

The use of official statistics and cadastral data for population and dwellings (Spanish Statistical Office, 2011; Spanish Cadastral Office, 2017) was combined with a GIS software (QGIS Development Team, 2017). To compute density and compactness, postal sections were used as geographical divisions. Population was randomly placed in each section. To calculate compactness, a total buildings volume estimation was divided by section area. OpenStreetMap database (OpenStreetMap, 2019) was consulted to gather the distribution of common commercial uses: small shops and offices, cafeterias, bars, retail business, bank offices…. Number of private car trips generated were also extracted from the origin/destination matrix from a mobility study included in the city General Plan (Burgos City Hall, 2014), which were later coherently and randomly dumped in the already mentioned sections. Different maps were performed as layers using QGIS tools as a result of these operations (Fig. 3), generating heat maps for population density, commerce and trips. Number of trips was normalized using population and areas of each section for comparison purposes.

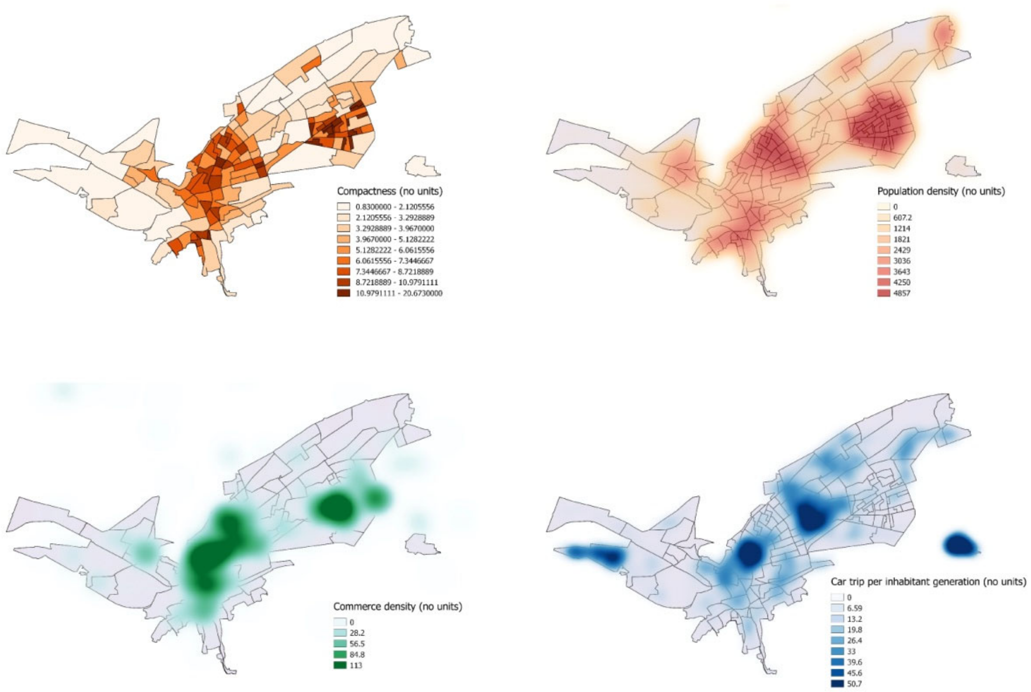

Fig. 3 – Top left: compactness density. Top right: population density. Down left: commerce density. Down right: generated private car trips density. In all cases, densities have no units but represent clearly the differences among the different sections.

As a result, a noticeable correlation can be identified between compactness and density, and also with the retail business distribution pattern. Regarding to mobility, zones with lower commerce presence are those with a higher generation of car trips. Moreover, the features of the urban tissues (Table 1) and the position on the city map are very connected with the generation of private car trips. The mentioned features have to be joined with some other section variables as the age of population and number of young families. Fig. 4 includes the map of the city and car trips, superimposing the characteristic tissue of each part of the city.

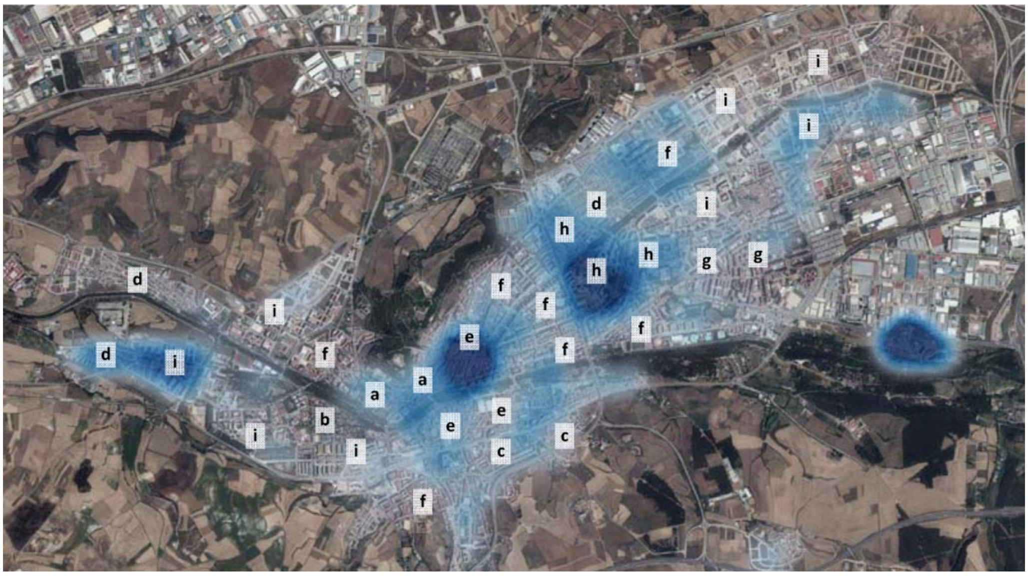

Fig. 4 – Density of generated car trips over the tissue map distribution.

4. PLANNING RECOMMENDATIONS

The links between urban environment characteristics and mobility shown by our results allow inferring a set of recommendations for future planning decisions in SMCs development:

- Regulation may be not enough to achieve sustainable mobility results if not clear objectives are prosecuted and implemented For instance, a minimum mix of uses can be applied in a development area without avoiding segregation of commerce.
- To obtain adequate results in diversity of uses, a minimum density of 80-90 dwellings per hectare may be considered as the standard.
- Although important, high density is not enough to reach adequate values of compactness and variety in the area where are placed. Additional requirements must be applied in addition to mere density, because it can be distorted by the use of high density buildings (e.g., tall towers) in a low density area. However, density may be a good indicator when compactness and short distance mix of uses are fulfilled.
- Number and position of parking lots must be strictly studied to avoid attraction of unnecessary car trips.
- Pedestrian friendly environments, and short trip distances by adequate mix of uses are adequate policies to promote. Open spaces are needed and coherent with these principles, but the size and position must be carefully designed in a bigger scale. Too big open spaces may become counter-productive, underused or empty islands, increasing also pedestrian distances.

4. CONCLUSIONS

Previous research has applied statistical models to huge databases in large metropolises or urban regions.

We have oriented our work to a visual mapping and comparison in a particular city reality, to identify local particularities in its daily trip context. Our study has shown not negligible links between urban planning decisions (i.e. urban tissues) and induced unsustainable mobility in a SMC. Therefore, we suggest a set of recommendations to promote active travel modes and reduce car dependence.

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GREENHOUSE GAS EMISSION IN URBAN PASSENGER TRANSPORT

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ABSTRACT

Public transport of passengers is one of the development axis of the communities, due to the positive impact on socio-economic activities and its link between central and peripheral communities. In the city of Salta this situation also occurs, where public passenger transport is conceived as a metropolitan service. Such transport meets the population's need for mobility and, among its impact, contributes to the generation of greenhouse gases from combustion engine emissions. This paper presents an estimate of CO2 emissions in urban passenger transport in Salta, based on the collection of data on fuel consumption and distances. At the same time, it analyzes the CO2 emissions as a consequence of the COVID-19 pandemic. The results allow to visualize a trend of this emissions.

1. INTRODUCTION

1.1 Objet of Study

In fulfilling its main objective of providing mobility, transportation generates numerous impacts, including the generation of greenhouse gases. Globally, emissions from the transport sector correspond to 73% to road transport, 9% to international maritime transport, 11% to aviation (international and cabotage), and only 2% to rail (Barbero and Rodríguez Tornquist, 2012). In Argentina, road transport has a greater share than the word average and the national emissions of the transport sector calculated by mode reach a 90% share for road transport, followed by a distance by 5% corresponding to navigation, 4% for the air transport and 1% for rail. If road transport emissions are discriminated according to the type of demand, it is estimated that freight transport generates 61%, and passenger transport 39% (Secretaría de Ambiente y Desarrollo Sustentable, 2007).

The present work has the purpose of estimating the amount of greenhouse gases, with regard to carbon dioxide, emitted by urban passenger transport in the city of Salta. For this, the amount of fuel consumed and the factor of GHG emission is considered. It is a descriptive work, based on documentary research and field research. On the documentary side, research antecedents on the subject of this work, were firstly analyzed. The field research was based on data collection and interviews in public transport companies of the city of Salta. This article is structured as follows: in section 1 a brief introduction is presented. Section 2 presents the results and same good practices to reduce emissions. The paper ends with conclusions and references.

1.2 Characteristics of the operation of passenger transport in the city of Salta

The city of Salta, capital of the homonymous province, is located in the northwest of the Argentine Republic, and concentrates 44% of the provincial population. It constitutes the center of the so-called metropolitan area with 536.113 inhabitants (INDEC, 2010). Its population has grown by 46% in a period of 19 years. The Salta Metropolitan Area is made up of four departments, which includes eight municipalities. The public transport service is provided through a private state-owned company that unifies the management of the contracted companies for 8 corridors. It operates the 49 lines of the route network that cross the metropolitan area. The service operations include a fleet of 618 units (1,2 units per 100.000 inhabitants) with an average urban frequency in peak time of 7 minutes between bus units, which carry 650.000 passengers per day and more than 183 million per year (Arenas et al, 2016; Tarcaya et al, 2018).

2. RESULTS AND DISCUSSION

2.1 Estimation of CO2 emissions

The total number of passenger transport units is 618 vehicles powered by diesel engines that use diesel as fuel. This total is distributed in 8 transport companies. Of the aforementioned fleet of public transport vehicles for the study, two companies, called “A” and “B” were considered (Transportation companies, 2021). They have 105 and 58 units respectively. The sample considered makes a total of 163 units, representing 26,4% of the fleet of transport vehicles. In both cases, data was taken on kilometer travelled and fuel consumed, detailed per month during the years 2019 and 2020.

For the estimation of carbon dioxide emission, the conversion factor proposed by the Secretary for the Environment and Sustainable Development (2008) in version 1.0 of the document “The carbon footprint of the average Argentinian” as considered. Such conversion factor is expressed in Equation (1):

$$\text{Diesel emission factor} = 2{,}77\ (KgCO2\text{-}e\ /litre) \qquad (1)$$

Based on the data collected, we proceeded to the estimation of carbon dioxide emissions during the years 2019 and 2020, which is presented in Tables 1 and 2.

Month	Distances (km)	Consumed diesel (liters)	$KgCO_2$-e
January	844.763	306.147	848.027
February	778.757	281.509	779.780
March	848.054	323.887	897.167
April	823.591	324.324	898.377
May	860.579	320.929	888.973
June	863.449	322.321	892.829
July	868.232	306.540	849.116
August	922.003	325.834	902.560
September	920.778	325.167	900.713
October	935.005	350.660	971.328
November	898.417	342.921	949.891
December	838.379	317.340	879.032
Total	**10.402.007**	**3.847.579**	**10.657.794**

Table 1 - CO2 emissions in company "A" during 2019

Month	Distances (km)	Consumed diesel (liters)	$KgCO_2$-e
January	853.412	306.798	849.830
February	790.954	280.202	776.160
March	593.039	207.275	574.152
April	292.284	82.930	229.716
May	431.229	131.160	363.313
June	464.065	150.481	416.832
July	505.277	154.621	428.300
August	493.483	156.447	433.358
September	398.222	140.558	389.346
October	484.965	148.779	412.118
November	482.431	154.780	428.741
December	568.148	186.335	516.148
Total	**6.357.509**	**2.100.366**	**5.818.014**

Table 2 - CO2 emissions in company "A" during 2020

In Figure 1, a comparison of carbon dioxide emissions is shown during the years 2019 and 2020, being able to observe the fall caused by the isolation measures as a consequence of the COVID-19 pandemic, stablished by the Decree of the President of Argentina in the second half of March 2020.

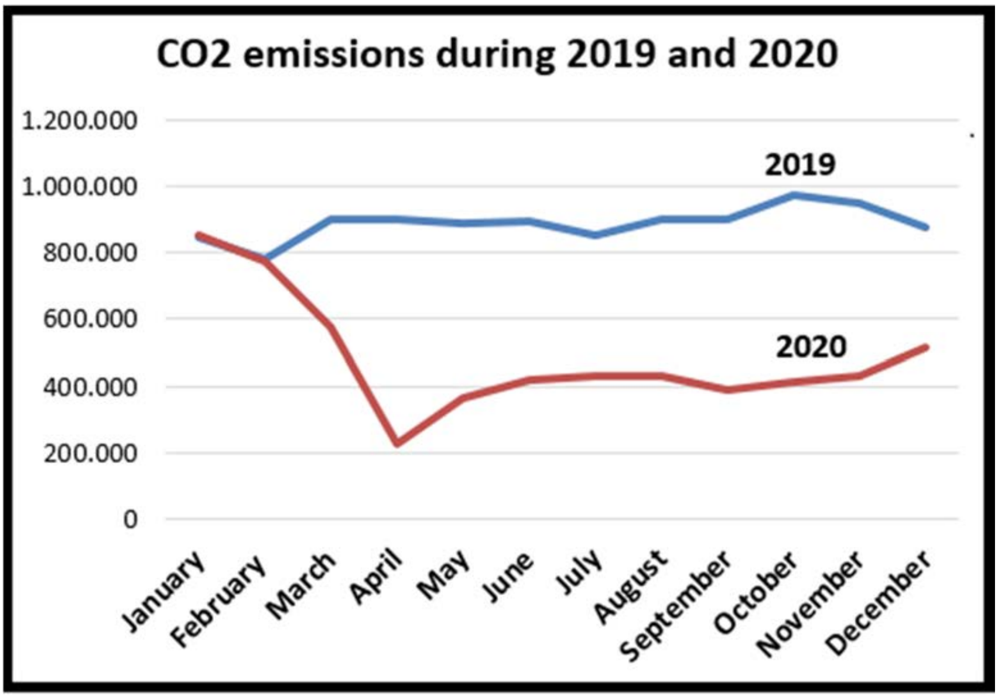

Figure 1 - CO2 emissions in company "A" during 2019 and 2020 years

Similarly, we proceeded with the data collected in company "B", which is shown in Tables 3 and 4.

Month	**Distances (km)**	**Consumed diesel (liters)**	**$KgCO_2$-e**
January	173.627	65.219	180.657
February	151.547	57.782	160.056
March	198.654	75.823	210.030
April	197.806	75.910	210.271
May	202.521	76.878	212.952
June	188.986	72.315	200.313
July	179.171	66.545	184.330
August	207.282	78.709	218.024
September	184.436	70.102	194.183
October	203.604	77.359	214.284
November	192.824	72.949	202.069
December	175.711	67.105	185.881
Total	**2.256.169**	**856.696**	**2.373.048**

Table 3 - CO2 emissions in company "B" during 2019

Month	**Distances (km)**	**Consumed diesel (liters)**	**$KgCO_2$-e**
January	177.689	67.640	187.363
February	166.610	63.781	176.673
March	125.170	47.175	130.675
April	60.099	20.114	55.716
May	90.290	30.787	85.280
June	96.988	33.703	93.357
July	106.222	34.955	96.825
August	103.325	34.790	96.368
September	84.379	28.192	78.092
October	102.113	34.874	96.601
November	101.954	34.215	94.776
December	117.959	39.994	110.783
Total	**1.332.798**	**470.220**	**1.302.509**

Table 4 - CO2 emissions in company "B" during 2020

In Figure 2, a comparison of carbon dioxide emissions during the years 2019 and 2020 in company "B" is shown. As in company "A", the fall caused by the isolation measures as a consequence of the COVID-19 pandemic is also observed, starting in the second half of March 2020.

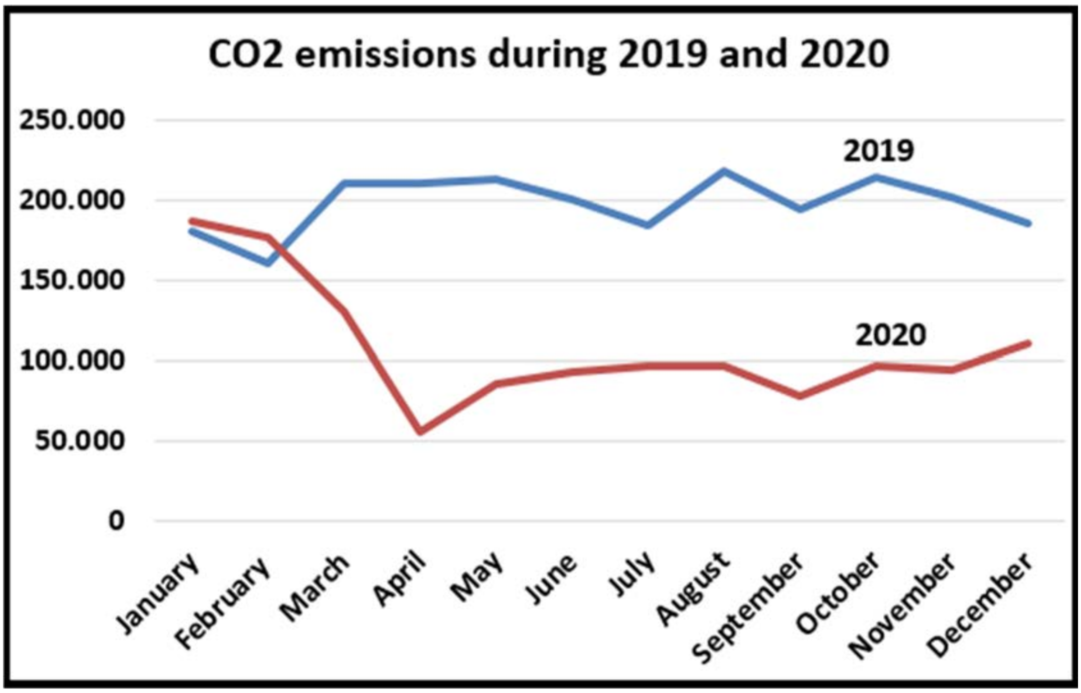

Figure 2 - CO2 emissions in company "B" during 2019 and 2020 years

In both companies, a similar trend is observed in carbon dioxide emissions proportional to the liters of fuel consumed.

This can be considered as the bases for an estimate for the entire fleet of transport vehicles.

Since the isolation measures were stablished in the city of Salta, mobility has not been the same again, since at first only essential workers could travel by public transport. This caused the buses to circulate with few passenger and, in many cases, without passenger at bus stops. This changes in mobility also caused reductions in CO_2 emissions per kilometer travelled, since driving with fewer stops, the fuel efficiency was higher, as it is observed in Figure 3.

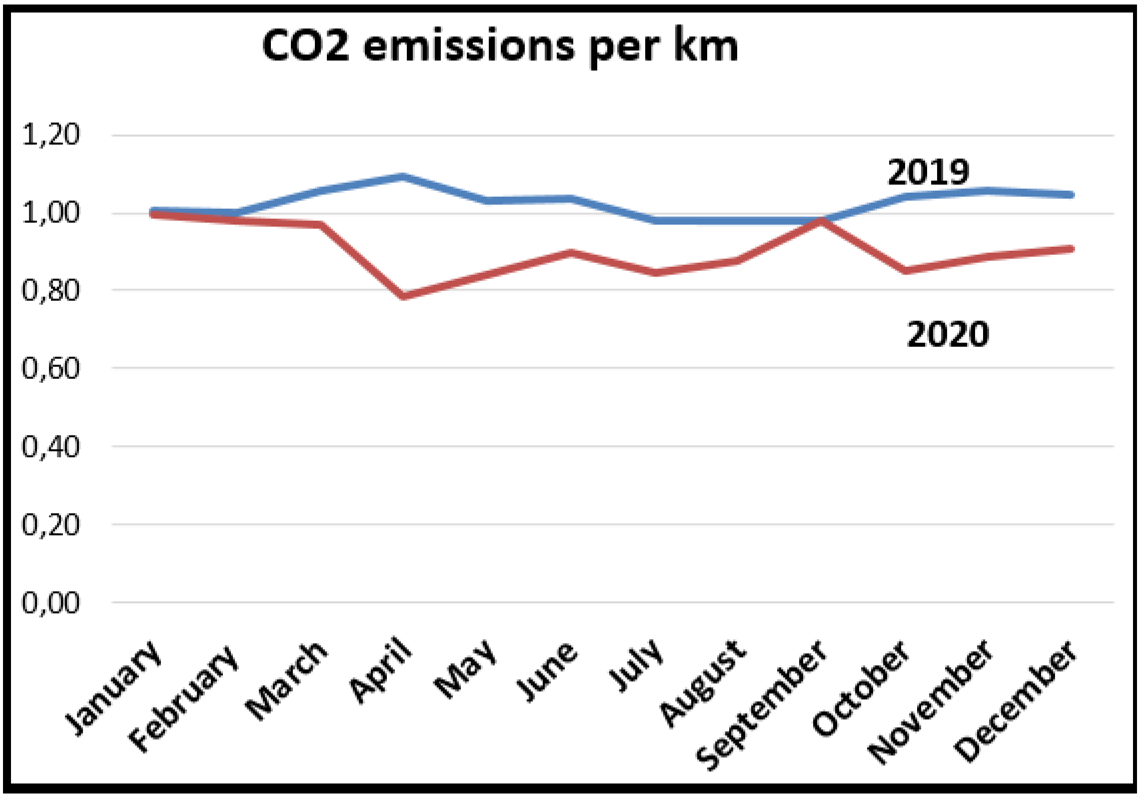

Figure 3 - CO2 emissions per km during 2019 and 2020 years

2.2 Good practices to reduce emissions

Among the good practices that are recommended to reduce carbon dioxide emissions in buss transports we can mention:

Maintenance controls: Maintenance is not only a strategy for reducing fuel consumption, but it also a key aspect of vehicles safety. Tires pressure control is substantive, since in case of being deflated they have greater resistance to rolling. Greater pressure translates into less flattening, reducing the area of contact with the pavement and reducing the resistance force (Instituto del Transporte, 2016). Air and fuel filter controls are also recommended, leading to a richer mixture in combustion, with a more rational use of fuel.

Efficient driving: Considering that fuel consumption increases at high and low speeds, it is recommended to ride in the longest possible gearbox and at low revolutions. It is also recommended to keep the speed of circulation as uniform as possible and driving with anticipation and foresight, avoiding sudden accelerations (Instituto del Transporte, 2016).

Fuel change: Public transport vehicles using compressed natural gas (CNG) engines is a pilot test in Argentina. The change from diesel fuel to CNG is an important mechanism not only to reduce emissions, but also to reduce total costs (Puliafito and Castesana, 2010; Montero Sanz and Díaz López, 2014; Scania, 2019).

3. CONCLUSIONS

The work shows a first approximation of the estimates of carbon dioxide emissions in part of the fleet of public transport of passenger vehicles, with the limitations and the availability of data and information by the time of doing it. However, even with these restrictions, it was possible to identify trends and good practices to improve fuel efficiency, and therefore reduce the emissions.

Some aspects of this study might be limited. For example, the sample considered represents only 26,4% of the fleet of transport vehicles. This and other limitations of the work will be the focus of further research.

This work is a starting point for future research to complement it, in order to reduce carbon dioxide emissions and thus contribute to the preservation of the environment.

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IMPACTO SOBRE EL CAMBIO CLIMÁTICO QUE GENERA LA MOVILIDAD EN LA UPM: CÁLCULO DE LA HUELLA DE CARBONO

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RESUMEN

La descarbonización de la movilidad urbana se ha convertido en uno de los principales objetivos de las ciudades, que ven cómo florecen diferentes planes y estrategias para hacer frente al cambio climático. Dentro de las ciudades, las universidades son áreas que propician la concienciación sobre estilos de vida respetuosos con el medio ambiente. El presente trabajo describe una acción que se puso en práctica en la Semana de la Movilidad Europea de 2019 en la Universidad Politécnica Madrid (UPM).

El objetivo fue que toda la comunidad UPM (más de 40.000 personas) conociese las emisiones de CO_2 diarias de sus desplazamientos a la UPM. Para ello, se realizó una sencilla encuesta de movilidad online en la que los encuestados indicaban los modos de transporte que utilizaban para llegar a los centros UPM, la distancia que recorrían y el motivo de escoger dichos modos. En 3 días que duró la campaña, se recogieron 2.149 respuestas.

El estudio incluye una metodología para calcular los factores de emisión de dióxido de carbono por modo de transporte del área metropolitana de Madrid. Los resultados demuestran que el transporte público es el modo principal utilizado por la comunidad UPM con más del 75% de viajes realizados, los modos privados representan el 17% y los modos blandos un 8%. Sin embargo, son los modos privados quienes emiten más del 55% de las emisiones de CO_2 totales de la UPM.

Tras un análisis en profundidad de los motivos que llevan a utilizar un modo u otro, se proponen un conjunto de políticas para la reducción de las emisiones. Se destaca la campaña de concienciación que se realizó en la Semana de la Movilidad con la difusión de los resultados en Ciudad Universitaria para hacer partícipe a la ciudadanía de los impactos al clima que tienen nuestras decisiones individuales.

1. NTRODUCCIÓN

El crecimiento de la población en las áreas urbanas -en 2018 el 55% de la población mundial residía en áreas urbanas y se prevé que para el 2050 más del 70% de la población mundial se concentre en áreas urbanas (United Nations, 2019)- conlleva un aumento de la movilidad urbana con sus derivados impactos medioambientales, como son las emisiones de Gases de Efecto Invernadero (GEI). Una de las consecuencias es que la descarbonización de la movilidad urbana se ha convertido en uno de los principales objetivos de las ciudades, con la implementación de planes y estrategias para hacer frente al cambio climático.

Este es el caso de España, donde las principales ciudades están tomando medidas para frenar las emisiones GEI y la contaminación en las áreas urbanas a través de planes de acción y estrategias de cambio climático y energía limpia, que se complementan con planes de calidad del aire y eficiencia energética. Una de las medidas que lleva implementándose desde la aprobación de la Estrategia Española de Eficiencia Energética 2004-2012 (E4) (IDAE, 2003) y el siguiente Plan de Acción 2011-2020 de la E4 son los Planes de Movilidad Urbana Sostenible (PMUS) junto con los Planes de Transporte al Trabajo (PTT) cuyos objetivos de reducción de emisiones son del 10% en las áreas urbanas. Entre muchas acciones, en el caso de la capital de España, en 2017 se aprobó el Plan de Calidad del Aire *PLAN A* (Ayuntamiento de Madrid, 2017) para cumplir con los objetivos de calidad del aire de la Unión Europea. Dentro de dicho plan se enmarca la *Zona de Bajas Emisiones (ZBE) Madrid Central* pionera en España, que comenzó a funcionar en diciembre de 2018, y donde se restringe el acceso libre de los vehículos en una amplia zona. Madrid Central tiene el doble objetivo de reducir la contaminación atmosférica y las emisiones GEI. Según apunta un estudio preliminar de Blázquez (2019), en los primeros meses demostró ser útil para mejorar la calidad del aire, aunque eran necesarias medidas más fuertes para logar reducir de forma más notable las emisiones.

Otra medida son las campañas de información y comunicación a la ciudadanía. Diversas fuentes señalan que si los ciudadanos son más conscientes de las posibilidades de estilos de vida y hábitos de consumo respetuosos con el medio ambiente, se les puede alentar a experimentar en su vida diaria acciones que ayuden a reducir las emisiones de dióxido de carbono (Delmas et al. 2013; Klöckner, 2015). Sobre estas campañas de sensibilización e información a la población trata de enfocarse el presente trabajo. Aprovechando la Semana de Movilidad Europea de 2019 se puso en marcha una acción en la Universidad Politécnica de Madrid (UPM) preguntando a la comunidad universitaria qué modo de transporte utilizan para ir a la universidad, su distancia de recorrido y el motivo de escoger ese modo de transporte. Se calcularon sus emisiones asociadas, y se informó en una campaña de concienciación en el campus de *Ciudad Universitaria* la huella de carbono de su viaje diario a la universidad (Global Challenge, 2019).

El objetivo principal de este estudio es doble: en primer lugar, proponer una metodología para estimar las emisiones totales de dióxido de carbono (CO_2) generadas por la comunidad UPM en su viaje diario a los campus, y en segundo lugar, comprender mejor las características del colectivo y cómo se viaja a la UPM para proponer una serie de políticas que den lugar a la reducción de la huella de carbono en la UPM. Esta comunicación se divide en varias secciones. A continuación se recogen estudios similares que analizan la movilidad en los campus universitarios y los impactos sobre el cambio climático (Sección 2). Seguidamente, se describe el caso de estudio de la UPM y la metodología llevada a cabo para la estimación de las emisiones de CO_2 de la movilidad en la UPM a partir de una sencilla encuesta online (Sección 3). Con la aplicación de dicha metodología al caso de estudio de la UPM, se analizan los resultados y se reflexiona sobre diferentes acciones que ayuden a la comunidad universitaria a reducir el impacto sobre el cambio climático de los movimientos diarios que se realizan a los centros de atracción de población, como son las áreas universitarias de las ciudades (Sección 4). Por último, se realizan las conclusiones y futuras investigaciones.

2. MOVILIDAD EN LOS CAMPUS UNIVERSITARIOS E IMPACTOS SOBRE EL CAMBIO CLIMÁTICO

Recientemente, las universidades están desarrollando un creciente interés en políticas institucionales que promuevan la movilidad sostenible (Leona et al. 2018). En efecto, las universidades son lugares ideales para explorar el impacto de medidas que promuevan hábitos de transporte más saludables, debido a la mayor predisposición de los estudiantes universitarios y su personal a utilizar medios de transporte activos (Balsas et al. 2003). Este es el motivo por el que las universidades alrededor del mundo están promoviendo iniciativas sostenibles, donde las medidas sobre la movilidad son importantes.

Para poder proponer medidas se necesita, en primer lugar, conocer los impactos sobre el cambio climático que la movilidad en las áreas universitarias genera. Son varios los trabajos de investigación que han analizado las emisiones de GEI de la movilidad en las universidades por todo el mundo y que se recogen a continuación.

En Canadá, Mathez et al. (2013) analizaron las emisiones diarias al campus del centro de la ciudad de la universidad McGill en Montreal a través de una encuesta online a los estudiantes y trabajadores. Entre sus resultados cabe destacar que las diferencias de género no obtienen grandes disparidades de emisiones, sin embargo, sí que hay grandes diferencias entre estudiantes y personal de la universidad. Los estudiantes generan 3,6 veces menos de gCO_2eq/persona-viaje que el personal de la universidad. Por modo de transporte utilizado, los conductores de vehículo privado son los que más emiten. Más recientemente, Hafezi et al. (2019) estimaron las emisiones de CO_2 de la universidad Dalhousie en Nova Scotia a toda su comunidad. Entre los resultados encontraron que el personal de administración y servicios son los que más emiten por persona y día

(370,23gCO_2/persona-día), siendo los resultados consistentes con los del estudio de Mathez et al. (2013).

En Estados Unidos, Appleyard et al. (2018) desarrollaron una metodología para calcular las emisiones anuales generadas por el transporte de sus viajeros a la universidad estatal de San Diego, en California, a través de una encuesta online. Los resultados con consistentes con investigaciones en otras universidades, y es que los que emiten más CO_2 per cápita son los miembros del colectivo de personal de la universidad, que en el caso de San Diego está explicado porque recorren más distancias para ir al campus y, además, más del 75% utiliza el vehículo privado. El estudio también incluye la evaluación de diferentes políticas, donde se destacan la utilización de vehículos eléctricos como una acción que podría reducir el 60% de las emisiones.

En Reino Unido e Irlanda, Davison et al. (2015) estudiaron los impactos sobre las emisiones del comportamiento modal de los estudiantes en 17 universidades de Irlanda y Reino Unido. Entre los resultados se destacó que los estudiantes que utilizan más el vehículo privado, y por ende lo que más emiten, corresponden a mujeres que estudian a tiempo parcial, mientras que los hombres tienden a utilizar más los modos activos. Las diferencias entre estudiantes de diferentes regiones son notables, siendo los estudiantes de Irlanda del Norte los más dependientes del coche y que recorren más distancias, con lo que son los más emisores. Por el contrario, los estudiantes escoceses emiten menos, pues son los que más utilizan los modos ferroviarios y modos activos.

Por último, en España, Pérez-Neira et al. (2020) analizaron los patrones de la movilidad de la Universidad de León y su potencial para mitigar las emisiones GEI. Los resultados son similares a los de estudios anteriores, el personal universitario emite el doble de emisiones de CO_2eq por viaje a la universidad (728 gCO_2eq/persona-viaje de los estudiantes frente a los 1531 gCO_2eq/persona-viaje del personal de universidad). Además, aquellos que utilizan el coche son los que emiten el 95% de las emisiones totales por movilidad de la comunidad universitaria. Se proponen en el estudio diferentes medidas para reducir los impactos al cambio climático, como estrategias de educación y concienciación del personal, estimular el uso de modos activos, mejorar las infraestructuras de transporte público entre otras.

Como se recoge de los estudios anteriores, las universidades tienen la extraordinaria capacidad de generar conciencia sobre todos los aspectos de la sostenibilidad en las comunidades, siendo el transporte un sector clave en la sostenibilidad. El efecto del uso de los diferentes modos de transporte para ir a la universidad sobre las emisiones es significativo y demuestra la importancia de la educación y difusión del impacto de los viajes a la universidad para el desarrollo de una política sostenible de transporte.

3. METODOLOGÍA

3.1 Ámbito de estudio: campus universitarios de la UPM

La Universidad Politécnica de Madrid (UPM) es una universidad pública con diferentes sedes en el área metropolitana de Madrid, área que ocupa unos 8.030km^2 y cuenta con una población total de 6.663.394 habitantes repartidos en 179 municipios en 2019. La ciudad de Madrid es la capital de España, con una población total de 3.226.126 en 2016, cubriendo 605km^2 (Comunidad de Madrid, 2020). La UPM se reparte en cuatro campus principales (Figura 1): *Campus Ciudad Universitaria* (que incluye 9 escuelas y el complejo del rectorado), *Campus Madrid Ciudad* (que incluye 4 escuelas cercanas a la Zona de Bajas Emisiones de Madrid –Madrid Central-), *Campus Sur* (justo al lado de la carretera de circunvalación M-40 y que incluye 4 escuelas, 2 centros/institutos de investigación y 1 biblioteca) y *Campus Montegancedo* (en el municipio de Pozuelo de Alarcón, que incluye 1 escuela y 7 centros/institutos de investigación). La accesibilidad del transporte público cercano a estos campus, así como la presencia de áreas de estacionamiento gratuitas son factores que impactan directamente en la elección modal de los viajeros hacia estos campus (Tyrinopoulos y Antoniou, 2013). La Tabla 1 resume las principales características de los cuatro campus de la UPM, incluyendo el transporte público cercano o infraestructuras de transporte. Como es de esperar, los campus cercanos al centro de la ciudad de Madrid tienen una mejor conexión en transporte público y menos áreas de estacionamiento para vehículo privado que los que se encuentran a las afueras de la capital.

La comunidad de la UPM son más de 40.000 personas, representando el 1,37% de la población total de la ciudad de Madrid. Sus principales colectivos son: 39.000 estudiantes (incluyendo estudiantes de grado, postgrado y movilidad internacional), personal docente e investigador (PDI) con 3.300 personas y el personal de administración y servicios (PAS) con 1.890. En noviembre de 2019, la UPM plasmó su compromiso de lucha contra el cambio climático creando “Comité para la Descarbonización de la UPM”, por el cual la universidad ha fijado la meta intermedia de anular sus emisiones directas netas de gases de efecto invernadero en el año 2030, con el fin de alcanzar la neutralidad climática en 2040 (UPM, 2020).

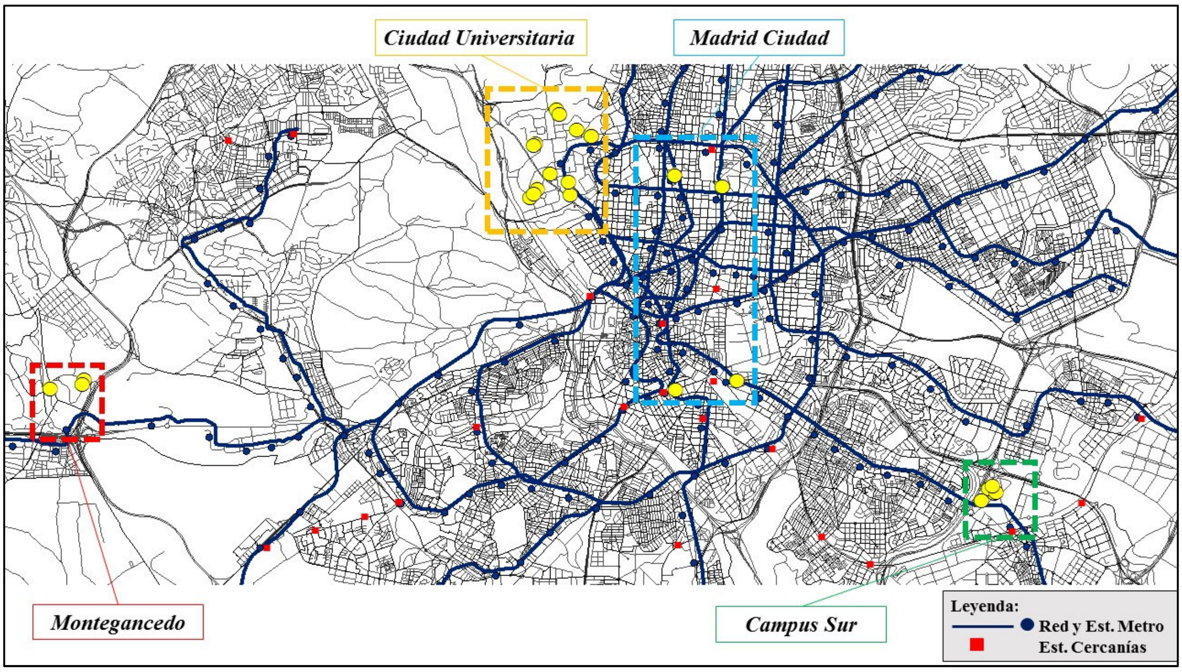

Fig. 1 – Mapa de los campus universitarios de la UPM en Madrid.

CAMPUS UPM	Nº EDIFICIOS	ESTACIONES DE METRO/CER-CANÍAS	LÍNEAS DE AUTOBUS	SISTEMA DE BICICLETA PÚBLICA	PARKING GRATUITO	DISTANCIA AL CENTRO DE LA CIUDAD
Ciudad Universitaria	9 Escuelas y rectorado	2 estaciones de metro	Si, líneas urbana e interurbana	No	Si	4km
Madrid Ciudad	4 Escuelas cercanas a “Madrid Central”	4 estaciones de metro & 3 estaciones de cercanías	Si, urbanas	Si	Parcialmente	2km
Campus Sur	4 Escuelas & 2 centros/ institutos de investigación, 1 biblioteca	1 estación de metro & 1 estación de cercanías	Si, líneas urbana e interurbana	No	Si	7km
Campus Montegancedo	1 Escuela & 7 centros/ institutos de investigación	No	Si, línea interurbana y 1 línea exclusiva para personal UPM	No	Si	11,5km

Tabla 1 – Características de los campus UPM en 2019

3.2 Encuesta de movilidad online en la Semana de la Movilidad Europea 2019

En la celebración de la Semana de la Movilidad Europea 2019, la UPM dentro del programa *Global Challenge* realizó en septiembre de 2019 una sencilla encuesta online de tres días (martes 10, miércoles 11 y jueves 12 de septiembre de 2019) preguntando a toda la comunidad UPM qué modo de transporte utiliza para ir a los campus UPM (Global Challenge, 2019). La participación fue voluntaria y anónima. Un cuarto día (el 19 de septiembre) se realizó la difusión de los resultados (después de aplicar la metodología, ver Sección 3.3) de la encuesta en la salida del Metro de Ciudad Universitaria con el objetivo de concienciar de los impactos del cambio climático al viajar a la universidad. El propósito de la encuesta fue comprender la elección modal diaria de la comunidad universitaria hacia los campus UPM y las principales razones de las elecciones modales (ver Tabla 2).

Preguntas	Respuestas
1. Género	Hombre / Mujer / No declara
2. ¿Cómo vienes a la universidad?	Pie / Bicicleta / Coche / Moto / Metro / Autobús Urbano (EMT) / Autobús interurbano / Tren - Cercanías / Otro (ej. Patinete)
3. ¿Por qué utilizas esos modos?	*Texto libre*
4. ¿A qué campus UPM vas?	Ciudad Universitaria / Madrid Ciudad / Campus Sur / Campus Montegancedo
5. ¿Podrías estimar los kilómetros que recorres para llegar a la UPM?	Hasta 5km / 5km-10km / 10-20km / Más de 20km
6. ¿A qué colectivo perteneces?	Estudiante / Personal Docente e Investigador / Personal de Administración y Servicios / Otros (proveedores, operarios, etc.).

Tabla 2 – Diseño de la encuesta online

3.2.1 Características de la encuesta

La encuesta fue respondida por un total de 2.142 personas de la UPM, siendo la tasa de respuesta del 4,8%. Para verificar si el número de encuestados cumple con los requisitos del tamaño mínimo de muestra, se utiliza la fórmula de Smith (Smith, 1979).

$$N_{min} = \frac{p(1-p)}{\frac{d^2}{Z^2}+\frac{p(1-p)}{N}} \quad (1)$$

Donde N_{min} es el tamaño de muestra mínimo, N es el tamaño de la población objetivo, p es la distribución de la respuesta desconocida (p=50%), Z es la normal para un 95% de confianza (Z=1,96) y d es un nivel absoluto de precisión (se aplica d=5%). Según la ecuación [1], el tamaño mínimo de la muestra para la población de 44.190 de la UPM es de 381. Por lo tanto, el número total de encuestados cumple con los requisitos de un tamaño mínimo de la muestra.

Aunque se tiene una sub-representación de los estudiantes en la encuesta, y una sobrerrepresentación del PDI y del PAS (ver Tabla 3), lo cual es común en encuestas universitarias (Mathez et al. 2013; Appleyard et al. 2018).

	Actual (absoluto; %)	Encuesta (absoluto; %)
Estudiantes	39.000; 88,3%	1.641; 76.6%
PDI	3.300; 7.5%	273; 12.7%
PAS	1.890; 4,3%	228; 10.4%
Total	44.190	2.142

Tabla 3 – Comparación del tamaño de la muestra con la población universitaria real.

3.3 Estimación de las emisiones de CO_2 por modo de transporte en el área metropolitana de Madrid

La estimación de los impactos sobre el cambio climático de los desplazamientos diarios individuales a los campus universitarios de la UPM se realiza combinando la distancia recorrida por diferentes modos de transporte y el factor de emisión medio específico de cada modo. De tal forma, que las emisiones diarias medias de CO_2 relacionadas con cada viaje se calculan de la siguiente forma (Stead, 1999; Nicolas y David, 2009; Ko et al. 2011; Sobrino & Monzon, 2013):

$$C_i = \sum_m D_{i,m} \times FE_m \quad (2)$$

Donde C_i representa las emisiones individuales de CO_2 de los viajes diarios al campus (gCO_2/persona-viaje), i denota el individuo y m es el modo de transporte utilizado. $D_{i,m}$ (km) es la distancia recorrida por el individuo i en el modo m que se deriva de la encuesta online (Sección 3.2.1, tomando el promedio de la distancia estimada), FE_m (gCO_2/pas-km) es el factor de emisión medio del modo principal m. En el presente estudio se considera modo principal siguiendo la siguiente jerarquía de modos: transporte público (tren>autobús interurbano>metro>autobús urbano)>coche>moto>bicicleta>pie.

Dependiendo del modo de transporte y los datos disponibles, la estimación del factor de emisión podrá tener dos enfoques (*top-down o bottom-upm*), ver Tabla 4. El enfoque *top-down* se basa en datos agregados a nivel macro (consumo total anual de energía, distancia total anual recorrida, tasa de ocupación anual). En el presente estudio, los factores de emisión se han estimado para el año 2017 (resultados en la Figura 2), que es el último año del que se dispone de datos suficientes para estimar dichos factores.

Se ha utilizado el enfoque *top-down* para estimar los factores de emisión del tren-cercanías, el metro y el autobús interurbano. En estos casos, el consumo anual de energía o las emisiones de CO_2 anuales de la flota se divide entre la distancia total recorrida en km y la tasa de ocupación media de la flota para obtener el factor de emisión por pasajero y kilómetro. La principal fuente de datos es el *Informe Anual del Consorcio Regional de Transportes de Madrid* (CRTM, 2019), ya que son modos de transporte público.

Por otro lado, en el enfoque *bottom-upm* se tienen en cuenta datos desagregados más detallados (tipo de la flota de vehículo, velocidad media, factor de emisión específico de cada vehículo, etc.). Se ha empleado este enfoque utilizando la metodología oficial de la Agencia Europea de Medioambiente (EEA, 2019) para estimar los factores de emisión de los autobuses urbanos, coches y motos empleando los siguientes pasos:

1. Obtener las características del tipo de vehículo utilizando el último estudio de la flota de vehículos circulantes en Madrid en 2017 para motos y coches, así como el Informe anual de operaciones de EMT para autobuses urbanos (Ayuntamiento de Madrid, 2018; EMT 2018, respectivamente).
2. Para cada categoría de vehículo se ha estimado el factor de consumo (MJ/km) utilizando la guía EEA (2019) considerando una velocidad promedio en áreas urbanas de 13km/h para autobuses urbanos, 35km/h para motocicletas y 40km/h para automóviles (según estudios de tráfico en la ciudad de Madrid).
3. El factor de consumo estimado se transforma en emisiones de CO_2 utilizando la fórmula de la densidad del combustible de cada categoría de vehículo (MJ/g), así como el factor de emisión de combustión de cada combustible (gCO_2/g de combustible) (EEA, 2019)
4. En función de la ponderación de todas las categorías de vehículos, se obtiene los gCO_2 por kilómetro por cada modo de transporte.
5. Finalmente, aplicando las tasas de ocupación, se obtienen los factores de emisión GEI por pasajero y kilómetro. Las tasas de ocupación son las siguientes: 13,6 para autobuses urbano; 1,1 para motocicletas y 1,2 para automóviles (según EMT 2018 y estudios de tráfico en la ciudad de Madrid).

MODO	TIPO DE ENFOQUE	FUENTE DE DATOS
Metro	*Top-Down*	- Para el consumo total de energía y las características de los trenes: *Informe anual de Metro Madrid* (Metro Madrid, 2018). - Para la producción y la demanda: *Informe Anual del Consorcio Regional de Transportes de Madrid* (CRTM, 2019)
Tren-Cercanías		- Para el consumo total de energía y las características de los trenes: *Observatorio del Ferrocarril en España* (OFE, 2018). - Para la producción y la demanda: *Informe Anual del Consorcio Regional de Transportes de Madrid* (CRTM, 2019).
Autobús interurbano		- Para el consume total de energía, características de la flota de autobuses, producción y demanda: Para la producción y la demanda: *Informe Anual del Consorcio Regional de Transportes de Madrid* (CRTM, 2019).
Autobús urbano	*Bottom-Up*	- Tipo de vehículo, velocidad media, ratio de ocupación: *Informe Anual de Operaciones de la EMT* (EMT, 2018). - Factor de consume y emisión por tipo de vehículo: *EMEP/EEA Air Pollutant Emission Inventory Guidebook* (EEA, 2019).
Moto		- Tipo de vehículo, velocidad media, ratio de ocupación: *Estudio del parque circulante en la ciudad de Madrid en 2017* (Ayuntamiento de Madrid, 2018). - Factor de consume y emisión por tipo de vehículo: *EMEP/EEA Air Pollutant Emission Inventory Guidebook* (EEA, 2019).
Coche		

Tabla 4 – Estimación de los factores de emisión de CO_2 por modo: tipo de enfoque y fuente de datos.

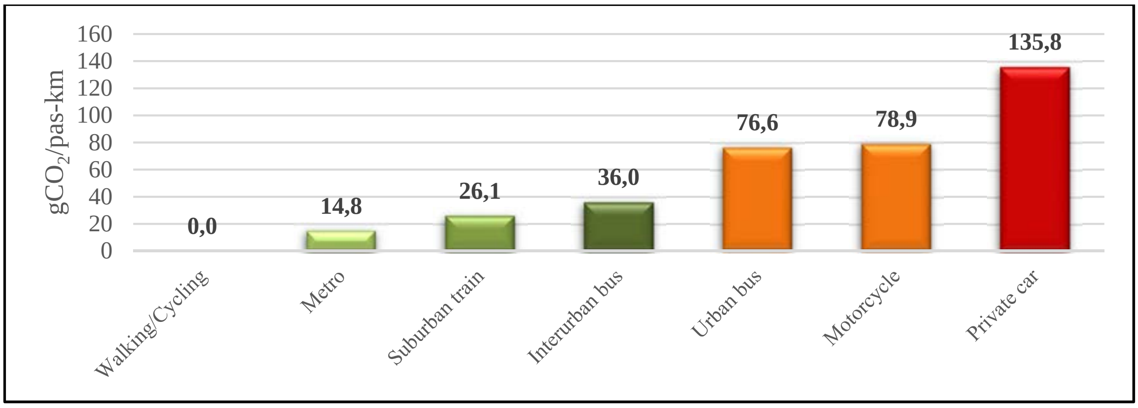

Fig. 2 – Factores de emisión de CO_2 medios para los principales modos de transporte en Madrid en 2017 (Fuente: elaboración propia).

4. RESULTADOS Y DISCUSIONES

4.1 Características de los viajes a los campus UPM

Distribución modal. Los resultados mostrados en la Tabla 5 son similares a las conclusiones de investigaciones anteriores (Mathez et al. 2013, Davison et al. 2015, Appleyard, 2018, Pérez-Neira et al. 2020). Si observamos a toda la comunidad de la UPM, en la cual los estudiantes representan el 88% de la población total, se obtiene que el transporte público es el modo principal para viajar a los campus de la UPM (75,4%), seguido de los modos privados (automóvil y moto, 16,9%), y modos blandos (a pie y bicicleta, 7,6%). Por colectivos, la mayoría del personal contratado en la UPM realiza su viaje en automóvil (45,4% y 41,2% del PDI y PAS, respectivamente). Sólo el 39,2% del PDI usa el transporte público, un modo predominantemente utilizado por el 85,2% de los estudiantes. En proporción, los modos blandos (a pie y bicicleta) son más utilizados por el PDI que los estudiantes (a pie: 7,7% versus 5,7% respectivamente) y en el caso de la bicicleta es el 4% versus 1,3%, respectivamente. En cuanto al género (Tabla 6), no existe una clara diferencia causada por cuestiones de género, solo que los que los hombres viajan más en bicicleta que las mujeres (3,1% versus 0,6), y las mujeres viajan más en metro y autobús urbano que los hombres (46,3% versus 38,4%, respectivamente). Las personas que no declaran su género caminan más a la universidad que el resto. Con respecto a la distribución modal por campus, la Tabla 7 muestra que en los desplazamientos a los campus cercanos al centro de la ciudad, como Madrid Ciudad o Ciudad Universitaria, se utilizan más el transporte público y modos blandos que los que están a las afueras de la ciudad, con menos accesibilidad al transporte público. Se observa que cuanto más cerca está el campus al centro de la ciudad, menor es la proporción de viajes en modos privados (Figura 3). Esto significa que la ubicación y la buena accesibilidad al transporte público son clave cuando se busca la movilidad sostenible (Soria-Lara et al. 2017).

Colectivo UPM	A pie	Bicicleta	Tren - Cercanías	Bus interurbano	Metro	Bus Urbano	Coche	Moto	Otros
Estudiantes	5,7%	1,3%	20,5%	19,0%	35,7%	10,0%	6,6%	1,0%	0,2%
PDI	7,7%	4,0%	7,3%	4,8%	21,2%	5,9%	45,4%	3,7%	0,0%
PAS	2,6%	4,8%	9,6%	10,1%	22,8%	6,6%	41,2%	2,2%	0,0%
Total comunidad UPM	5,6%	2,0%	17,6%	16,2%	32,5%	9,1%	15,3%	1,5%	0,1%

Tabla 5 – Distribución modal por tipo de colectivo en la UPM

Género	A pie	Bicicleta	Tren - Cercanías	Bus interurbano	Metro	Bus Urbano	Coche	Moto	Otros
Hombres	5,1%	3,1%	18,9%	16,7%	30,8%	7,6%	15,4%	2,1%	0,2%
Mujeres	6,0%	0,6%	16,1%	15,3%	34,9%	11,4%	14,9%	0,7%	0,2%
No declara	13,8%	0,0%	13,8%	24,1%	31,0%	3,4%	13,8%	0,0%	0,0%

Tabla 6 – Distribución modal por género

Campus UPM	A pie	Bicicleta	Tren - Cercanías	Bus interurbano	Metro	Bus Urbano	Coche	Moto	Otros
Ciudad Universitaria	6,6%	2,1%	11,5%	17,0%	35,4%	9,7%	16,1%	1,5%	0,2%
Madrid Ciudad	7,0%	1,8%	21,1%	11,5%	40,2%	8,6%	8,1%	1,4%	0,2%
Campus Sur	1,8%	2,9%	33,6%	10,0%	19,6%	10,7%	19,6%	1,4%	0,4%
Montegancedo	0,0%	0,6%	21,2%	37,0%	9,1%	3,6%	26,7%	1,8%	0,0%

Tabla 7 – Distribución modal por campus

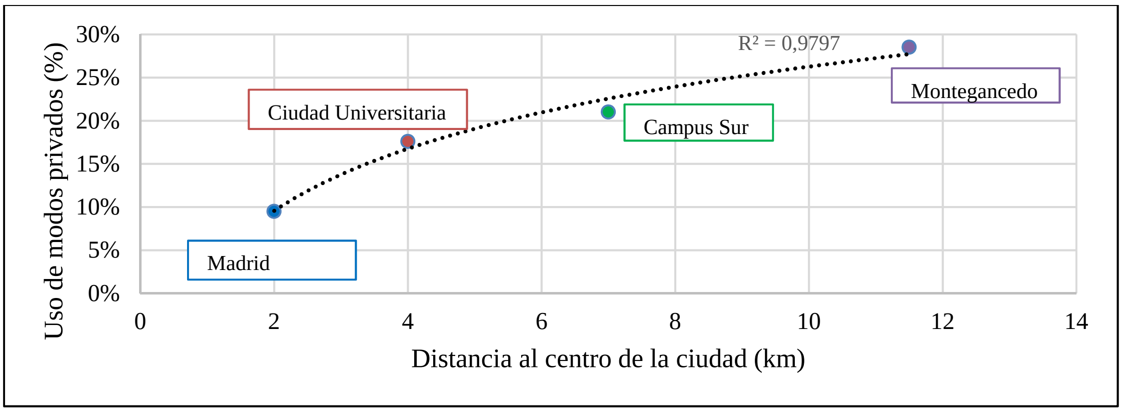

Fig. 3 – Relación entre la distancia del campus al centro de la ciudad y la distribución modal en viajes privados.

Criterios de selección del modo de transporte. La gran mayoría de los encuestados respondieron a la pregunta de cuál es su principal motivo de elección del modo de transporte para los viajes a la universidad. Se puede comprobar (Tabla 8) que los encuestados en el que su modo principal es el modo blando están relacionados principalmente con vivir cerca de los campus universitarios. Por otro lado, el colectivo que utiliza el transporte público aprecia el tiempo, la comodidad y el coste del transporte como motivos principales de su elección. Los usuarios de los modos privados valoran muy notablemente el tiempo, la comodidad y la accesibilidad directa a los campus. Cabe destacar que el compromiso o concienciación por el medio ambiente no se encuentra entre los principales criterios de elección de modo de transporte. Se debería, pues, realizar un mayor esfuerzo en el colectivo universitario en la concienciación medio ambiental respecto a las elecciones diarias de movilidad.

Criterios	Modos Blandos	Transporte Público	Modos Privados
Tiempo	10,4%	31,1%	61,7%
Comodidad	9,7%	17,6%	14,1%
Costes	3,5%	12,7%	3,4%
Accesibilidad	0,7%	5,9%	9,8%
No tengo otra opción	0,7%	9,7%	2,5%
Medio Ambiente	8,3%	6,3%	0,9%
Accesibilidad directa	1,4%	5,3%	4,3%
Vivir cerca	50,0%	0,7%	0,3%
Seguridad	0%	2,7%	0%
No hay parking gratis	0%	0,3%	0%
No dispone de coche	0%	3,9%	0%
Salud y Actividad Física	11,1%	0,5%	0%
No hay bicicleta compartida	0%	0%	0,3%
Eficiencia	0%	2,2%	1,2%
Disfrute / Placer	4,2%	0,2%	1,5%

Tabla 8 - Criterios declarados de elección de modo de transporte por parte del colectivo de la UPM

4.2 Resultados de las emisiones de CO_2 medias en los viajes diarios a la UPM

Esta sección presenta los principales resultados del análisis de las emisiones de CO_2 medias generadas en los desplazamientos diarios a la UPM a partir de la información recogida en la encuesta y utilizando la metodología propuesta. De acuerdo con esto, los 2.142 encuestados en la UPM son responsables de la emisión de 1.532,2kgCO_2 en un día por todos los viajes desde sus hogares a la universidad, lo que significa un promedio de 715,3gCO_2/viaje-persona. Sin embargo, estas emisiones se distribuyen de manera desigual dependiendo del colectivo de la UPM, la distancia al campus o el modo principal.

Comprender quién está emitiendo más ayudará a generar políticas que puedan reducir los impactos al cambio climático de los mayores emisores de dióxido de carbono.

Entre los diferentes colectivos de la UPM, la Figura 4 muestra los diferentes colectivos en el eje X y las emisiones GEI medias por viaje emitido por los individuos de cada colectivo en el eje Y. El eje secundario Y muestra el número de encuestados de la encuesta que pertenecen a esta categoría. Los mayores emisores son el personal de la universidad, con un promedio de 1.303,8gCO_2/viaje-pers y 1.159 gCO_2/viaje-pers, PAS y PDI, respectivamente. Estas cifras son más del doble del promedio de emisiones GEI de los estudiantes (559,7 gCO_2/viaje-pers). Estos resultados son consistentes con los obtenidos en estudios similares anteriores como Mathez et al. (2013), Appleyard et al. (2018) y Pérez-Neira et al. (2020). Como se adelantaba en el subcapítulo 4.1, el personal de la UPM viaja más en vehículos privados que los estudiantes, modo más contaminante, y por lo tanto aumentan sus emisiones medias. En este caso, se deberían poner en práctica medidas específicas para este colectivo.

Si nos centramos en los cuatro campus UPM, la Figura 5 muestra que para los que viajan a los campus más distantes del centro de la ciudad las emisiones medias por viaje son más altas que para los que viajan a los campus más cercanos al centro de la ciudad (1.301,3gCO_2/viaje-pers al *Campus de Montegancedo* a 11.5km del centro de la ciudad frente a 559,7 gCO_2/viaje-pers al *Campus Madrid Ciudad* a tan solo 2 km del centro). Son necesarias, por tanto, medidas concretas para mejorar o reforzar la accesibilidad en transporte público en campus alejados de la ciudad.

Con respecto al modo principal, la Figura 6 muestra la distribución de las emisiones totales de CO_2 por modo y la distribución modal de los encuestados UPM. Los resultados confirman que solo el 16% de los viajeros usan los modos privados (coche y moto), pero emiten más de la mitad de las emisiones de CO_2 totales estimadas.

Finalmente, usamos la Curva de Lorenz para explorar la variabilidad de las emisiones de CO_2 de los encuestados en sus viajes diarios a la UPM. Encontramos que el 10% de los emisores principales son responsables del 54% de las emisiones totales (con una media de 3,4 kgCO_2/viaje-pers), mientras que si tomamos el 30% de los emisores principales contribuyen con el 76% del total de las emisiones de CO_2 (ver Figura 7). Por tanto, esta desigualdad pone en evidencia que son necesarias medidas más contundentes para los pequeños colectivos que, sin embargo, son los más contaminantes.

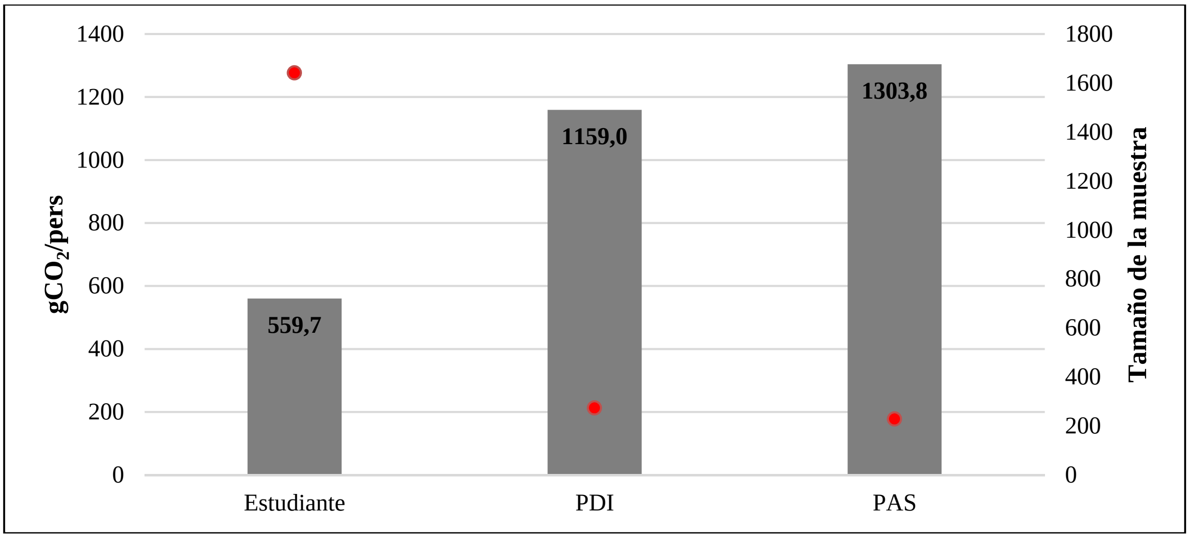

Fig. 4 – Emisiones medias de CO_2 por viaje y colectivo UPM

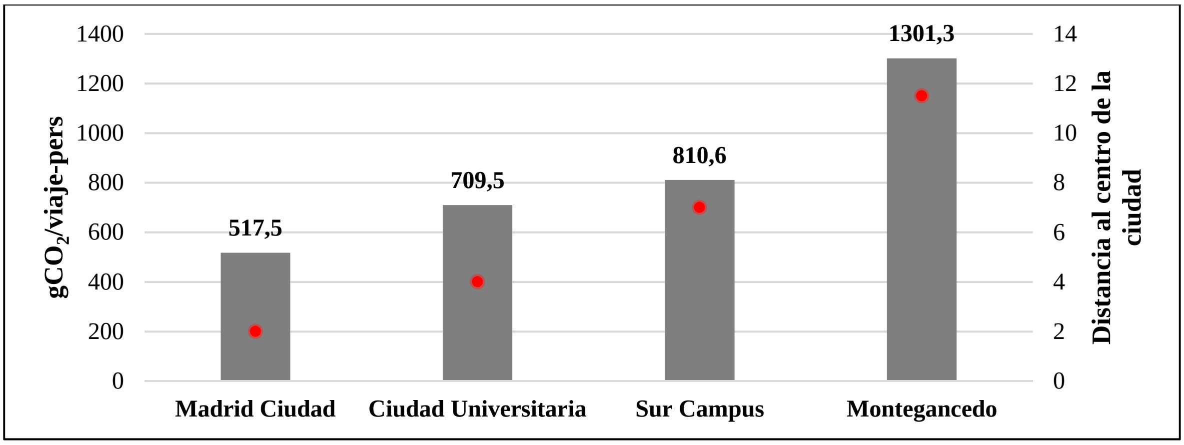

Fig. 5 – Emisiones medias de CO_2 por viaje a los cuatro campus y persona

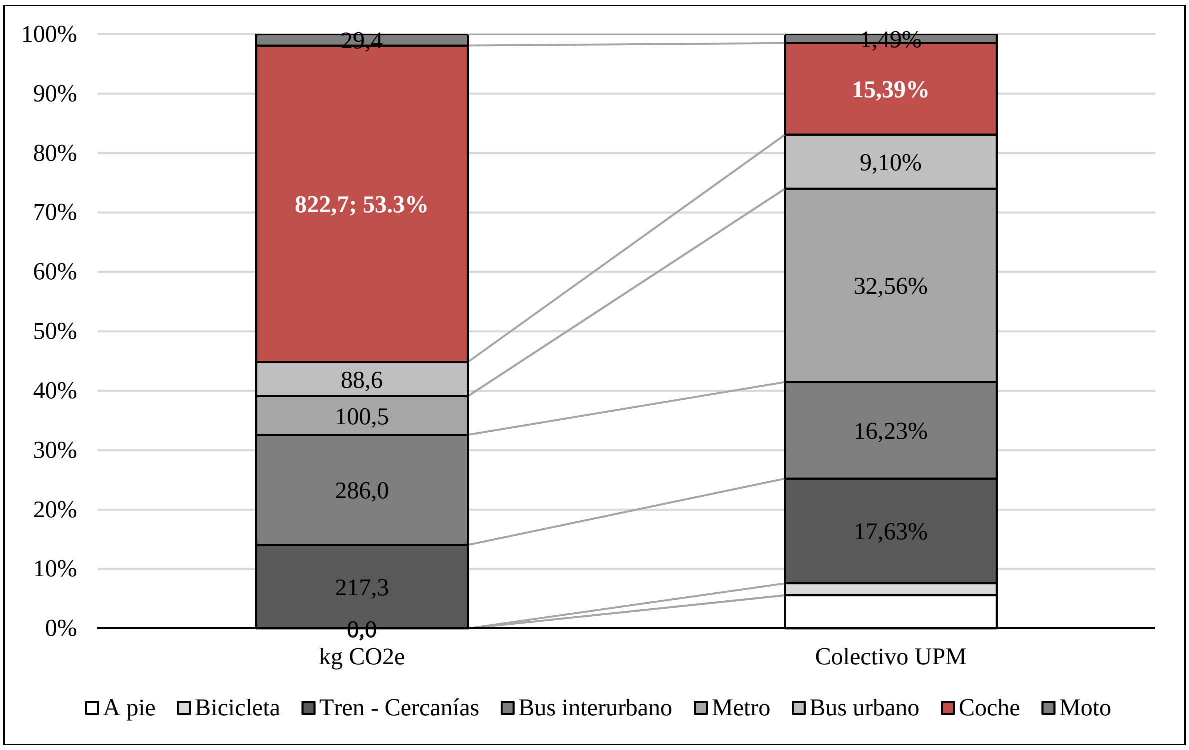

Fig. 6 – Emisiones de CO_2 totales diarias por distribución modal de los encuestados UPM y distribución modal UPM.

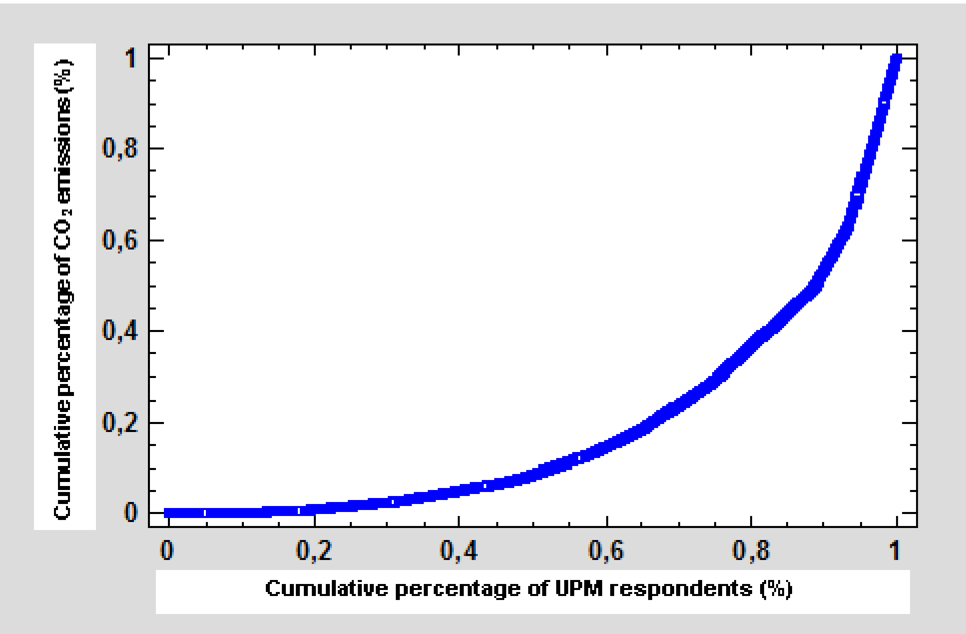

Fig. 7 – Curva de Lorenz de las emisiones de CO_2 de los viajes diarios a la UPM

4.3. Discusión y políticas universitarias

De los datos y resultados obtenidos para la comunidad universitaria de la UPM se deduce que el uso del coche privado para ir a la universidad genera más de la mitad de las emisiones, y solo representa el 15% de los viajes, por lo que es una prioridad que hay que atender. La reducción de los viajes en vehículo privado es el primer objetivo que debe conseguir la UPM.

Para hacer una mejor propuesta de acciones orientadas a reducir el uso del vehículo privado es importante, por un lado, destacar cuáles son los principales motivos del uso de vehículo privado en el colectivo UPM, en concreto, el menor tiempo de viaje, seguido de comodidad y accesibilidad directa entre el origen y destino (ver Tabla 8), y, por otro lado, analizar las opciones disponibles al vehículo privado. Por ello, una de las acciones que se pueden poder en marcha es el uso de coche compartido (car pooling) para las personas que vayan al mismo centro de destino mediante medios apps (similar a *BlaBlaCar,* pero exclusivo para la comunidad de la UPM). También, para frenar el uso del vehículo privado, se podría limitar el uso de los aparcamientos de vehículos privados en los centros de la UPM. Otra acción es el fomento del transporte público. Mediante ayudas y mejorando las frecuencias y accesibilidad en aquellos campus que están más alejados del centro de la ciudad. Aunque ya se vienen fomentando las ayudas al personal de la UPM para el uso del transporte público, que dichas ayudas sean mayores -por ejemplo, pagando el 50% del abono transporte).

Otra línea de acción es la educación: las universidades son espacios privilegiados para la creación de conocimiento y la introducción del concepto de "movilidad sostenible" en los planes de estudio y los procesos de aprendizaje de facultades, escuelas y otras instituciones públicas de gran valor (Larsen et al. 2013). Entre las medidas pueden estar campañas promocionales de modos alternativos (uso durante un tiempo gratuito de sistemas de bicicleta pública, sistemas de coches compartidos, vehículos eléctricos, etc.) que lleven a los usuarios a tener experiencias reales que les hagan cambiar sus hábitos. También sería interesante la difusión del impacto que generan sobre la sociedad sus acciones individuales.

En conclusión, es necesario establecer objetivos y estrategias para reducir las emisiones de carbono en las universidades. Esto es aún más importante dados los efectos de la COVID 19 en los patrones de movilidad, como es la reducción en el uso del transporte público debido al miedo al hacinamiento y la transmisión de virus (véase por ejemplo el estudio Jenelius y Cebecauer, 2020 en Suecia). Entonces, los planificadores de transporte tendrán la oportunidad de reformular la movilidad después de la pandemia de COVID-19 (Gutiérrez et al. 2020).

5. CONCLUSIONES

Pocas son las acciones que se han abordado hasta el momento para descarbonizar las universidades, pero el interés de las mismas por reducir sus emisiones tiene que vincularse a actuaciones importantes sobre la movilidad. Es verdad que sería necesario conocer la participación de la movilidad en el conjunto de las emisiones totales de la universidad, y ello debería ser objeto de investigación en un futuro próximo, pero, con carácter general, cabe pensar que el sector transporte representa un alto porcentaje de las emisiones de CO_2 derivadas de la actividad en los campus.

Solamente con actuaciones decididas en varios frentes puede llegar a conseguirse un resultado de disminución de emisiones apreciable. Probablemente en las zonas en las que hay más posibilidades de uso de transporte público, las acciones habrán de ser de concienciación e incentivación. Sin embargo, en los campus más alejados del centro, las actuaciones ofrecen más posibilidades, porque el transporte público es, actualmente, una opción inexistente o escasa y es donde más posibilidades de mejora existen.

Es preciso plantear objetivos de reducción y medidas que los acompañen, buscando buenas prácticas y buscando los puntos y las acciones con las que se pueden obtener mejores resultados. Para ello, sería necesaria una investigación detallada de la contribución de cada campus, por un lado, y la aplicación de medidas inspiradas en las guías de movilidad sostenible al trabajo diseñadas para las empresas.

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IMPLEMENTATION OF ASSET MANAGEMENT SYSTEMS AS A GUARANTEE OF SUSTAINABILITY WITHIN THE FRAMEWORK OF THE SOCIAL, BUSINESS AND FINANCIAL OBJECTIVES OF TRANSPORT COMPANIES. CASE OF APPLICATION TO RAILWAY ADMINISTRATORS AND OPERATORS

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ABSTRACT

Asset Management, internationally, is a mature discipline with strong support in database processing, automation, and organizational change management systems being launched by numerous infrastructure managers (ADIF, AENA, DB).

Recently the UIC has issued guidelines for the application of Railway application guide: *Practical Implementation of Asset Management through ISO 55001 (2016)*. It is a document that sets out guidance on international standards for the railway sector.

INECO is a provider of railway managers and operators in the field of asset management, in the development of railway technical regulations and in the analysis of the economic and financial sustainability of companies and projects in different geographical areas.

Asset Management is a set of systematic and coordinated activities and practices, through which a company manages its assets in an optimal way and the performance, risks and expenses associated with them, throughout its life cycle, with the purpose of achieving the business goals of the organization.

The objective of this paper is to present those actions and starting bases that, according to what has been published by other agents and institutions of the railway market and according to INECO's experience, are the keys to implementing an Asset Management System based on the UNE Standards - ISO 55000 in Railway Administrators and Managers.

1. SOSTENIBILIDAD ECONÓMICA, SOCIAL Y MEDIOAMBIENTAL COMO NUEVO PARADIGMA EN LA CREACIÓN DE VALOR DE LAS ORGANIZACIONES

La sostenibilidad económica tiene numerosas definiciones, pero en términos generales existe el consenso de que es la capacidad que tiene una organización o institución de administrar sus activos generando una rentabilidad de largo plazo de manera responsable.

Las organizaciones empresariales, al diseñar sus estrategias empresariales y los planes de negocio que las soportan han de fijar una estructura de inversiones, costes e ingresos que garanticen estar por encima del punto de equilibrio económico y financiero.

En paralelo a este objetivo económico, es comúnmente aceptado, que la responsabilidad de una organización desborda el ámbito económico y son muchas las iniciativas que promueven la sostenibilidad económica, social y medioambiental. En el sector de la movilidad estas iniciativas forman parte estructurante de cualquier estrategia nacional y se impulsa de manera efectiva por todos los agentes implicados.

En 2015, 193 estados miembros de Naciones Unidas aprobaron la Agenda 2030 para el Desarrollo Sostenible. Esta Agenda define 17 Objetivos de Desarrollo Sostenible para luchar contra cuestiones como la pobreza, la desigualdad, la injusticia o el cambio climático en el mundo, NACIONES UNIDAS A/70/L.1 (2015). Estos objetivos proporcionaron un marco común para que las partes interesadas públicas y privadas establezcan sus agendas y definan sus políticas y estrategias durante los siguientes 15 años.

En INECO nos sumamos al reto y nos comprometemos con la Agenda 2030 y los 17 ODS, pero no somos la única organización que asumió esta responsabilidad. Como consultora e ingeniería de transporte, INECO ha visto cómo sus principales clientes internacionales y nacionales han integrado estos ODS en sus estrategias y se están acostumbrando a desarrollarlos.

Con este punto de partida, lo que está resultando más difícil es llegar a protocolos comunes para asegurar y medir el impacto que consigue de la inversión necesaria para lograr esos objetivos de desarrollo sostenible. La Tercera Conferencia Internacional sobre Financiamiento para el Desarrollo, NACIONES UNIDAS. A/RES/ 69/313. (2015), estableció la Agenda de Acción de Addis Abeba que apoya y complementa el logro de los 17 Objetivos de Desarrollo Sostenible (ODS) y ayuda a contextualizar sus medios de implementación con políticas y acciones concretas.

En 2017, el Comité de Innovación, Competitividad y Asociaciones Público-Privadas, de Naciones unidas, NACIONES UNIDAS. ECE/CECI/2017/CRP.1 (2017), organizó su sesión anual en Ginebra focalizadas en la Financiación de la innovación y asociaciones público-privadas prioritarias para el desarrollo sostenible. Se aprobó un documento de posición denominado. En dicha sesión se corroboraba esta apreciación de que hace tiempo que existen métodos, normas y regulaciones bien establecidos para contabilizar e informar sobre el desempeño financiero, pero, por el contrario, la medición del impacto social y ambiental aún se encuentra en una etapa relativamente temprana.

Muchas empresas, especialmente las grandes, y los inversores de impacto utilizan sus propias medidas idiosincrásicas, y muchas no miden el impacto de forma coherente. En lugar de intentar medir el impacto real ex post, algunos inversores se dirigen a sectores y modelos de negocio en los que, ex ante, esperan generar un gran impacto positivo.

Si bien el desarrollo de estándares más armonizados para la medición y la presentación de informes de impacto está siendo impulsado por la propia industria, estas iniciativas también han generado desarrollos regulatorios y legislativos para cumplir los objetivos energéticos y climáticos de la UE para 2030 y alcanzar los objetivos del Pacto Verde Europeo, a efectos de orientar las inversiones hacia proyectos y actividades sostenibles.

Para lograrlo, la UE consideró que se necesita un lenguaje común y una definición clara de lo que es "sostenible". Por eso, el plan de acción sobre la financiación del crecimiento sostenible pedía la creación de un sistema de clasificación común para las actividades económicas sostenibles, o una “taxonomía de la UE”. Recientemente la Unión Europea ha publicado el Reglamento sobre taxonomía UNIÓN EUROPEA (2020) que establece los criterios para determinar si una actividad económica y cualquier producto de inversión asociado a ella pueden o no clasificarse como ambientalmente sostenibles. Antes de esta normativa no existía un estándar armonizado en Europa para clasificar las inversiones sostenibles.

Recientemente, UNEP FI (2021), organización de las Naciones Unidas y la Federación Europea Bancaria (EBF), lanzaron una propuesta para que el Sistema Bancario internacional pusiese en uso esta taxonomía como la columna vertebral de una agenda que aumente la transparencia del mercado y se emplee para señalar lo que es "suficientemente bueno" desde una perspectiva de sostenibilidad, la taxonomía de la UE tiene el potencial de dirigir el flujo de financiación necesario hacia la innovación verde y sostenible en la economía.

El proyecto fue esponsorizado por bancos comprometidos a andar un camino hacia la sostenibilidad y hacia la implementación de la taxonomía de la UE de acuerdo con la agenda europea para las finanzas sostenibles (https://www.unepfi.org/banking/high-level-recommendations-on-the-voluntary-application-of-the-eu-taxonomy-to-core-banking-products/ UNEP FI (2021) asss Testing the application of the EU Taxonomy to core banking products: High level recommendations).

También hay especialistas que exponen su escepticismo sobre los mismos, SOLVERE (2020). Donde identifican como una reserva a tener en cuenta es que la normativa deja los aspectos sociales y de gobernanza de las inversiones al arbitrio de estándares mundiales.

Según este autor el aumento de la desigualdad en muchas economías avanzadas apunta a deficiencias considerables en estos estándares, en su aplicación, o en ambos.

SOLVERE (2020) detecta un problema aún más fundamental: los datos disponibles. El autor considera que son muy pocos los datos disponibles para probar y validar los criterios y, más aún, para evaluar una amplia gama de actividades y activos económicos según estos criterios. Sin unos estándares adecuados para el intercambio de datos, tanto sobre las inversiones en sí mismas como sobre los mecanismos de gobernanza (públicos y privados), la estandarización puede disolverse en un sistema tecnocrático, o una máquina de "greenwashing" masiva, o ambas cosas.

Volviendo al sector de infraestructura, varios estándares y métodos voluntarios se están utilizando actualmente en la industria, por ejemplo, INECO ha estado involucrado con las instituciones financieras evaluando los Principios de Ecuador como un marco de gestión de riesgos, adoptado por las instituciones financieras, para determinar, evaluar y Gestión del riesgo ambiental y social en la financiación de proyectos de infraestructura.

En este artículo se considera que la implantación de sistemas de Gestión de Activos de normas ISO 55000, permite implantar un sistema estructurado para las gestión de activos con el fin de resolver prioridades que compiten entre sí, garantizar que los beneficios a largo plazo no se sacrifiquen en pos de necesidades inmediatas y generar un sistema de registro y documentación que de soporte al cumplimiento de los objetivos estratégicos que se fijen las organizaciones.

Un Sistema de Gestión de Activos (SGA) basado en la familia de normas ISO 55000 ayuda a una organización a establecer un enfoque coherente y la asignación coordinada de recursos y ejecución de actividades apropiadas. También incorpora el seguimiento y elementos de mejora continua para asegurar el logro sostenido de los objetivos estratégicos.

La Gestion de Activos puede generar valor al optimizar criterios financieros, ambientales, de impacto social, de gestión de riesgos, calidad de servicio y desempeño a lo largo de la vida de un activo.

Una buena Gestion de Activos asegura que los activos satisfarán la responsabilidad de una organización porque requiere:

- desarrollar e implementar procesos que conecten los propósitos y el desempeño requeridos de los activos con los objetivos de la organización;
- implementar procesos para garantizar la capacidad en todas las etapas del ciclo de vida;
- implementar procesos de seguimiento y mejora continua; y proveer los recursos y el personal competente necesarios para lograr el éxito.

2. GESTIÓN DE ACTIVOS EN EL SECTOR FERROVIARIO COMO MODELO DE GOBERNANZA EN EL DISEÑO DE LA MOVILIDAD SOSTENIBLE Y EL CUMPLIMIENTO DE LOS OBJETIVOS DE DESARROLLO SOSTENIBLE

En el sector transporte, recientemente la Ley de Movilidad Sostenible y Financiación del Transporte, MITMA (2020), considera la movilidad como un derecho, un elemento de cohesión social y de crecimiento económico. Entre los principales objetivos a alcanzar se ha destacado establecer un modelo de gobernanza que permita un diseño coherente de las políticas de movilidad y, en definitiva, avanzar hacia un modelo de transporte y movilidad sostenible como factor clave para el futuro de nuestro país.

Como se ha comentado, los indicadores clásicos del buen gobierno corporativo son, entre otros, los de índole económica y de gestión, pero estos se han de ampliar con indicadores tales que permitan conocer labor que realizan los activos de la compañía en el cumplimiento de los objetivos de sostenibilidad económica, social y medioambiental.

Siendo cierto que la sostenibilidad empieza por la viabilidad de las organizaciones, que es lo que permite conseguir que a los beneficios económicos que se generen se puedan añadir los beneficios sociales y ambientales, se considera práctica común que la empresa haya de certificar los resultados de su Gobernanza ante los agentes interesados en el gobierno corporativo, midiendo su participación en los criterios de sostenibilidad social y ambiental y económica.

Para muchos administradores de infraestructuras europeos, esta evolución conduce a una situación en la que las partes interesadas (como el Gobierno y las autoridades locales, las empresas ferroviarias y el público en general) empiezan a imponer requisitos más estrictos que los rendimientos y los costes, lo que obliga a los administradores de infraestructuras a tomar nuevas y transparentes medidas para poder tomar las decisiones correctas.

Esta forma alternativa de gestionar la infraestructura y los servicios de transporte en mi opinión desemboca en la implantación de sistemas de gestión de activos. La gestión de activos comprende todos los sistemas, métodos, procedimientos y herramientas necesarios para optimizar los costes, el rendimiento y los riesgos durante todo el ciclo de vida de la infraestructura ferroviaria. El objetivo es conseguir la mejor relación objetivo-precio.

Estas optimizaciones se referirán a todas las actividades de infraestructura (construcción, mantenimiento y renovación, incluidas las máquinas y los materiales) a lo largo de todo el ciclo de vida, así como a las consecuencias de estas actividades para el gobierno en su calidad de propietario y para los operadores ferroviarios y los viajeros en su calidad de usuarios.

Por lo tanto, la gestión de activos que impulso los objetivos de sostenibilidad fijados se ha de apoyar en los siguientes instrumentos:

- Definición clara de la misión de la empresa, valores compartidos y aspectos liderazgo y comunicación.
- Gestión de la información y gestión del conocimiento: acceso directo a todos los datos relevantes, en el nivel correcto de integración, en el formato correcto.
- Conciencia del riesgo: la realización de análisis de riesgos y la evaluación de los resultados será una práctica habitual en el proceso de toma de decisiones para el cumplimiento de los objetivos de desarrollo sostenible.
- Visión a largo plazo: tener en cuenta los efectos a largo plazo a la hora de tomar decisiones a corto plazo (Análisis de costes del ciclo de vida),
- Instrumentos adecuados: registro de objetos, métodos de análisis de riesgos, conceptos de mantenimiento, planificación del trabajo, control, medición y monitorización de infracondición y archivo de historial de mantenimiento de activos e historial de estado de activos.

El Objetivo de la Gestión de Activos como técnica, o Asset Management (AM), es la coordinación de las actividades y aspectos organizacionales que permiten optimizar el valor de los activos durante todo su ciclo de vida para el cumplimiento de objetivos estratégicos.

3. CARACTERÍSTICAS DIFERENCIALES DE UN SISTEMA DE ASSET MANAGEMENT SEGÚN EL ESTÁNDAR 55000

Según a UIC (UIC Railway Application Guide (2016)) las razones que llevan al sector ferroviario a impulsar la aplicación de los estándares ISO 55000, 55001 y 55002 son:

- Mejora el resultado del ferrocarril poniendo el foco de la gestión de iniciativas de confiabilidad de activos en las partes críticas de la red ferroviaria, soportada por información sobre las condiciones de los activos y una mejor comprensión de la probabilidad y las consecuencias del fallo a lo largo de su ciclo de vida.
- Reduce los costes al hacer el trabajo correcto, en el lugar correcto y en el momento correcto, con intervenciones de coordinación para conseguir el balance óptimo entre mantenimiento, renovación y mejora en toda la base de activos.

- Brindar a los clientes y a los financiadores opciones informadas basadas en escenarios que describen cómo funcionará la infraestructura a largo plazo, bajo diferentes niveles de gasto, crecimiento del tráfico, longitud de las obras de ingeniería e implementación de la automatización.

Bajo esta consideración la UIC entiende que los ferrocarriles no están aún operando a su total potencial en términos de proveer a sus clientes con un seguro servicio de calidad que sea eficiente en términos de coste beneficio o valor por dinero y que esto se conseguiría en esta Industria implementando técnicas de gestión de activos.

La norma 55000 provee los aspectos generales para la gestión de activos y sistemas de gestión de activos. La Norma ISO 55001 especifica los requisitos para establecer, implementar, mantener y mejorar un sistema de gestión de activos, mientras que la ISO 55002 proporciona directrices para clarificar los requisitos especificados en la Norma ISO 55001 y proporciona ejemplos para apoyar la implementación.

La ISO 55000 de Gestión de Activos es una evolución de los modelos tradicionales aunque tiene tres características diferenciales:

1.- Que las actividades de mantenimiento, renovación y mejora se hacen con el menor coste posible del ciclo de vida completo no solo de los activos físicos, sino también de resto de activos de la compañía
2.- Genera mecanismos de integración entre administrador de infraestructuras y empresas de contratación
3.- Da mayor énfasis en la toma de decisiones basada en la evidencia (utilizando conocimiento sobre degradación y fallo de los activos)

4. ELEMENTOS PARA DIAGNOSTICAR EL GRADO DE IMPLANTACIÓN DE LA ISO 55000, 55001 Y 55002 EN EL SECTOR FERROVIARIO

El sector ferroviario suele disponer de una estructura de gestión de activos apoyada en la Ingeniería de Mantenimiento y en la Ingeniería de Confiabilidad o RMAS. Lo cual fija una excelente situación de partida.

Para dar el salto a un Sistema de Gestión de Activos, si aún no se ha dado, habría de dotarse de directrices estratégicas que le aporten un conjunto de elementos interrelacionados para establecer políticas, objetivos y procesos para alcanzar esos objetivos de Gestión de Activos.

Es de destacar que los Planes Programas de los Administradores de Infraestructuras y Operadores de Transporte púbicos definen, en cierto grado, un Marco de Gestión de Activos que podría homologarse en el marco de la ISO 55001, y fijarían la senda para generar sistemas de gestión de activos (SGA) al solicitar modelos e indicadores sobre los proyectos de inversión y / o actuaciones empresariales que integren tanto los costes de capital (CAPEX) como de operación (OPEX) de las actuaciones incluyendo el ciclo de vida completo de los activos (LCC o análisis por ciclo de vida).

Aunque estos programas no resuelven un elemento clave como es la gobernanza del Sistema de Gestion de Activos y su encaje dentro de la estructura de la organización, los roles y las responsabilidades, la planificación, la operación, y los objetivos fijados por una parte de los agentes interesados sí que podrían quedar fijados.

A efectos de poder diagnosticar de forma efectiva y justificada el grado de implantación de los criterios definidos por la ISO 55000 se considera fundamental analizar los siguientes elementos constitutivos del sistema de Gestión de activos de una compañía:

- Si se fijan los objetivos para los activos requeridos por clientes
- Si se fijan objetivos para los activos requeridos por los propietarios de las infraestructuras
- Si se fijan criterios de sostenibilidad con el menor coste posible en el ciclo de vida total de los activos
- Si se incluyen acciones de integración de la Gestión de Activos en el contexto de la organización
- Si se incluye acciones de Liderazgo y RRHH de la Gestión de Activos
- Si se incluye acciones de Planificación de la Gestión de Activos
- Si se incluye acciones facilitadoras de Apoyo y Operación de la Gestión de Activos
- Si se incluye acciones de evaluación y mejora continua de la Gestión de Activos
- Si se define la gobernanza de la gestión de activos y del alcance de esta
- Si se define la Política de gestión de activos
- Si se define el Plan Estratégico de Gestion de Activos (PEGA)
- Si se documenta el Marco de gestión de activo. Planes gestión de activos
- Si se define la Implementación, evaluación y mejora de la GA: Decisiones y Mecanismos de habilitación y revisión

5. RECOMENDACIONES GENERALES PARA LA IMPLEMENTACIÓN PARA LA IMPLEMENTACIÓN

La Gestión de Activos es el conjunto de actividades y prácticas sistemáticas y coordinadas a través de las cuales una empresa ferroviaria gestiona de manera óptima sus activos y el rendimiento, riesgos y gastos asociados a los mismos, a lo largo de su ciclo de vida, con el propósito de alcanzar los objetivos de negocio fijados en su Contrato Programa y en su Plan de Actuación.

Los pilares fundamentales en los que se basaría la propuesta de implementación de la Gestión de Activos serían:

1. Planes y objetivos organizacionales: definir el alcance de la gestión de activos en la organización, la filosofía y misión de la empresa para evaluar el estado actual de los activos.
2. Políticas y estrategias: establecer objetivos a corto y largo plazo, definiendo las actividades de negocios presentes y futuras de la organización.
3. Marco de la Gestión de Activos: formular estrategias posibles, planes de gestión y elegir la que será adecuada para conseguir los objetivos establecidos en la misión de la empresa, así como desarrollar una estructura organizativa para conseguir la estrategia.
4. Implementación y operación: asegurar las actividades necesarias para lograr que la estrategia se cumpla con efectividad.
5. Verificación y acciones correctivas: controlar la eficacia de la estrategia para conseguir los objetivos de la organización.

El siguiente flujograma conecta adecuadamente todos estos elementos:

Fig. 1 - Relación entre los elementos clave de un sistema de gestión de activos. Fuente: Elaborado a partir de Anexos B de ISO 55000.

El Sistema de Gestión de Activos incluirá:

- La Política de gestión de activos
- Los objetivos de la gestión de activos
- El Plan estratégico de la gestión de activos (PEGA)

El plan o planes de gestión de activos, que se implementa en: planificación y control operacional, las actividades de apoyo, actividades de control y otros procesos pertinentes

5.1 Definición de planes y objetivos organizacionales

El sistema de gestión de activos es una parte integrante del sistema de gestión de la organización y posee una estructura preestablecida. Debería estar alineado y ser coherente con los objetivos de la organización.

Se recomienda definir dos categorías de alcance:

- ✓ Activos físicos de aplicación
- ✓ Decisiones, procesos y actividades (relativos a mantenimiento, renovación y mejora y explotación de la red) que relacionan la Estrategia a Alto Nivel con el trabajo sobre el terreno

5.2 Políticas y Estrategias

Para establecer objetivos a corto y largo plazo, definiendo las actividades de negocios presentes y futuras de la organización.

El objeto de la Política de gestión de activos es una declaración de intenciones a alto nivel por parte de la dirección de la empresa. El documento debería ser reducido en su extensión y por él se comunica a empleados, clientes y grupos de interés:

- Visión de la organización
- Papel de gestión de activos
- Principios esenciales
- Cómo se va a implantar el sistema de GA

En cambio, la Estrategia de gestión de activos define el modelo de gestión de la empresa a medio y largo plazo. Según la UIC se recomienda que establezca:

- requisitos de rendimiento (frecuencia de servicio, rendimiento de trenes, seguridad, impacto ambiental,)
- Cómo se va a implantar el sistema de GA
- Conviene que incluya las Interfaces con otros departamentos y grupos externos.

5.3 Marco de la gestión de activos

La UIC caracteriza con acierto el marco de gestión de los activos mediante la formulación de estrategias posibles para el sector ferroviario identificando la dualidad entre gestión de los activos y condiciones de operación de los mismos. Recomienda definir objetivos de red y por itinerarios o rutas, elegir los que sean adecuados para conseguir los objetivos establecidos en la misión de la empresa, así como desarrollar una estructura organizativa para conseguir su desarrollo para la cartera de activos que serán objeto de atención por el Sistema de Gestión.

A efectos de gestión de activos, es común que, en el sector ferroviario, al menos en el europeo y algunos latinoamericanos, se haya definido un Contrato Programa, un plan de negocio o un Plan de Actuación con los Objetivos que se han de seguir en la red, entendidos como los requisitos de alto nivel para el ferrocarril desde la perspectiva de los clientes, el gobierno y los usuarios y clientes de los activos.

Dichos documentos ya incluyen especificaciones sobre el nivel de financiación disponible.

Las estrategias de itinerarios deberían especificar los objetivos a nivel de itinerarios, la financiación y las limitaciones a lo largo de un período de al menos 5 años, coherentes con los objetivos de red. Es una tarea que podría desarrollarse de una forma más sistemática y homogénea. En esta tarea se podría:

- Mantener las prioridades señaladas por el Plan de Actuación diferenciando entre el escenario “compromiso", el escenario "base", y el escenario potencial
- Traducir los objetivos de red a nivel de itinerarios, con un presupuesto basado en rendimientos
- Incluir especificaciones de los itinerarios

La definición de estrategia de activos sería la conexión entre requisitos cliente/financiador y la planificación y finalización de los trabajos. Debería de incluir criterios de intervención y mantenimiento, umbrales y estrategia de costes.

Los Planes activos por itinerarios definirían, como ya hace el Plan de negocio o planes de actuación, ubicación de actuaciones de mejora específica, necesidades de renovación/mantenimiento, asegurando a la alta dirección y a grupos de interés externos una justificación de costes y de resultados finales para la infraestructura.

Los Planes de explotación por itinerarios en los que debería estar basada la gestión de activos deberían de incluir requisitos de los operadores ferroviarios, planes detallados/asignación de surcos, y así como una planificación detallada, al menos de 10 años, que incluya intervalos entre trenes para trabajo en infraestructura.

5.4 Planes de gestión de activos

Estos planes detallados están relacionados o con activos muy concretos o con rutas específicas, y aseguran las actividades necesarias para lograr que la estrategia se cumpla con efectividad.

Una vez esté desarrollado el plan estratégico de gestión de activos, se ha de evaluar cuáles son los activos y qué aspectos de los mismos son más relevantes para redactar un posible plan de gestión de dichos activos.

Tampoco se puede olvidar el sector ferroviario de las Herramientas LCC (coste del ciclo de vida) y predictivas que deben apoyar la optimización de las decisiones y la previsión de volúmenes de trabajo, costes y resultados.

El Plan de gestión de activos debe abordar tanto riesgos estratégicos como operativos dentro de un solo marco e incluir procesos de negocio_claros para sustentar y ligar componentes del Marco de gestión de activos.

Los planes de gestión de activos dan soporte al diseño de la estructura organizativa y facilitan una estrategia de comunicación clara.

5.5 Verificación y acciones correctivas

Los trabajos de verificación y acciones correctivas permiten controlar la eficacia de la estrategia para conseguir los objetivos de la organización.

Apoyándose en el Sistema de gestión de la calidad ya implantado desde hace tiempo en numerosas empresas ferroviarias la verificación se apoyaría en la implantación de un programa sistemático de auditorías basado en riesgos, centrándose en áreas en las que las carencias o los incumplimientos en gestión de activos tengan efecto fundamentalmente en Objetivos de Negocio.

También se recomienda implantar un conjunto completo de KPIs, Key Performance Indicators, que proporcionen información detallada sobre impactos de las decisiones estratégicas y sobre su implantación táctica. Al igual que otros resultados de los procesos de auditoría del Sistema de Gestión de Calidad, los resultados de auditorías y revisiones de KPIs son revisados regularmente por el equipo directivo.

Lo cual permitirá mejoras del rendimiento de la infraestructura a corto plazo y mejoras a largo plazo en componentes de gestión de activos. Incluso podría producirse cambios en el marco de gestión de activos propiamente dicho.

6. RECOMENDACIONES ESPECÍFICAS. INFORMACIÓN DOCUMENTADA

Del proceso de valoración y conciliación contable de activos surgen áreas de mejora y recomendaciones que pueden aportar mejoras a los procedimientos actuales de alta y baja de los activos identificados en las etapas anteriores así como en el proceso de dotar de información fiable al modelo económico sobre los proyectos de inversión y / o actuaciones empresariales que integre tanto los costes de capital (CAPEX) como de operación (OPEX) de las actuaciones incluyendo el ciclo de vida completo de los activos (LCC o análisis por ciclo de vida).

6.1 Mejorar la información sobre los activos

La cuantificación de los costes vinculados a la gestión de activos puede representar un peso muy relevante en la cuenta de una compañía ferroviaria, como compañía con uso intensivo de capital. Por lo tanto, identificar el coste del proyecto por ciclo de Vida del Activo es fundamental de cara a **maximizar su valor y aumentar su contribución al negocio**.

La piedra angular para la optimación de la gestión y que los objetivos de la organización estén alineados correctamente con los objetivos de Gestión de Activos es el **conocimiento de los activos** a lo largo de todo el ciclo de vida, de forma que pueda sacarse el mayor partido a los activos de la empresa desde el concepto inicial del proyecto.

En este sentido la Información sobre los activos es esencial para desarrollar estrategias de activos apropiadas e implantar planes de trabajo y planes de explotación (tipo, localización, fecha instalación, capacidad, estado, historial de fallos, historial y planes de mantenimiento, costes unitarios,).

Se cree conveniente incorporar y completar estos conceptos a los sistemas contables de los administradores y operadores ferroviarios, ya que serán de gran utilidad para las futuras tareas de valoración.

Otro aspecto a destacar en relación a la información de los activos es que los principales activos que constituyen el material rodante suelen están dados de alta en el inventario contable como unidades y no como las partes o elementos que lo componen. Para una correcta identificación taxonómica que permita a su vez la asignación del método de valoración a aplicar, se recomienda desagregar los activos de material rodante actuales, generando nuevos números de activo que hagan referencia a los elementos y no al todo.

En relación con el punto anterior, sería interesante disponer en los inventarios de las compañías de registros agregadores de las unidades de material rodante que permita de forma sencilla agrupar todos los números de activo relacionados con una misma unidad, y que además sirva para categorizarla dentro de la tipología de material rodante a la que pertenece (unidad de tren, vagón de carga, coche de pasajeros, etc).

6.2 Trabajar en la conexión de las bases de datos de activos

De cara a enriquecer y facilitar la mecanización y sistematización de procesos y de mantenimiento predictivo, sería de vital importancia incorporar a las bases de datos contables toda la información descriptiva relevante del activo, y que está disponible actualmente en otros sistemas de las compañías.

Otra información de especial utilidad es la referente a la localización geográfica de los activos. El uso de sistemas compatibles con la mayoría de las aplicaciones GIS permite el cruce de información catastral de Open Data.

Este cruce de información y el uso de otras APIS que proporcionan acceso a información de geolocalización se considera muy útil para enriquecer la información de los activos y se considera básico en el proceso de ubicación de los activos y su coordinación con herramientas de trabajo colaborativo, Gobierno de España (2018), y sistemas de gestión de activos.

Por lo tanto, se recomienda hacer interoperables las diferentes Bases de Datos a efectos de poder tomar ventaja de las posibilidades que aporta en la actualidad el tratamiento masivo de datos procedentes de diferentes fuentes.

6.3 Homogeneizar criterio al registrar grandes intervenciones de mantenimiento y/o rehabilitación y/o incremento de capacidad

De cara a poder hacer hipótesis sobre el estado de conservación de los bienes se considera conveniente generar en los inventarios contables registros que permitan caracterizar el tiempo transcurrido desde la última intervención de reposición o transformación, como por ejemplo las actuaciones RS/RSI del material rodante u otras inversiones de incremento de capacidad en infraestructura ferroviaria o edificaciones, tan habituales en las compañías ferrovirias.

Como alternativa a estos registros, que se entiende puede ser una información de difícil obtención para los sistemas contables de las compañías, se puede dar alta de estas grandes intervenciones de mantenimiento como mayor valor de cada uno de los activos a los que afecta, y no como unidades de activo independientes, tal y como se suele hacer comúnmente por los equipos de administración y finanzas.

6.4 Desarrollar metodología para el sistema de activación de las bajas de los activos en los registros de las compañías e indicadores de seguimiento de la evolución de la vida útil de los activos

La implantación de un sistema de indicadores de evolución de la vida útil permite documentar un sistema en un entorno de digitalización y transformación de las organizaciones con el apoyo de las tecnologías para optimizar y planificar los costes de mantenimiento de las inversiones de reposición e incremento del ciclo de vida de los activos mediante una gestión activa en base a los datos e índices de seguimiento y monitorización de los mismos.

Se considera que el resultado de la implantación del procedimiento de revisión y actualización periódica del valor de reposición y due diligence de los bienes incluidos en el balance de activos de las compañías genera unas base firmes en su senda hacia un modelo empresarial que integra los objetivos de desarrollo sostenible tanto de los proyectos de inversión como de las actuaciones empresariales operativas.

7. CONCLUSIONES. PRÓXIMOS PASOS EN LA ESTANDARIZACIÓN DE LA GESTIÓN DE ACTIVOS COMO SOPORTE PARA EL DESARROLLO DE POLÍTICAS PÚBLICAS DE MOVILIDAD

Como se ha comentado en este artículo, para los gobiernos y las autoridades de políticas públicas, una buena gestión de activos es un factor clave para quienes buscan equilibrar la inversión en necesidades inmediatas con objetivos a largo plazo para lograr los resultados sociales deseados, incluido el logro de los Objetivos de Desarrollo Sostenible de las Naciones Unidas.

Desarrollar políticas públicas de una manera que promueva una buena gestión de activos es importante para que los gobiernos y sus autoridades de políticas públicas hagan el mejor uso de los recursos públicos mientras maximizan el retorno social y financiero de las inversiones.

Esta ponencia ha presentado acciones y bases de partida que a tenor de lo publicado por otros agentes e instituciones del mercado ferroviario y a tenor de la experiencia de INECO son las claves para implantar un Sistema de Gestión de Activos basado en los Estándares UNE – ISO 55000, AENOR (2015), en Administradores y Gestores Ferroviarios que permitan demostrar y hacer ver que los activos de la compañía se gestionan con criterios de sostenibilidad. De tal forma que las compañías deban certificarse con los estándares que ya existen y para ello deben aportar datos ante un auditor independiente que acredite el cumplimiento de estos requisitos.

El buen gobierno corporativo y el cumplimiento de estos objetivos fijados por las empresas se ha de dotar de sistemas certificados que permita medir y evaluar el cumplimiento de los objetivos establecidos, AENOR (2018).

En paralelo a estas acciones se habla de establecer sistemas de coordinación y cooperación en materia de transporte y movilidad entre las administraciones ferroviarias con competencia en la materia. Uno de sus pilares sería el establecimiento de sistemas de información globales sobre transporte y movilidad, digitalizado y en tiempo real.

Como consecuencia de estos hechos, los administradores de infraestructuras y las empresas ferroviarias aparte de adoptar una actitud más empresarial como consecuencia de la legislación europea, en la actualidad han de adoptar un enfoque de gestión económico, social y medioambiental que supera el enfoque técnico hacia los costes y el rendimiento, por un enfoque integral que soporte el cumplimiento de los objetivos estratégicos de las organizaciones ferroviarias y del cumplimiento de los acuerdos entre estos y los gobiernos nacionales, provinciales o locales que los financian.

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UNDERSTANDING TRANSPORTATION PREREQUISITES TO BE INTEGRATED WITH URBAN DEVELOPMENT IN DEVELOPING COUNTRIES: IRAN AS A CASE

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ABSTRACT

Transit Oriented Development (TOD), as an integrated transportation and land use policy and practice, was given attention in recent decades to (re)formulate urban areas worldwide. Amongst different TOD planning dimensions at play in, the transportation design and policies tend to basically form the backbone of TODs, since a multimodal sustainable movement — public transportation (PT) for long trips as well as non-motorized transportation (NMT) for short ones — is on the agenda. Although it is agreed that TOD can provide even greater benefits than in wealthier countries in long term, developing countries (DCs) are characterized with specific transport-related issues such as vexing congestion, inadequate PT infrastructure, financial obstacles, etc., that should be dealt with to deliver successful integrated TOD projects. In this regards, the present study sheds further lights on the transportation prerequisites of transit oriented urban planning in DCs.

First, a systematic review of global literature provided a set of transportation dimensions integrated with urban development. Due to the recent national policies on TOD, Iran was selected as a case and a set of semi-structured interviews was conducted with Iranian urban and transport planners along with government officials in April-June 2019. The results showed that although there are some favorable conditions to TOD developments in Iran e.g., amalgamated transportation and urban development ministries, urban transportation is hindered by pro-car policies such as subsidized fuel price and lack of multi-modal infrastructure in comparison with the best practices in such DCs as Curitiba. The findings have also implications for transportation policymakers, city officials, planners, and interested readers and practitioners in Iran and other DCs interested in TOD.

1. INTRODUCTION

Nowadays, TOD is globally known as an integrating strategy of transportation and land use planning. Initiated by *Peter Calthorpe* (1993), the key idea was based on a movement and urban development linkage, in line with *Smart Growth* and *New Urbanism* in nature (Xu et al., 2017; Dunphy & Porter, 2006) in order to fight against the car dependence issue and its hostile impacts (Shibley, 1998; Goetz, 2013). Apart from urban development and land use readjustment, transportation initiatives can play an important role in TOD planning, too.

Ideally, a quality PT for long trips should be connected to NMT infrastructures for local short destinations. By this, TOD calls for an easy and reasonable NMT accessibility to transit infrastructures. In addition, the location (i.e., centrality) and design of transit stations are key, so that it should be well integrated into urban textures to attract a higher ridership number. The realization of such transportation principles relies on a set of supportive policies. There is consensus that transport policies can widely steer urban spatial growth in general, and transit supportive patterns in particular, including urban form pattern, public services accessibility, etc. They refer to a set of consistent policies on both transit actors and transit context by which transit ridership are increased and, walking and cycling are facilitated within urban settings. They usually include (1) demand-oriented incentives policies such as tax credit, subsidy for PT (e.g., fares), and (2) supply-oriented plans like regional transportation plan, visioning and policy reform, design policy (e.g., road capacity), and auto equalizers (Abdi, 2019).

Recognized with low-quality PT and, subsequently, the predominance of informal transport, walking and/or cycling, as the main modes of urban transports (United Nations Human Settlements Programme, 2013), DCs have recently made some efforts to revolutionize their planning system by developing the sustainable paradigms of urban transportation such as the integrated transport land use model. It can be illustrated by the cases of Curitiba, and partly Bogotá, in which bus-based rapid transit (i.e., BRT) has been developed in connection with urban planning (land use) strategies (i.e., articulated density, mixed development, pedestrian oriented design).

However, the sustainable models in developing world have remained unknown or initiated recently. Of which, Iran's car-oriented transportation development and policies, coupled with subsequent inclement traffic-caused damages (e.g., pollutions and traffic fatalities) put some pressures on the central government and policymakers to adopt a sustainable trajectory, including public transit development. More recently, Iranian Ministry of Road and Urban Development (MRUD) approved a national guide of TOD. While multimodal quality PT and NMT are the focus of guide, transportation challenges and opportunities associated with the TOD policy and planning remained unclear. In this regard, major transportation prerequisites and mechanisms required for the integration have not been paid attention, so far.

To fill this gap, this study endeavors to scrutinize transportation aspects of TOD planning process in Iran. Both transportation development and transportation policies are discussed in this way. To this end, the study benefits from urban and transportation professionals' point of view through conducting a set of semi-structured interviews. They are supported by reviewing the realities of urban mobility in the Iranian context as follows:

2. URBAN TRANSPORTATION CONTEXT IN IRAN

The data for vehicle in use in Iran show that the motorization and private car use rate is rapidly growing in Iran (OICA, 2015). The heavy trend of vehicle use is faster than most of the developed countries (Shaygan et al., 2017) with 15 percent of annual growth rate (Soltani, 2017). What makes this a threat is the coincidence of motorization growth with the lack of sufficient PT services (Mirmoghtadaee, 2016). Although subway system and bus rapid transit (BRT) have recently been introduced in large cities (e.g., Tehran, Tabriz, Isfahan, Mashhad, Shiraz), the conventional buses are the most common system of formal PT in Iranian cities with different population, ranging from medium- sized to large cities.

Despite encountering a different situation across Iran, the bus operation generally suffers from several challenges in Iranian urban areas. Inadequate bus fleet, deterioration and limited capacity, dearth of a special dedicated lane, rare fixed-time plan at the stations, poor coverage of urban buses excluding low-income urban areas or newly-built areas like new suburban housing projects (e.g., Maskan-e-mehr) are some vexing challenges recorded for urban buses, to name a few. On the contrary, formal PT fares remained very low under a high level of subsidization since the relative poverty allows just low prices, even in comparison to the other developing countries in Latin America (Allen, 2013). As an opportunity, it can spur PT and correct price distortions of the fuels, especially those subsidized for private cars (World Bank, 2005).

The barriers facing PT, bus circulation in particular, have made taxis reasonable choices. They are much faster than buses on the same corridor with no big gap in fare and consequently, people prefer to ride collective taxis, or recently introduced much affordable app-based services such as SNAP. In Tehran, taxis are responsible for about 22 percent of daily urban trips, the most modal share among the others (Transportation and Traffic Organization, 2015). It rises up to 80 percent in some small and medium-sized cities with lack of coverage by other PT systems (Soltani & Falah Manshadi, 2017). In addition, there are other informal services by private cars, moto taxis and minibuses, transferring passengers citywide as illegal taxis with no work permits. They provide additional services at the times of day and prices that their formal counterparts are not willing to do so.

The increasing traffic congestion has resulted in constructing an extensive road infrastructure at the expense of limited space for walking and cycling in most Iranian cities. As a result, the quality pedestrian zones and sidewalk can rarely be found in many urban areas. They are typically narrow, non-continuous pedestrian paths interrupted at intersections, and occupied by parked or in circulation motorcycles, mailbox, and wares, with broken pavements, and unlit at nights. Inside under-construction areas, they were also left unpaved. Considering all these issues, it can be found that urban transportation in Iran follows a way projecting unsustainability in general, although several recent improvements have been on the agenda in part.

3. METHOD

In this research, two well-known means of the qualitative method were applied to data collection: literature review and interview. They are used based on the general objective of the paper formulating a case-study qualitative research in Iran. The literature was reviewed to derive transportation dimensions in the process. As Abdi (2019) detailed, two set of *transportation design* and *transport-oriented plan and policies* were found through a systematic review of TOD literature. The interviews were conducted with TOD actors, involved/interested in Iran's urban policymaking and planning system. A total of 11 TOD professionals including academic bodies, practitioners, and politicians and government officials were queried during April-June 2019.

More than half of the participants were academic specialists since they were the most aware group of the TOD actors from the TOD proposals in Iran. They were mostly from Tehran, the capital city. The authors made some efforts to interview other TOD activists in other groups such as transportation associations and bus organizations, but they were reluctant or left the invitation unanswered.

To conduct analysis, a directed qualitative content analysis was applied using the framework mentioned above. Although rarely applied in the urban studies, this method fits the present study’s aim, since it can discover the latent concepts (i.e., opportunities and challenges) in the interviews’ texts. In this regard, the codes relevant to each dimension were extracted and the perspectives of attendees were comparatively analyzed to draw a general image of transportation prerequisites for TOD planning in Iran. Moreover, a degree of agreement was calculated for all the categories based on the summative degree of agreement between the interviewees. To do this, first, all items (challenges and opportunities) mentioned in the interviews' transcription were summarized, and then the frequency of cited items were summed as the weighted final scores. In addition, the results for Iran were compared with those of DCs already systematically studied at (Abdi & Lamíquiz-Daudén, 2020).

4. RESULTS AND DISCUSSION

In this section, the result of interviews is presented. They are in addition and complement to those reviewed in the section 2. In terms of the realities of urban transportation development, the interview participants were asked to consider the general situation of Iranian cities and avoid exceptions in specific cities. However, it was thus clear that Tehran's urban transportation is highlighted more than the rest as most of participants were from Tehran. With regard to the transport policies, the centralized, top-down nature of policymaking and dominant government-led initiatives in Iran have resulted in a set of central, national transport policies by MRUD and supreme Traffic Council with very few local exceptions.

4.1 Transportation development

Transportation design is referred to the realities of urban movement with regard to the primary measures of TOD success in terms of transportation: increasing transit ridership and active transportation modes (Lierop et al., 2016). The core idea of TOD relies on a multi-modal transportation network, including an efficient public transit system joined to NMT network. Such a network should be accessible and cover multiple destinations. Integrated non-motorized initiatives were also the center of transit-oriented proposals in pioneer developing cities reviewed like Curitiba (e.g., Plano Director Cicloviario) and Bogotá (e.g., Cicloruta, Ciclovia). With regard to their mechanisms applied for PT development, both cities provided reliable high-quality mass transit services in the form of BRT and feeder conventional buses, aiming at covering most of the built-up areas.

Not surprisingly, a handful of transportation challenges were recorded during the interviews against the scant opportunities of improved quality of public transport services in large cities, outer Park and Rides connected to the subway and bus services for preserving the historical centers, and new practice of developing pedestrianized zones in a number of cities. On the challenges side, two transport planners referred to the weak regional integration of transport and urban development in Iran criticizing inefficient site selection of central train stations, which are often located out of the city boundaries. One of them clarified that railway have been developed far away from the cities (urban settlements) due to the separated railway and urban planning efforts in Iranian cities, which have already caused unplanned, informal settlements around the rail lines (e.g., Arak and Mashhad). In this regard, they added that the lack of integration between inter-city and urban transport means has been an aggravating factor. Even the urban-suburban connections within the construction works in the newly founded towns around the major cities, have not been under focus of attention after many years.

Moreover, what made general consensus among the participants was the dearth of multimodal urban transport network, especially around major transit stations. In this sense, an urban planner depicted PT stations as a set of isolated islands because of lack of integration with the complementary infrastructures (i.e., walking and cycling) so that another participant, as a walkability specialist, also believed that lack of efficient non-motorized networks thwarts all other policies and practices concerning sustainable mobility in Iran. There were complaints on the inefficient non-motorized transport infrastructures by other participants as well. The chair of national TOD project cited that “walking and cycling are still not recognized as transport modes in formal transport engineering literature”. Accordingly, one transport planner expressed concern on decreasing rate of bicycling in those cities that it had already been the principal transport mode, such as Yazd and Isfahan.

More importantly, more than half of the participants directly criticized the general low-quality of PT services in Iranian cities. An academic body with expertise in sustainable transport planning noted that the quality of public transport is not yet acceptable and there is a long way to establish a high-quality system in place. Accordingly, he suggested that instead of performing a trial-and-error process, the experiences of other pioneer countries be adopted for restarting such systems with higher efficiency and lower operation and maintenance costs, rather than the current systems. Although the status quo might be subject to changes, the city-by-city, bus fleet deterioration, lacking scheduled services, and limited vehicle capacity were some cited issues among the relevant challenges for the general situation of Iranian urban settings.

Similar to the findings presented in the interviews, the literature affirmed that the improvement in PT services has not been paid sufficient attention since the results revealed that despite some improvements, the system still suffers from the lack of quality services. In response, Taxi and informal transport could provide services as a paratransit mode, but not essentially connected to the PT. This would be another positive environment for car movement, in the absence of quality PT and NMT infrastructures, which is in clear contrast to the TOD policy. Hence, the result is high fuel consumption and an increase of the externalities (i.e., pollutions) as well as traffic injuries across Iranian cities.

The table below lists all major opportunities and challenges associated with Transportation Development. It also displays the degree of agreement on the issues (as relative importance) and consider their similarity to the other DCs' experiences. Accordingly, it is clear that there is a convergence of the challenges cited for TOD transportation design in Iran and other DCs. Reviewing developing world studies, the global evidence revealed that the regional transit issue in coordination with the land use planning was underestimated in other studied developing-country cities, where urban transit networks are incomplete in terms of connecting to other public and active transport infrastructures. In addition, the inadequate public transit services and low capacity of vehicles, informal transport and poor coverage were criticized, which were similar to what was claimed for Iran in the above discussion.

Item		Frequency	Similarity to other DCs
Opportunities	Recent improvements in PT services	5	*
	Park and Ride strategy	1	
	New practice of developing pedestrianised zones (NMT infrastructures)	3	*
Challenges	Weak regional integration of transport and urban development	2	*
	Dearth of multimodal urban transport network	4	*
	Lack of integration between inter-city and urban transport means	2	

Table 1 – Major opportunities and challenges associated with TOD transportation development in Iran, their frequency of citation by the interviewees and their similarity to other DCs

4.2 Transportation policy

Several TOD professionals believed that while the recent provision of national TOD guideline, the new guideline of urban street deign, and (re)planning to multi-modal, connected regional rail infrastructures would be opportunities for TOD planning, there are rare assistive transportation policies in line with TOD. One of the urban planning experts pinpointed the fact that there have been some short-term transport plans and decisions to alleviate current urban challenges in Iran but with no forward-looking strategies in Iran. He exemplified the BRT project in Tehran and other large cities in which inter-modal connection, land use integration and similar issues have not been yet adjusted. There was a common consensus on the challenge of subsidized, cheap fuel price in Iran by which car ownership is encouraged (Many opposing views, however, claim that in comparison to the indicator of minimum wage for a worker in Iran, purchasing power for the fuel is quite limited in Iran and thus, the price is still not low. Compared to the cases of Saudi Arabia, Venezuela, Canada and France, Iranian workers can purchase less gasoline per month (Hassannia, 2019) . A municipal official desperately noted that this is a problematic national economic and a political issue which cannot be easily dealt with. The data here shows that the average daily gasoline consumption has been 94 million liters during mid-2018 to mid-2019 in Iran (NIOPDC, 2018) of which a share of 58 percent of final oil products consumption goes to the transport sector (IEA, 2018).

Another major challenge was lack of coordination among transportation policies as well as among responsible bodies. The chief of national TOD project cited that a variety of the corresponding entities, laws and regulations handle the urban transport policy and planning in Iran, which has partly caused a kind of discordance in the planning process. Reviewing the structure and responsibilities of the actors we found that Ministry of Interior (MOI), as the main actor, is responsible for urban transportation policymaking and planning along with city councils at local levels. Meanwhile, MRUD handles the whole transportation sectors excluding the urban transport, while prepares urban development plans.

At local scale, even though municipalities under MOI are in charge for almost all the transportation planning and executive plans, parallel sectoral sub-institutions based on the different transport modes (e.g., metro, bus and taxi) do not play the integrated roles (Mirmoghtadaee, 2016). While Urban Transport Plans are mandated to be coordinated with the city comprehensive and detailed plans, there are typically discordances between the strategies.

The table below lists all major items related to transport and built-environment policies and plans and reveal the similarities between Iran and other DCs. As with the short-term policy adopted for developing PT in Iran, what followed in DCs has been development of BRTs with the hope of directing such cities into a trajectory of sustainable development. Together with Iran, pro-road policies and unsupportive national policies and propositions for PT in the transport planning process were associated with barriers to the integrated transport and land use practices in a number of case studies (see Abdi & Lamíquiz-Daudén, 2020). However, the opportunity of setting TOD policy at national level makes Iran a different country among others.

Item		**Frequency**	**Similarity to other DCs**
Opportunities	National TOD policy	2	
	urban street deign guideline	1	*
	(re)planning to multi-modal, connected regional rail infrastructures	3	*
Challenges	Subsidised (low) fuel price	4	
	Short-term transport vision and policy	1	*
	Inattention to potentials of NMT in transport policies	2	*
	Less attention given to affordable transport alternatives	1	*
	Lack of supportive transportation policy for TOD planning	4	*
	Uncoordinated transport policies and policymakers	2	*

Table 2 – Major opportunities and challenges associated with TOD transport policies in Iran, their frequency of citation by the interviewees and their similarity to other DCs

All in all, the content analysis of modern Iranian urban policies could confirm that except for little evidence of recent transit-based urban policies, urban development policies generally tend to facilitate car mobility, something that is contradictory to TOD principles, through encouraging sprawled developments (i.e., car-oriented new towns and far-reaching constructions) which lack in PT connections and placing priority on pedestrians. In the same vein, some transportation policies also facilitate car use (e.g., fuel subsidy, minimum parking, car purchase loans, etc.).

5. CONCLUSION

The present study tried to find urban transportation prerequisites, to be integrated with urban development in TOD planning process. To this end, the study went through the the context of urban transportation development in Iranian cities as well as ruling policies and regulations. The interview conduction helped to better understand the latent aspects of urban transportation in Iran, going beyond explicit affecting factors. In reality, the car-oriented urban transportation is recognized with the poor quality of PT, disconnected transportation modes at urban and regional scales, and hindered walking and cycling.

These can be stumbling blocks for successful TOD implementation in Iranian cities. Such environment has been the result of the car-oriented policy design over the past decades of transportation policymaking and planning. In fact, the TOD policies are in its very infancy stage and the problematic nature of unsustainable transportation policies still exists.

However, there have been several TOD-supportive transport policies at national tier in recent years, including PT development with a look towards the integration with urban development. They mainly portray a trend towards more sustainable choices for urban and inter-city mobility including rail development, inter-modal connection, etc.

In spite of the fact that TOD is a highly context-sensitive planning instrument (De Vos et al., 2014; Tan et al., 2014), it is important to confirm that there have been some common challenges in DCs as transnational challenges, such as disparate land-use and transport policy-making, uncoordinated transport governance, financial barriers, and technical and planning capacity, as cited in previous relevant studies (e.g. Cervero, 2013; Cervero and Dai, 2014; Suzuki et al., 2013; Pojani & Stead, 2018; Abdi & Lamíquiz-Daudén, 2020). In this regard, most scholars agree that the TOD practices in DCs are usually hindered by weak regional and multimodal connections. Consequently, PT systems do not have sufficient access to the destinations in metropolitan areas. In a study on DCs' transit and land use integration, Cervero (2013) criticised the lack of perpendicular connectors to transit stops and feeder systems. This has been the case in the specific cases of TOD in Hanoi and Bangkok, for instance, where urban transit networks are incomplete (Christine Bae & Suthiranart, 2003; Nguyen et al., 2019).

Similar to the items found in the content analysis of the interviews, the existing body of literature highlights an inter-national set of transportation physical and policy prerequisites is to be dealt with when TODs are under planning and constructions. In this respect, Iranian policymakers and government officials are highly recommended to give their attention to the provision of quality, interconnected PT systems in parallel with urban development readjustments, such as policies for density and zoning regulation, and parking during TOD policy design and planning. In fact, two spheres of the quality transport (i.e., *Node*) and the quality urban spaces (i.e., *Place*) should meet each other to have successful transportation environments built upon the sustainable movements: high ridership, and high walkers and cyclists. In addition, besides direct transport policies, other transport-related policy domains like fuel consumption, travel cost by car, financial mechanisms and social attitudes (education) should be more given weight for policymakers.

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SUPERVISED MACHINE LEARNING ALGORITHMS FOR MEASURING AND PROMOTING SUSTAINABLE TRANSPORTATION AND GREEN LOGISTICS

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ABSTRACT

The sustainable development of freight transport has received much attention in recent years. The new regulations for sustainable transport activities established by the European Commission and the United Nations have created the need for road freight transport companies to develop methodologies to measure the social and environmental impact of their activities. This work aims to develop a model based on supervised machine learning methods with intelligent classification algorithms and key performance indicators for each dimension of sustainability as input data. This model allows establishing the level of sustainability (high, medium or low). Several classification algorithms were trained, finding that the support vector machines algorithm is the most accurate, with 98% accuracy for the data set used. The model is tested by establishing the level of sustainability of a European company in the road freight sector, thus allowing the establishment of green strategies for its sustainable development.

1. INTRODUCCIÓN

Concerning the current environmental situation regarding climate changes has impacted people and businesses, making sustainability a trend in all economic activities around the world. The constant design of strategies to mitigate the damage generated by humans' activities on the planet is more than a trend. In the business world, it is becoming a requirement. Integrating technologies to measure the impact of their activities leads to control over them and supports the strategies established to alleviate the generated impact.

Freight transport in the European Union has been growing significantly in the last decade. In 2017, it registered a total increase of 2.4 %, compared to 2016, being road freight transport (RFT) the main contributor with +4.7% (EEA, 2019). This means an increase of the demand for services in freight transport caused by the development of the global trade and influenced by the consumerism of the society (Nowakowska-Grunt and Strzelczyk, 2019; Nowicka-Skowron and Mesjasz-Lech, 2013). RFT is the main source of greenhouse gas (GHG) emissions because of the growth of its activities, which is offering important business opportunities to this sector but also challenges in the emissions reduction (Diemer and Dittrich, 2018). To achieve the proposed objectives, both governments and entrepreneurs have set out to develop sustainable strategies. Currently, there are different frameworks for sustainable freight transport (SFT) with several key performance indicators (KPIs) but with a limited agreement about the general logic and even the basic terminology to use in sustainability status of RFT providers. The common factor in assessing sustainability is that the three pillars of sustainability have to be considered and ensured that they are managed in a holistic way (Gudmundsson et al., 2016).

SFT aims to balance the economic, social and environmental dimensions of the sector in an integrated way to ensure synergy, complementarity and coherence (Zeimpekis et al., 2018; Kumar et al., 2019). From all regulations on the environmental, social and economic impacts left by RFT activities arises the need for businesses and governments to have methodologies to measure that impact. There is an exhaustive list of what SFT entails (Kumar et al., 2019). Among the characteristics, we can highlight the ability to provide safe, socially inclusive, accessible, reliable, affordable, fuel-efficient, environmentally friendly, low-carbon transport that is resistant to shocks and disruptions, including those caused by climate change and natural disasters (Youssef et al., 2017). The European Commission’s 2018-2020 work programme for “the smart, green and integrated transport” called for the development and validation of new solutions that can be rapidly deployed.

These solutions should address, systematically, modes of transport, infrastructure and operating patterns, apart from integrating them into a user-friendly European transport system. This must be characterized by connectivity and intelligence, evolving according to the needs of customers and allowing the assessment of the impact of transport solutions on society and the economy, while contributing to the competitiveness of the European transport industry (European-Commission, 2017).

Currently, there is no widespread and structured way to integrate traditional and sustainable objectives of the RFT sector, creating a gap between theory and practice in the development of sustainable strategies. This leads to the question of how to integrate and evaluate the sustainability of enterprises in this sector in order to identify and mitigate negative environmental and social impacts. Recent studies have proposed machine learning techniques to analyze real-world data for decision- making problems (Kaab et al., 2019; Nilashi et al., 2018; Molina-Gómez et al., 2020; Kartal et al., 2016; Nilashi et al., 2019).

Therefore, this paper presents the development of a supervised machine learning model based on classification algorithms, for monitoring the RFT activities and determining the level of sustainability on each of its dimensions. As consequence, it allows companies to define and achieve sustainability strategies in the short, medium and long term. This paper is organized as follows: in section 2, a brief literature review on related topics is presented; section 3 details the proposed methodology; section 4 provides the experimental results in the design and development of the sustainability assessment model; section 5 contains the results of the model implementation in a RFT company; section 6 presents some managerial insights; and finally, Section 7 highlights the main conclusions of this work with future research recommendation.

2. LITERATURE REVIEW

The transport sector is essential for the productive development of any economic and social system. This indispensable sector distributes goods throughout the world and transports people to their homes, work, and schools (Crafts et al., 2005). In Europe, the transport sector represents approximately 5% of the gross domestic product, that jointly with storage, represents between 10% and 15% of the total costs of finished products (Kallas, 2011). As a result, maintaining SFT has gained growing interest within the transportation sector. According to Gatto (1995), SFT is “sustained economic development, without compromising the existing resources for future generations”. In addition, Salas-Zapata and Ortiz-Muñoz (2019) point out that sustainability itself is based on four points: (i) sustainability as a set of socio-ecological criteria that guides human action; (ii) sustainability as a vision of humanity realized through the convergence of social and ecological objectives of a given reference system; (iii) sustainability as an object, thing, or phenomenon which occurs in certain socio-ecological systems; and (iv) sustainability as an approach that involves the incorporation of social and ecological variables in the study of a human activity, process, or product. On the other hand, freight Transport “supports production, trade, and consumption activities by ensuring the efficient movement of raw materials and finished goods and their on-time delivery” (Rajabi, 2011).

According to Centobelli et al. (2020), an effective sustainability program adopted by freight transport providers must include long-term environmental strategies, management execution, and information technologies (ITs) support. Its environmental strategies must focus on prior assessment of opportunities and impacted areas. In addition, SFT involves a balance between the effectiveness and efficiency of the planning and provision of transport services, and the environmental effects resulting from both economic and social circumstances. Similarly, the United Nations conference on trade and development (UNCTAD) established an ecological and socially measurable framework approach for SFT by incorporating the triple bottom line (TBL) framework (Youssef et al., 2017), which addresses the economic, environmental, and social dimensions applying indicators for defining and evaluating sustainability policies. The gathered information from the evaluation provides a broader insight for establishing sustainability guidelines, provided that these dimensions are aligned with the corresponding goals, or United Nations sustainable development goals (UN, 2015). In addition to the TBL, the global reporting initiative is put into place. According to Zhang et al. (2019), this framework that captures economic, environmental and social performance is used as an assessment of sustainability through the reliability of indicators. Additionally, UNCTAD devised a series of framework steps to achieve RFT sustainability. Furthermore, Mostert and Limbourg (2016) substantiate the growing interest in environmental sustainability research in their literature review which identifies various researchers who investigate five environmental challenges: air pollution, climate change, noise, accidents, and congestion. Correspondingly, the RFT sector's environmental sustainability program is aligned itself with measures for reducing carbon dioxide (CO_2) emissions. This alignment includes a framework of four critical points established by the evaluative and logical approach to sustainable transport indicator compilation: measurability, ease of availability, speed of availability, and interpretability.

Also, this framework is required for identifying and selecting sustainable transport indicators (Castillo and Pitfield, 2010). Altogether, research developed for assessing and measuring both logistics and transport sustainability consists of conceptual articles or empirical studies (Marchet et al., 2014).

Reaching and maintaining SFT requires more than just complying with environmental regulations and ordinances. As a result, the transportation sector must devise and incorporate green strategies into its transport operations. A strategic approach proposed by Seroka-Stolka (2014) indicates that green strategies for implementing sustainable development comprises three perspectives: the public or private (stakeholders), the operational and strategic (sustainable performance), and the local or global (geographical location). It should be noted that operational and strategic perspectives are complemented with the adoption of operational changes and the incorporation of environmental principles for strategic planning. In addition, alternative green concepts are devised for reducing the impact of road transport operations. Kadzinski et al. (2017) develop various multi objective application methods for optimizing environmentally compliant supply chains. Measuring environmental sustainability requires an extensive assessment of economic, social, and environmental principles. Although there is no definite model for measuring environmental sustainability, these three principles are fundamental for an effective and efficient sustainable project. From this perspective, additional methods supporting environmental sustainability are considered. For example, when the RFT sector adopts multi-actor and multi-criteria decision-making methodologies (Bandeira et al., 2018; Awasthi et al., 2018), and combined them with fuzzy models (Rai et al., 2017). These methodologies and models collectively allow the assessment of transport sustainability while taking into account the economic, social, and environmental principles. In addition, other factors affecting the sustainability frameworks are defined by the overall goal of the sustainability strategies, whether they be economic, social, or environmental. Moreover, measuring environmental sustainability requires aligning sustainable strategies and the three TBL dimensions mentioned in the early stages of this literature review. Today, many environmental sustainability investigations are limited to one or two TBL dimensions. As a result, not adopting the three TBL dimensions reveals that these three factors are not always attainable for measuring or evaluating environmental sustainability. With the adoption of sustainability measures, the reduction of emissions becomes an evident measurable equation. Therefore, measurable equations can lead not only to minimizing costs and GHG emissions, but also to generating green benefits (Arseculeratne and Yazdanifard, 2014). Consequently, the literature for assessing the sustainability of transportation remains limited and provides only valuable ecological methodologies and strategies and no evaluative framework that measures sustainability itself.

3. METHODOLOGY

The methodology of this research is based on supervised machine learning techniques for the assessment of sustainability through a set of sustainability KPIs. Figure 1 presents the proposed methodology in a schematic way, which consists of four main steps -the selection of the KPIs, the data preparation and training, the evaluation, and the selection of the classification algorithms- and several sub-steps.

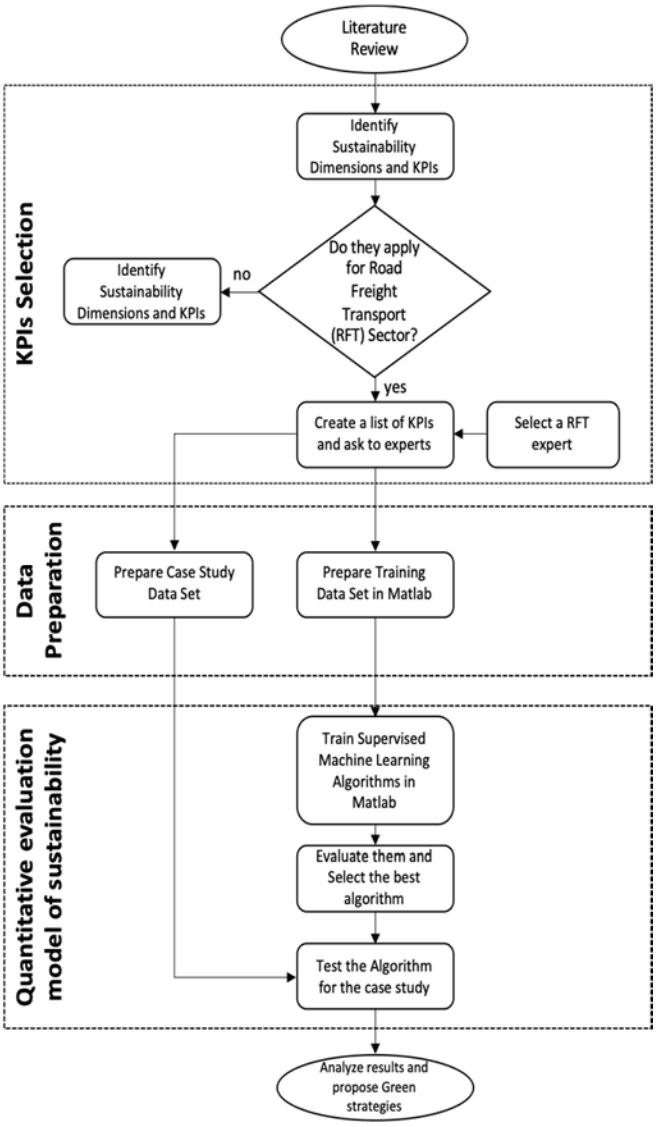

Fig. 1 – Methodology

3.1 Data selection and preparation

Sustainability comprises the TBL, economic development, environmental preservation and social development (Mihyeon Jeon and Amekudzi, 2005). Each of these is made up of a group of KPIs that allow to determine the level of sustainability in that dimension, and also serve as a reference for the quantitative evaluation of sustainability. This case study is based on the European RFT sector and the data was prepared as described in figure 2.

The methodology developed is constructed on the analysis of the KPIs included in different frameworks previously developed by governmental entities, such as the UNCTAD's framework and other scientific proposals, such as the complex performance indicators proposed by Dočekalová and Kocmanová (2016), and the assessment structures of sustainability transport networks (de Campos et al., 2019; Dobranskyte-Niskota et al., 2007; Prause and Schröder, 2015). Once the RFT expert defines the KPIs to be included in the model, the results for the evaluated company are calculated to obtain a total rate for the performance in each of the dimensions. Based on these results, its level of sustainability is measured.

In machine learning techniques, it is important to develop a correct and appropriate training data set, since the algorithms use that information to learn. Because there is no pre-defined data set for measuring sustainability for any of its dimensions, a data set is generated in Matlab with a structure similar to the well-known iris data set from Fisher and Marshall (1936). The values that represent the performance in each of the dimensions are generated as random values with a uniform distribution.

Fig. 2 – Data preparation for the case study

The methodology for the calculation is based on the weighted average. This method is also known as a weighted linear combination or scoring method. It is commonly used in multi-criteria decision-making (Chen, 2012). Generally, the weights of the relative importance may directly be assigned by decision-makers (Afshari et al., 2010). In this case, apart from selecting the most accurate KPIs to the study context, the RFT experts are responsible to assign the corresponding weights, too.

3.2 Development of the Quantitative Evaluation Model

The creation of the model to evaluate sustainability begins with the generation of the training data as aforementioned. For doing that, a series of algorithms available in “Statistics and machine learning toolboxTM” in Matlab which provides functions and apps to describe, analyze, and model data structures is employed. It includes the application called “classification learner” which allows us to train, develop, test, and evaluate several classification algorithms simultaneously. According to the results obtained in the training, the best algorithm is selected for the model development, which is determined according to the classification error (the smaller the error, the greater its accuracy in making predictions) and the metrics for performance evaluation, i.e., the predictive capability of the model (e.g., confusion matrix, cost matrix, ROC curve, etc.). The aim of training several algorithms simultaneously is to find the one that is most accurate for the type of data to be predicted. Figure 3 summarizes the workflow in Matlab for the development of the model. Within the trained algorithms, are included decision trees (Kotsiantis, 2013), discriminant analysis (DA) (Tharwat, 2016), the nearest neighbor (KNN) (Kataria and Singh, 2013; Dhanabal and Chandramathi, 2011), naive bayes (Tripathy and Rath, 2017; Al-Aidaroos et al., 2010), and support vector machines (SVM) (Kotsiantis et al., 2006; Platt, 1998).

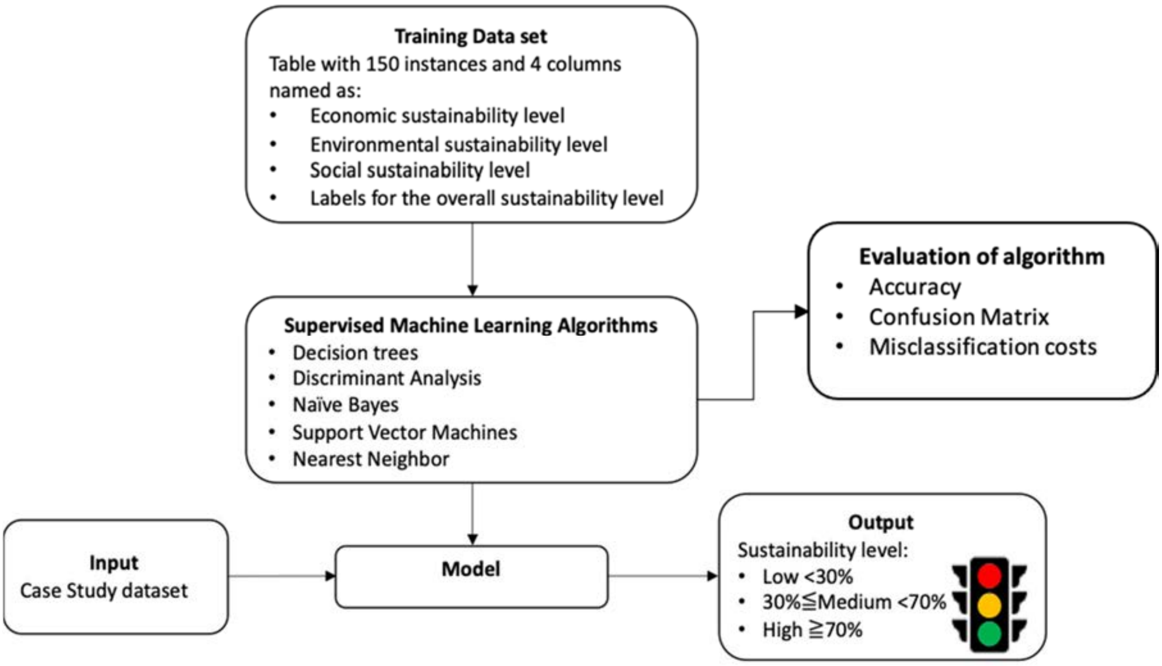

Fig. 3 – Workflow in Matlab

The validation and evaluation of the results of these algorithms are performed in terms of accuracy and classification errors. The estimation of their performance on the predictions for new data compared to the training data is determined by the cross-validation process.

The evaluation of the predictive accuracy of the fitted models is based on the performance in the automated training and the confusion matrix analysis to understand how the model has performed in each class (Amin and Ali, 2018). In addition to these metrics, the performance of the model is also evaluated through a sensitivity analysis to observe how the accuracy of the model changes according to the weights assigned to the dimensions of sustainability.

4. RESULTS AND DISCUSSION OF THE MODEL DEVELOPMENT

For testing our approach, a training data set of 150 instances was randomly generated with a uniform distribution from 0 to 1. As mentioned, these values represent the overall performance in each of the dimensions of sustainability. The data set consists of four columns, each of the first three representing a dimension of sustainability and the fourth the level of sustainability. This level measures the overall level of sustainability, being represented as one of the three following categorical values: “low”, “medium”, or “high”.

For each instance, the RFT expert has defined that its sustainability level is: *(i)* “low” when the weighted sum of the total performance in each dimension of sustainability is greater than 0% and less than or equal to 30%; *(ii)* “medium” when these results are greater than or equal to 30% and less than 70%; and *(iii)* “high” when the values are greater than or equal to 70%. The initial model was trained with the level of impact (weight) on sustainability defined by the expert which was 70% for the economic dimension, 20% for the environmental dimension, and 10% for the social dimension. For each classifier class, Table 1 presents the trained algorithms and their respective results, described by their overall accuracy, the misclassification cost, the prediction speed (in observations per second), and training time (in seconds).

Classifier class	Algorithm	Overall Accuracy	Misclassification cost	Prediction Speed (obs./s.)	Training Time (s.)
Decision trees	Fine tree	89.3%	16	1600	7.7
	Medium tree	89.3%	16	1700	7.0
	Coarse tree	86.7%	20	1500	6.4
	Boosted trees	56.7%	65	4000	11.5
	Bagged trees	88.0%	18	420	14.7
	RUSBoosted trees	89.3%	20	1500	6.4
Discriminant Analysis (DA)	Linear DA	97.3%	4	1300	9.2
	Quadratic DA	95.3%	7	2700	8.8
	Subspace DA	96.0%	6	320	14.6
Naive Bayes (NB)	Gaussian NB	88.7%	17	2700	8.2
	Kernel NB	87.3%	19	2100	9.7
SVM	Linear SVM	95.3%	7	1300	8.9
	Quadratic SVM	96.7%	5	1700	9.5
	Cubic SVM	96.7%	5	1800	9.4
	Fine Gaussian SVM	76.7%	35	1800	9.7
	Medium Gaussian SVM	95.3%	7	3100	9.1
	Coarse Gaussian SVM	79.5%	31	3100	9.5
KNN	Fine KNN	86.7%	20	2400	9.8
	Medium KNN	82.0%	27	2400	9.6
	Coarse KNN	56.7%	65	3200	10.1
	Cosine KNN	77.3%	34	3800	10.0
	Cubic KNN	82.7%	26	4300	9.9
	Weighted KNN	88.0%	18	4900	9.8
	Subspace KNN	81.3%	28	230	15.6

Table 1 – Results for all trained algorithms

According to the accuracy obtained, the best algorithm is the linear DA with an accuracy of 97.3% to define the sustainability level and the lowest misclassification costs of 4.

Although its training time of 9.2 s. is not among the lowest, it is close to the mean of all times obtained, which is equal to 9.6 s., and a prediction speed of approximately 1300 obs./s. The quadratic SVM, cubic SVM, and linear DA algorithms obtained the highest accuracy. For each of them, Figure 4 presents the obtained confusion matrix, where the number of correctly and incorrectly classified instances is observed.

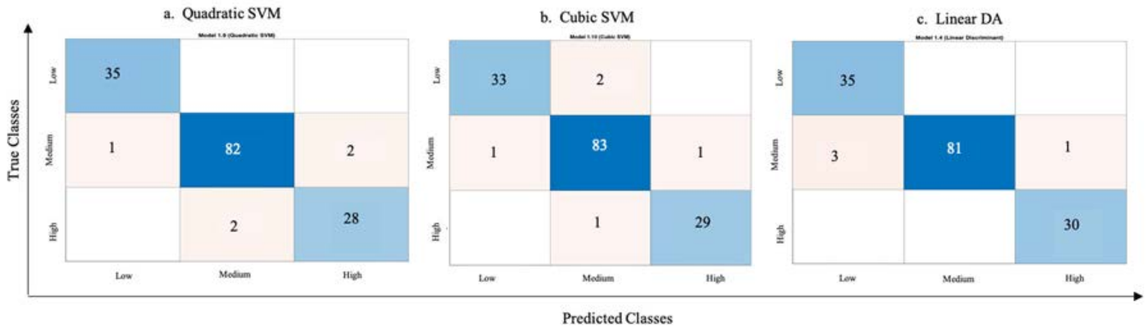

Fig. 4 – Confusion matrix [No obs.] of quadratic SVM, cubic SVM and linear DA

For the Linear DA, a total of 4 misclassifications are observed, being 2 instances as false negatives (FN) for the low and high level of sustainability and 4 false positives (FP) values for the medium level of sustainability. The results obtained show that, in general, the model can be quite accurate, with an F1-Score of 97%. The SVM algorithms have 5 misclassifications. The Cubic has, at least, one FN and one TN for each class, while the Quadratic has no TN for the low class. According to this analysis, both algorithms have a good fit to the data, even though the DA algorithm is more accurate. Comparing the number of misclassified instances, they differ only by one, being 4 for the DA and 5 for SVM. It is possible that by optimizing the hyperparameters of both algorithms, a clearer solution can be obtained as to which one of them fits better to the data used to measure the level of sustainability. When optimizing the hyperparameters of the algorithms with the Bayesian optimizer the SVM algorithm shows accuracy of 98% for measuring the level of sustainability, with 3 misclassified instances. Finally, this model is selected and exported as a code to evaluate the sustainability level of the case study which is a European RFT company.

A sensitivity analysis is performed for the model based on the SVM algorithm. 18 different scenarios were evaluated changing the weights assigned to the dimensions of sustainability. Table 2 presents the accuracy results obtained for each of them after the retraining. The results show that the accuracy of the model can change by approximately 2%, either positively or negatively from the initial 98% accuracy according to the percentage distribution given to the sustainability dimensions to define their impact on the level of sustainability. In particular, the model accuracy is more sensitive to variations where the environmental dimension has the greatest impact on the level of sustainability.

Scenario	Dimension weight			Accuracy
	Economic	Environmental	Economic	
1	0%	100%	0%	99%
2	100%	0%	0%	100%
3	0%	0%	100%	99%
4	33%	33%	33%	97%
5	50%	50%	0%	99%
6	0%	50%	50%	99%
7	50%	0%	50%	99%
8	10%	70%	20%	97%
9	20%	70%	10%	97%
10	10%	20%	70%	99%
11	20%	10%	70%	99%
12	25%	50%	25%	97%
13	50%	25%	25%	99%
14	25%	25%	50%	99%
15	70%	10%	20%	97%
16	60%	20%	20%	99%
17	20%	60%	20%	99%
18	20%	20%	60%	99%

Table 2 – Sensitivity analysis scenarios

5. MODEL IMPLEMENTATION RESULTS IN A CASE STUDY

As a case study, a European company in the freight transport sector with a global transport network is used to evaluate our methodology. This logistics service provider offers not only RFT but also other modes of transport such as rail freight, air freight, shipping, and more services. Since one of its characteristics is the decentralization in the decision-making processes, the sustainability assessment was done only for the region of southern Europe (Iberian countries). From the literature review, the UNCTAD's framework for Sustainable Freight Transport (Youssef et al., 2017) was identified as the most comprehensive framework for the freight transport sector. As KPIs are defined according to the particular circumstances of each case, table 3 presents the KPIs defined for this company with the corresponding definition and formulas according to the experts' criteria.

Dimension	KPI	Definition	Formula
Environmental	Shipments with reported CO_2 emissions	Rate of shipments with monitored CO_2 emissions in relation to total shipments in 1 year (between 0 and 1, the higher the better)	(Shipments with CO_2 emissions reported / Total shipments) * 100%
Economic	Engine Standards	The share of available Euro 6 standards-compliant vehicles (between 0 and 1, the higher the better)	% of vehicles that meet Euro 6 standards
	Transportation cost	Transportation costs as % of turnover (between 0% and 100%, the lower the better)	(Transportation costs / Total turnover) * 100%
	On-time shipments	Rate of on-time shipments in relation to total shipments (between 0 and 1, the higher the better).	[(Total shipments - Shipment delays) / Total shipments] * 100%
Social	Gender equality	Gender equality index among hired employees in the company (between 0 and 1, the higher the better. 1: very good gender equality 0: extreme gender inequality)	(Total number of women employees / Total number of men employees) * 100%
	Workforce Stability	Total workforce Stability index in the company (between 0 and 1, the higher the better. 1: very good workforce stability 0: extreme workforce instability)	(Total number of female employees / total number of employees) * 100%

Table 3 – Case Study KPI definitions and formulas

For the assessment of the level of sustainability, the company provided the data of each KPI for 2019. The weighted average methodology is applied to the company's performance values according to the impact of each of the KPIs determined by the RFT expert for each dimension. As environmental sustainability is given only by one KPI, the company presents a level of environmental sustainability of 77%. The economic dimension is defined as the one with the greatest influence on overall sustainability, and its performance is the lowest of the three with 58%. Transport costs are the most important KPI according to the weight assigned, followed by the other two. For the social dimension, both KPIs present the same level of importance, obtaining a performance of 63%. Based on these values, the input data is calculated to evaluate the sustainability level of the company.

Numerically, the company scored 62% for overall sustainability. Categorically, a high level of sustainability is achieved from a performance of 70%, the company is 8% away from reaching a high level of sustainability, so it has a medium level of sustainability. The greatest weight of the economic dimension on the overall sustainability, and transport costs representing more than 70% of the total turnover, influence negatively the overall performance of this dimension. The results for the other two KPIs of this dimension are good, as on-time deliveries are at 88% and engine standards (Euro VI) are at 90%. These results only represent 40% of overall sustainability. As the environmental dimension is only 20% relevant, its performance only contributes to the overall sustainability by 15%.

The social dimension only represents 10% of the total, contributing 6.3% to the total. With an equitable distribution of the weights, an overall return of 68% is obtained, which only represents a difference of 6% concerning the real value obtained, being also an average level of sustainability. This result means that the company must improve the performance of its sustainability indicators, especially transport costs.

The sustainable strategies are proposed based on the previous results obtained for overall sustainability and each of its dimensions. The selected KPIs reveal the strategies currently proposed by the company for its sustainable development. It can be seen that the company has as its strategy to implement concepts such as the use of IT systems to monitor and control CO_2 emissions, to use environmentally friendly vehicles, to monitor and control the costs and efficiency of transport, and to ensure the equality and well-being of both its employees and the society in general. Understanding the current strategies and performance of the company leads to a medium level of sustainability that allows for the identification of which strategies and which dimension of sustainability should be focused on in the future. Within the company’s results, it is noted that all its KPIs are defined on the basis of European regulations for the RFT. Currently, the company does not have any environmental sustainability indicators that actually show the impact of its activities. The integration of a system for measuring and monitoring GHG and CO_2 emissions as well as fuel consumption is a starting point and a valid strategy for the near future.

The evaluated company needs a more solid long-term strategy to continue its sustainable development. Promoting sustainable transport and involving all stakeholders in the development of the strategy is the best way to promote sustainability among customers and employees and to increase business. The proposed methodology for a sustainable strategy consists of establishing KPIs with a clear objective for each of the dimensions. In this case, for each of the dimensions, different KPIs are proposed based on the available frameworks for sustainable RFT. It is also proposed to include as many externalities caused by activities such as accidents, air pollution, climate change, noise, and management as possible. In addition, maintain the commitment to the continuous improvement of its performance for the KPIs that have been initially established for each of the three dimensions of sustainability. This allows for the evaluation of their level of sustainability and to maintain a historical record of the evolution of their sustainable development.

6. MANAGERIAL INSIGHTS

The growing awareness of sustainability in society is putting pressure on companies to integrate the principles of sustainable responsibility into their strategies and policies. Beyond the development of quantitative criteria for evaluating the sustainability of companies based on automatic learning techniques, such as the methodology developed in this work, companies in the RFT sector need to define and adopt sustainable strategies that integrate their three pillars. In the methodology developed, it can be observed that in order to apply these methods, a whole subsequent administrative process at the strategic level is also necessary, which initiates with the definition of sustainability objectives that integrate the three dimensions. Within the objectives, the key performance indicators for each dimension must be integrated and the performance in each dimension, and the general sustainability must be evaluated, as it has been done for the case study. As a final and starting point of a new strategic sustainable cycle, it is required the commitment of the stakeholders supported by ongoing monitoring, reporting, and communications among stakeholders that, at the same time, promote awareness and engagement. This becomes a cycle that must be constantly updated to continue the sustainable development of the company.

Today's customers are concerned about sustainable development (León et al., 2014). The development and integration of these quantitative models that integrate the three dimensions of sustainability support the decision-making process that integrates sustainability criteria. These methodologies teach companies that they can establish guidelines for their sustainable development that guide them in setting objectives and at the same time evaluate the company's performance in relation to them. Besides, they are adapted to the particular situation of each company or context of the study. This can be seen in that the input data can vary, i.e., the KPIs, and yet these tools fulfill their purpose. In general, the adoption of this type of strategy shows the social and environmental responsibility that companies in the RFT sector have and how they contribute to sustainable development.

7. CONCLUSIONS AND FUTURE RESEARCH

Nowadays, people and many businesses around the world are trying to develop strategies to mitigate the damage generated by humans' activities on the planet, and therefore, reducing the environmental impacts caused by climate changes. With the increase of road freight transport in Europe, the demand for related services in freight transport has been increased and, consequently, greenhouse gas emissions have been potentialized. To overcome this problem, in this paper, we developed a model based on supervised machine learning methods based on classification algorithms to integrate and evaluate the sustainability of enterprises in the road freight transport sector. This methodology aims to monitor the RFT activities and determining the level of sustainability on each of its sustainability dimensions.

For testing our methodology, a data set was generated in Matlab to represent the overall performance in each of the dimensions of sustainability. Each algorithm has been trained through this data, and that one which presented the best performance was selected to evaluate the sustainability dimensions of a European company in the freight transport sector with a global transport network. According to the results, the optimized SVM classifier obtained using Bayesian optimization has presented the best adaptation to the data and predicted with greater accuracy the level of sustainability. For environmental sustainability, the company presented a level of 77%. For the economic sustainability dimension, the company got 58%, which is mainly represented by transport costs (the most important KPI). Finally, for the social dimension, a performance of 63% was concerned. Numerically, the company got a 62% of sustainability out of the 100% possible, being the company 8% away from reaching a high level of sustainability. Therefore, it implies that the company needs a more solid long-term strategy to continue its sustainable development, where promoting sustainable transport and involving all stakeholders in the development of the strategy is the best way to promote sustainability among customers and employees and to increase business.

Future work could be derived on the basis of this paper. This model could be implemented for other companies and in other economic sectors by modifying the KPIs and adapting them according to the studied context. This would make it possible to verify that the model is not only limited to the RFT sector, but it serves to determine the level of sustainability regardless of the sector being evaluated. This therefore provides an opportunity to explore how accuracy may be affected by the results of the context. On the other hand, the developed SML model is subject to a certain level of subjectivity or bias since the parameters were defined by an expert in the sector. Therefore, the subjectivity could be mitigated by integrating this SML methodology with optimization methods based on heuristics and metaheuristics associated to sustainability criteria such as fuel consumption, external costs, CO_2 emissions, among others. These methodologies are characterized by the use of algorithms that allows for the optimal selection of KPIs that maximizes sustainability based on their impact level. A hybrid model such as this would not only allow a more objective and standardized evaluation of the level of sustainability but would also automatically establish the sustainability strategies.

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¿CUÁL ES EL IMPACTO DE LAS POLÍTICAS DE TRANSPORTE EN LA PROPIEDAD DE AUTOMÓVILES? EVIDENCIA EMPÍRICA DE LA CIUDAD DE MADRID

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RESUMEN

Con el fin de mejorar la calidad de vida y la sostenibilidad, a nivel mundial los gobiernos han aplicado múltiples políticas de transporte para reducir el uso y la propiedad del vehículo privado, así como para incentivar y ofrecer alternativas de viaje más sostenibles.

Las características de la ciudad y las políticas de transporte influyen en las decisiones de los individuos de poseer y utilizar su automóvil privado, lo que repercute en la generación de externalidades.

En Madrid se han implementado dos políticas que promueven la movilidad sostenible. En primer lugar, el Servicio de Estacionamiento Regulado (SER) que gestiona, regula y controla el estacionamiento en la vía pública, con el fin de racionalizar y compatibilizar el uso del espacio público y el estacionamiento de automóviles. En segundo lugar, el Plan de Calidad del Aire y Cambio Climático, que tiene como objetivo reducir la contaminación del aire. En este último se definió una Zona de Bajas Emisiones conocida como 'Madrid Central', que establece limitaciones de tráfico y de estacionamiento con la intención de reducir el acceso de los vehículos a la zona, especialmente los más contaminantes.

Esta investigación explora en qué medida la propiedad de automóviles está influida por la implementación de políticas de transporte que reducen el uso del vehículo privado. Para ello, mediante la calibración de un modelo logit ordenado multinivel, la propiedad de automóviles en los hogares se explica en función de las características sociodemográficas, variables del entorno construido de la ciudad, atributos de la red de transporte y variables relacionadas con las políticas de transporte.

Los resultados indican que los factores del entorno construido desempeñan un papel fundamental en la explicación de las tendencias de la propiedad de automóviles. Además, las políticas de transporte destinadas a disuadir el uso de automóviles parecen desalentar a los hogares su adquisición.

1. INTRODUCCIÓN

Los responsables de la política pública son conscientes de que las externalidades del transporte están aumentando considerablemente en muchas ciudades del mundo. Lo anterior, debido al creciente uso de los vehículos privados (Gakenheimer 1999; Moriarty y Honnery 2008). Las externalidades más conocidas relacionadas con la carretera son la congestión del tráfico, accidentes, daños al medio ambiente y el deterioro de las carreteras.

Para hacer frente a este problema, los responsables de la política pública y los profesionales dedican grandes esfuerzos a comprender cómo influyen ciertas características de las ciudades en el uso de los vehículos privados y, en particular, en la decisión de adquirir un vehículo. En este sentido, la propiedad de vehículos en los hogares representa una variable importante para que los planificadores locales puedan prever futuras medidas de política de transporte destinadas a garantizar ciudades sostenibles (Ding et al. 2016).

Como menciona Banister (2008), la mejora de la sostenibilidad del transporte requiere no sólo actuar sobre la capa física de la ciudad (forma urbana y flujos de tráfico), sino también sobre su dimensión social (personas y proximidad). Promover la movilidad sostenible y reducir el efecto de las externalidades negativas requiere, por tanto, crear zonas atractivas en la ciudad y mejorar la calidad de los barrios. Estas políticas pueden ser de mando y control (CAC por sus siglas en inglés) o de incentivos (IB por sus siglas en inglés). Una política de mando y control es esencialmente una regulación que hay que hacer cumplir, mientras que las políticas de IB proporcionan incentivos económicos y actúan para alterar el beneficio privado de una determinada respuesta de comportamiento (Santos et al. 2010). Con el fin de mejorar la habitabilidad urbana y la sostenibilidad, los gobiernos locales de todo el mundo han aplicado múltiples políticas para reducir el uso de vehículos privados y la propiedad de automóviles, así como para incentivar y ofrecer una alternativa atractiva a los coches privados.

El efecto de las políticas de transporte sobre el uso de los coches privados, y en particular sobre la decisión de los individuos de poseer un coche, necesita más estudios. Esto proporcionaría a los responsables políticos nuevas herramientas para mejorar el diseño de las políticas o aumentar las medidas de apoyo (Hanying 2018). Además, el impacto de la política de transporte está en consonancia con la fuerza de la construcción del transporte público urbano o el cambio del modo de desplazamiento de los residentes para mejorar el efecto de la aplicación de la política. Sin embargo, hasta la fecha son escasas las contribuciones de investigación que analizan empíricamente el efecto de las políticas de transporte sobre las decisiones de propiedad de automóviles a nivel internacional, especialmente en lo que respecta a las políticas destinadas a restringir el uso de vehículos privados en las zonas urbanas.

El objetivo principal de este trabajo es explorar hasta qué punto la propiedad de automóviles se ve influida por la aplicación de políticas de transporte destinadas a mejorar la sostenibilidad urbana, en particular las restricciones al uso de vehículos privados. Para ello, nos centramos en la ciudad de Madrid (España), ya que este caso de estudio presenta algunas características interesantes. En primer lugar, es una de las ciudades más grandes de Europa, con una presencia tradicionalmente alta de los modos de transporte sostenibles (transporte público y modos activos) en el reparto modal y una marcada expansión urbana experimentada en las últimas décadas. En segundo lugar, Madrid ha puesto en marcha recientemente políticas de transporte posteriores (aparcamiento de pago en la calle, zona de bajas emisiones, protocolo de NO_2) destinadas a reducir el uso del vehículo privado. Por lo tanto, este trabajo pretende contribuir a la literatura actual explorando cómo la propiedad del coche se ve influenciada tanto por las características de la ciudad como por la implementación de políticas de transporte sostenible. Los resultados obtenidos para la ciudad de Madrid pueden ayudar a los planificadores a implementar políticas dirigidas a promover el transporte sostenible y a mejorar la habitabilidad en las zonas urbanas.

El resto de este trabajo se divide como sigue. La sección 2 revisa la literatura previa relativa a la propiedad del coche en entornos urbanos, con especial atención a las características urbanas y a la aplicación de políticas de transporte para reducir las externalidades relacionadas con la carretera. La sección 3 presenta el caso de estudio analizado en este trabajo, la ciudad de Madrid (España). La sección 4 describe los datos recogidos para esta investigación y la metodología adoptada, mientras que la sección 5 presenta y discute los resultados de la modelización. Por último, la sección 6 expone las principales conclusiones de este análisis y señala las recomendaciones políticas para las zonas pobladas.

2. REVISIÓN LITERARIA

En las últimas décadas se han dedicado muchas investigaciones a estudiar las decisiones de propiedad de automóviles. En el campo de la investigación sobre el transporte, se han adoptado preferentemente métodos cuantitativos para analizar las decisiones de los individuos de poseer un vehículo privado, así como las tendencias generales sobre la propiedad de automóviles a nivel agregado. De acuerdo con Gu et al. (2020), los enfoques de la propiedad de automóviles con una perspectiva cuantitativa pueden dividirse en modelos exógenos y endógenos. Los modelos exógenos consideran que las decisiones de propiedad de automóviles son independientes de las restricciones, como la elección modal. Por otro lado, los modelos endógenos analizan conjuntamente la propiedad del coche y otras elecciones (Giuliano y Dargay 2006). Además, los estudios científicos en la literatura consideran variables más específicas como la demografía de los hogares, el empleo de los individuos, los atributos del tránsito, el entorno construido, los atributos del ciclo de vida y las políticas (Anowar, Eluru y Miranda-Moreno 2014).

Se ha comprobado que muchas características sociodemográficas, tanto a nivel individual como de los hogares, influyen en la propiedad del coche. Varios estudios (Dargay 2001; Dargay y Vythoulkas 1999; Golob 1989) muestran que los ingresos de los hogares tienen una fuerte relación positiva con la propiedad de automóviles, siendo las elasticidades de los ingresos generalmente mayores a largo plazo que a corto plazo (Dargay y Vythoulkas 1999). Además, se ha comprobado que la elasticidad con respecto al aumento de la renta es mayor que con respecto a la disminución de la misma, por lo que, una vez adquirido el coche, dejar de usarlo se hace más difícil aunque la renta del hogar disminuya (Dargay 2001). Con una perspectiva similar, otros autores como Chatterton et al. (2016) se han centrado en cómo influye en la propiedad del coche el coste global del vehículo, que se compone de los costes fijos anuales, los costes esporádicos (reparación y mantenimiento), los costes de combustible y la depreciación. También se ha comprobado que la propiedad de un coche está influenciada por la edad (Klein y Smart 2017), ya que los jóvenes (nacidos en las décadas de 1980 y 1990) tienden a tener menos vehículos que las generaciones anteriores.

Además, algunos acontecimientos del curso de la vida influyen en la decisión de poseer un coche. Gu et al. (2020) estudiaron la trayectoria de vida (eventos educativos, matrimoniales, ocupacionales de la vivienda y de la propiedad del coche) de los ciudadanos holandeses y descubrieron, por ejemplo, que los hogares jóvenes sin coche son más sensibles a los eventos relacionados con la composición del hogar como tener un nuevo hijo. En entornos propensos al uso del coche, como Estados Unidos, existe un fuerte efecto positivo entre la propiedad del coche y la probabilidad de estar empleado (Raphael y Rice 2002). Descubrieron que el empleo a tiempo completo tiene una mayor influencia en la obtención de un coche en comparación con el empleo a tiempo parcial. También se llegó a la conclusión de que el comportamiento es diferente según el género y la raza.

Los hogares de las zonas de alta densidad poseen menos coches que los de las zonas de baja densidad (Ding et al. 2016), dado que las zonas urbanas de baja densidad están mal servidas por alternativas de transporte (Giuliano y Dargay 2006). Además, los barrios del centro de la ciudad tienen mayor densidad y heterogeneidad de usos del suelo que los suburbanos. Se ha comprobado que una mayor mezcla de usos del suelo, así como una mayor proximidad a centros comerciales y restaurantes, están asociados negativamente a la propensión a poseer un coche (Li y Zhao 2017).

Christiansen et al. (2017) para Noruega y Guo (2013) para Estados Unidos mostraron una relación positiva entre la disponibilidad de aparcamiento y la propiedad de un coche.

Según estos autores, los hogares con aparcamiento privado tienen una disposición a poseer un coche tres veces mayor. La disponibilidad de aparcamiento en la calle y fuera de ella también influye en la decisión de poseer un coche, y está fuertemente influenciada por la distancia a pie entre la zona de aparcamiento, el hogar y el aparcamiento gratuito.

La propiedad del coche también está fuertemente asociada al modo de transporte que se utiliza habitualmente (Kitamura 1989). Los gastos en transporte público y en tiempo de viaje en coche influyen positivamente en las decisiones futuras de propiedad del coche. El acceso al transporte público puede ser decisivo para reducir la propiedad del coche en los jóvenes (Klein y Smart 2017). Cervero (2002) descubrió que la accesibilidad al trabajo mediante redes de tránsito reducía el nivel de propiedad de automóviles, mientras que la accesibilidad al trabajo mediante redes de vehículos se asociaba positivamente con la obtención de más automóviles.

En todo el mundo se han aplicado algunas políticas de transporte para restringir el uso de vehículos privados y disminuir la propiedad de automóviles. Las políticas de CAC son las más comunes de este tipo. En Singapur (Smith 1992) y China (Hanying 2018), se aplicó una política eficaz que controla el número de coches nuevos comprados, conocida como "Sistema de cuotas de vehículos", para gestionar los niveles de propiedad de coches. En el caso de Singapur, en los dos primeros años de funcionamiento se redujo a la mitad el crecimiento de la propiedad de automóviles.

Las políticas de transporte destinadas a reducir la congestión de las carreteras también influirían, en teoría, en la propiedad de automóviles. Por ejemplo, Wang et al. (2014) exploraron el efecto de una restricción de matrículas sobre las decisiones de propiedad de automóviles en China. Sorprendentemente, aunque la política tenía como objetivo retirar los coches de la carretera, los autores descubrieron que la política aumentaba la propiedad de coches, en el sentido de que los usuarios con intención de evitar la medida conseguían varios coches con diferentes números de matrícula. Hasta donde sabemos, no se aportan pruebas empíricas de otras medidas políticas destinadas a reducir la congestión, como la tasa de congestión, aplicada en varias ciudades del mundo, como Londres, Estocolmo o Singapur.

El aparcamiento de pago es una política aplicada en todo el mundo que establece algunas normas para el uso del aparcamiento en la calle. Dentro de las regulaciones, el precio y la oferta tienen más influencia en la propiedad del coche. Por ejemplo, en Barcelona (España), Albalate y Gragera (2020) llegaron a la conclusión de que un aumento de la densidad de plazas de aparcamiento reguladas incrementa la posesión de coches a nivel de barrio en 0,26 coches por cada 1.000 habitantes.

También se han aplicado algunas políticas de IB, como el "Plan de coches de fin de semana". Esta política permite matricular los coches para utilizarlos únicamente durante las horas de menor afluencia y obtener un importante ahorro económico para los propietarios (Olszewski y Turner 1993). En San Francisco, se ha puesto en marcha el programa City CarShare para promover el uso compartido del coche. Alrededor de 9 de cada 10 miembros del programa pertenecían a hogares con cero o un coche (Cervero y Tsai 2004). La reducción de la propiedad de automóviles se consiguió al facilitar el acceso a los hogares con vehículo, que a menudo evitaron adquirir un segundo o tercer vehículo.

Como puede observarse, existe una amplia literatura que analiza la propiedad de automóviles y sus factores explicativos, con múltiples estudios que explican el comportamiento de la propiedad de automóviles. La mayoría de las contribuciones anteriores se centran en la relación entre la propiedad del coche y la sociodemografía de los hogares y, en menor medida, en los parámetros relativos al entorno construido de la ciudad. Sin embargo, por lo que saben los autores, es necesario investigar más a fondo el efecto de las políticas de transporte urbano en las decisiones de propiedad de automóviles, en particular las políticas de restricción de automóviles. Esto es especialmente interesante en contextos como el de las ciudades europeas, que suelen presentar altas densidades de población y cuentan generalmente con servicios de tránsito de calidad.

3. CASO DE ESTUDIO: MADRID CIUDAD

Esta sección ofrece una breve descripción del estudio de caso seleccionado para explorar hasta qué punto la propiedad de automóviles se ve influida por la aplicación de políticas de transporte destinadas a mejorar la sostenibilidad urbana y reducir el uso de vehículos privados.

Madrid es la capital de España y su ciudad más poblada, con un total de 3,3 millones de habitantes (Ayuntamiento de Madrid 2020a). Madrid sigue la tendencia general europea de mayor densidad, con un valor de 8.832 habitantes/km^2. La concentración de población es especialmente densa en la zona central dentro del primer anillo vial (24.326 habitantes/km2).

Tradicionalmente, la ciudad se divide en dos zonas principales (véase la Figura 1): el centro de la ciudad, dentro del primer anillo vial (M-30), y la periferia, que comprende los distritos fuera de la M-30. En las últimas décadas, la ciudad de Madrid ha experimentado un rápido crecimiento y un proceso de suburbanización, por lo que muchos residentes y puestos de trabajo se están desplazando del centro de la ciudad a la periferia (Díaz-Pacheco y García-Palomares 2014; Gallo Rivera y Garrido Yserte 2012). En la actualidad, alrededor del 30% de los habitantes viven en el centro de la ciudad y el otro 70% en la periferia (CRTM 2020b). El empleo se distribuye por igual entre el centro de la ciudad de Madrid y su periferia (ambos representan el 60% de los empleos), pero la evolución de la localización del empleo en los últimos años muestra un aumento hacia los municipios exteriores del área metropolitana de Madrid (Tobarra Gómez et al. 2016).

El tamaño de los hogares es menor para Madrid Centro en comparación con la periferia, 2,13 y 2,41, respectivamente. En consonancia con el CRTM (CRTM 2020b), Madrid muestra una reducción progresiva del tamaño del hogar.

La movilidad en Madrid se caracteriza por la gran oferta de alternativas de transporte público. Su red de metro es especialmente extensa. Tiene 288 km de longitud y un total de 302 estaciones. La oferta de servicios de autobús de cercanías también es elevada, ya que Madrid cuenta con 209 líneas que recorren 10.877 paradas. Esta red principal de transporte se complementa con servicios adicionales que conectan la ciudad de Madrid con su área metropolitana, como 444 líneas de autobús de cercanías, 8 líneas de ferrocarril de cercanías y 4 líneas de tranvía/ferrocarril ligero (Monzón, A., Cascajo, R., Romero, C., Calzado, R. Lopez 2019). Los modos de transporte público se integran de forma física y financiera para fomentar la intermodalidad. El sistema de bicicletas públicas, conocido como BiciMAD, ofrece una alternativa limpia y saludable a los ciudadanos. El sistema cuenta con una oferta de 2.964 bicicletas eléctricas, 4.116 anclajes y 258 estaciones (Ayuntamiento de Madrid 2020b). Los servicios privados de movilidad compartida han florecido en la ciudad de Madrid en los últimos años. Estas nuevas formas de movilidad incluyen el coche compartido, el ciclomotor compartido, la bicicleta y el patinete compartidos.

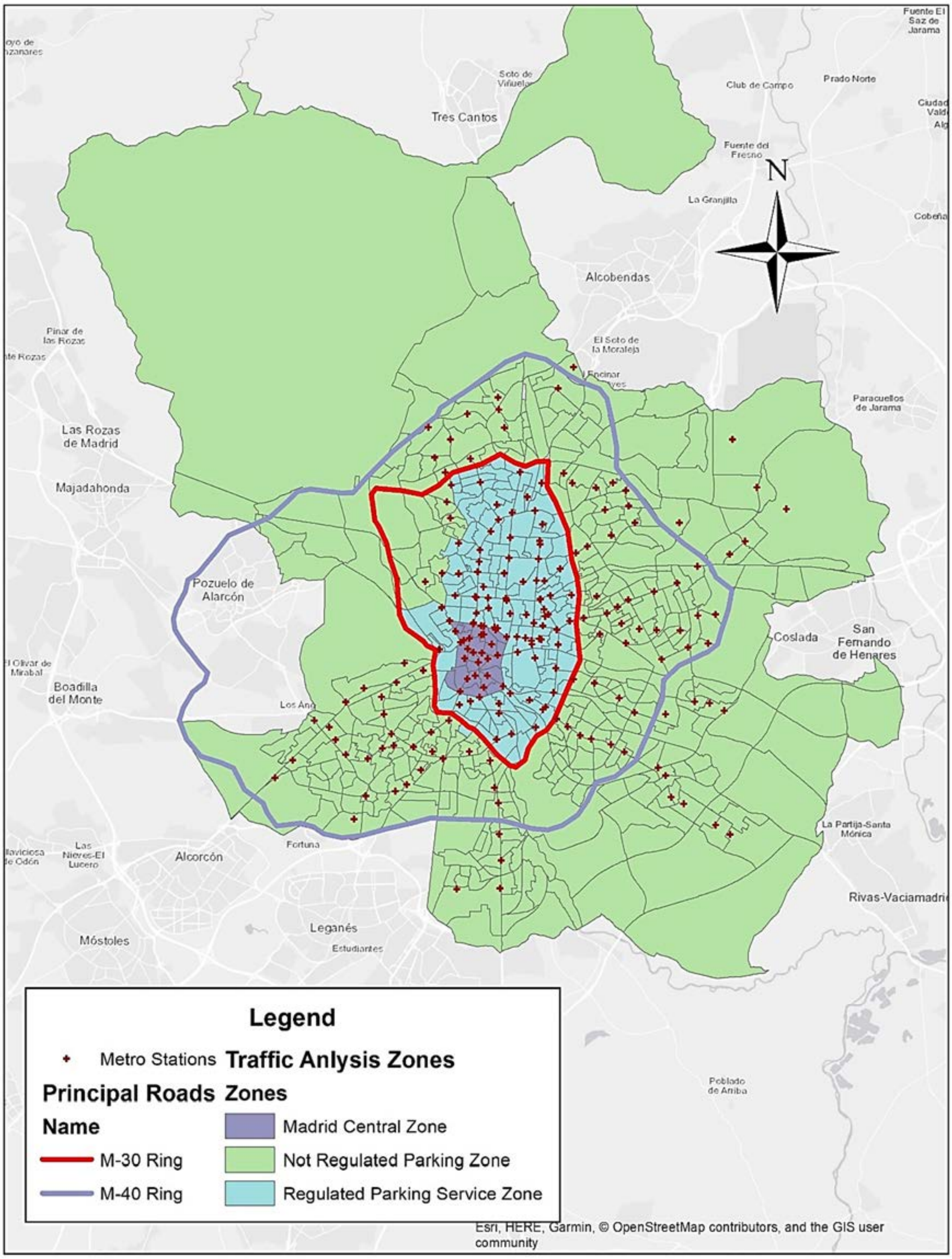


Figura 1 Madrid Ciudad

En los últimos años se han desarrollado dos políticas de transporte fundamentales: El Servicio de Estacionamiento Regulado (SER) y el Plan de Calidad del Aire y Cambio Climático de la Ciudad de Madrid, comúnmente conocido como PLAN A.

El SER se encarga de gestionar, regular y controlar el estacionamiento de vehículos en superficie en los distritos centrales de la ciudad, con la intención de racionalizar y compatibilizar el uso del espacio público y el estacionamiento de vehículos privados (Ayuntamiento de Madrid 2018). Madrid cuenta con más de 150.000 plazas de aparcamiento regulado de pago, divididas en cuatro tipos: i) 26.481 plazas en "Zona Azul" disponibles para todo tipo de usuarios; ii) 124.822 plazas en "Zona Verde" con prioridad para los residentes, aunque los no residentes también pueden utilizarlas a un precio superior al de la "Zona Azul"; iii) 1.397 plazas en "Zona Naranja" para larga estancia disponibles para todo tipo de usuarios, y iv) 382 plazas en la "Zona Roja" para el servicio sanitario. El área cubierta por la política SER puede observarse en la Figura 1.

El PLAN A tiene como objetivo reducir la contaminación atmosférica y contribuir a la mitigación del cambio climático (Ayuntamiento de Madrid 2017). Una de las acciones más importantes de este Plan fue la definición de una Zona de Bajas Emisiones (ZBE) conocida como "Madrid Central" (MC), véase la Figura 1. Esta ZBE se implementó con un conjunto de medidas específicas con el fin de promover un estilo de vida de movilidad de bajas emisiones y promover un centro de la ciudad más amigable para los peatones, ciclistas, vecinos y visitantes MC establece limitaciones de tráfico y estacionamiento con la intención de reducir el acceso de vehículos en la zona, especialmente los más contaminantes. Las condiciones de aparcamiento y las restricciones de tráfico para los vehículos privados se basan en una clasificación armonizada a nivel nacional (Cero, Eco, C, B o A) que tiene en cuenta tanto el motor como la antigüedad del vehículo. Además, el MC incluye otras estrategias para liberar espacio vial para los peatones y las bicicletas.

4. DATOS Y METODOLOGÍA

4.1 Recolección de datos

Esta sección presenta los datos recogidos para esta investigación. Las variables explicativas consideradas en el análisis de las tendencias de propiedad de automóviles en la ciudad de Madrid incluyen las características sociodemográficas de los hogares, las variables del entorno urbano, los atributos de la red de transporte y las variables relacionadas con la política. Los datos se han recogido en dos niveles principales de información: hogares y Zonas de Análisis de Tráfico, ZAT, dependiendo de la disponibilidad de los datos necesarios. Para realizar el análisis se han consultado múltiples fuentes de datos e información a nivel local, regional y nacional

Las características sociodemográficas de los hogares se han recogido principalmente de la Encuesta de Movilidad de Madrid, EM (CRTM 2020b), que proporciona información detallada de un total de 58.492 hogares del Área Metropolitana de Madrid. La muestra utilizada para esta investigación se compone finalmente de 28.794 hogares.

Las variables sociodemográficas de los hogares proporcionadas por la EM incluyen: número de miembros del hogar por edad, miembros del hogar con movilidad reducida, propiedad de aparcamiento privado, número de permisos de conducir y abonos de transporte público adquiridos, por hogar, y número de viajes diarios realizados por hogar. Para describir mejor la estructura familiar, se definieron variables categóricas adicionales, como la presencia de niños en el hogar (entre 0 y 4 años), el número de personas que trabajan y el número de personas con titulación universitaria. Esta fuente también proporcionó información sobre el número de vehículos privados por hogar, que es la variable modelada en esta investigación.

La EM no recogía datos sobre los ingresos. Para hacer frente a este problema, los autores de este trabajo incluyeron la información proporcionada por el Instituto Nacional de Estadística, INE (INE 2016) a nivel espacial de sección censal. A efectos de modelización, esta información debe trasladarse a un nivel espacial de ZAT, por lo que se ha aplicado una media ponderada espacialmente.

El análisis también incluyó variables explicativas relativas al entorno construido de la ciudad. La información sobre la densidad de población se recogió a nivel de ZAT para 2018 (Ayuntamiento de Madrid 2020a). Los atributos de uso del suelo se recogieron del Departamento de Catastro del Ayuntamiento (2020), en particular: áreas residenciales, comerciales, industriales y de oficinas (medidas en metros cuadrados) por ZAT. Un primer análisis exploratorio mostró una alta correlación entre las diferentes áreas de uso del suelo.

La investigación también incluyó información sobre la red de transporte, en particular la accesibilidad del transporte público. Para ello, se recopilaron datos de tránsito de las bases de datos abiertas de la Autoridad Regional de Transporte de Madrid (CRTM 2020a). Se eligió el número de paradas de autobús y de estaciones de metro por ZAT como proxies de la accesibilidad geográfica al transporte.

Finalmente, se incluyeron dos variables ficticias para controlar si el Servicio de Estacionamiento Regulado (SER) y la Zona Central de Madrid (MC) se aplican en cada ZAT. Estas variables permiten explorar si las tendencias de propiedad de automóviles de los hogares difieren entre los barrios en los que se aplican estas políticas o no.

4.2 Metodología: un modelo logit ordenado multinivel

Este trabajo realiza un modelo logit ordenado multinivel para explorar las tendencias de la propiedad de automóviles en la ciudad de Madrid (España). La variable que modelar es el número de coches por hogar, que puede representarse como una variable categórica.

Debido a la naturaleza ordinal y discreta de la variable dependiente, se ha adoptado un marco logit ordenado (Hanushek y Jackson 1977).

Los modelos logit ordenados se basan en los modelos logit tradicionales derivados de la teoría de maximización de la utilidad, es decir, la teoría de la utilidad aleatoria (estocástica). Según Ortúzar y Willumsen (2011), la teoría de la elección discreta supone que cada individuo asigna los recursos de forma que maximiza su utilidad o satisfacción personal (teoría de la utilidad aleatoria). Uno de los principales supuestos de los modelos logit ordenados es el de las probabilidades proporcionales (Wang et al. 2018), por lo que se supone que la relación entre cualquier par de categorías de resultados es igual.

Para explorar las decisiones de propiedad de un coche, adoptamos un modelo logit ordenado multinivel. Los modelos multinivel también se conocen como modelos de efectos aleatorios, mixtos o jerárquicos. En comparación con los modelos clásicos, los modelos multinivel tienen en cuenta la posible correlación entre las observaciones de los datos debido a las estructuras jerárquicas/anidadas de los datos. En este sentido, podemos esperar, por ejemplo, una alta correlación de las tendencias de propiedad de automóviles entre los hogares situados en el mismo barrio/distrito. Ignorar este efecto puede llevar a violar el supuesto de observaciones independientes, con importantes consecuencias negativas en los resultados.

Como se ha señalado anteriormente, los modelos logit ordenados estiman la relación entre un conjunto de variables independientes y la variable de resultado ordinal en una escala del logit (Agresti 2010). Además, la modelización multinivel para las variables de respuesta ordinales permite estimar la relación entre las variables predictoras en diferentes niveles y la variable de respuesta ordinal (Liu 2016). Para este marco de modelización, adoptamos una estructura de dos niveles, en la que el nivel 1 está relacionado con los individuos, y el nivel 2 se refiere a las zonas TAZ. Las especificaciones multinivel consideran un modelo diferente para cada nivel de datos y permiten explorar la variabilidad entre los distintos grupos en los diferentes niveles (Gomez, Papanikolaou y Vassallo 2016). En este caso, el modelo capta la heterogeneidad espacial a través de la TAZ (Giuliano y Dargay 2006).

La especificación del modelo logit ordenado multinivel para el nivel 1 se muestra en la ecuación 1

$$\text{Level 1: } Y_{ijk} = logit\,[\pi_{kl}(Y \leq k)] = \ln\left(\frac{\pi\,(Y_I \leq k)}{\pi\,(Y_I > k)}\right) = \alpha_k - (\beta_{1j}X_{1ij} - \beta_{2j}X_{2ij} - \ldots - \beta_{pj}X_{pij}) \quad (1)$$

Donde α_k son los puntos de corte con $k = 1, 2, 3, \ldots, K-1$; $X_{1ij}, X_{2ij}, \ldots, X_{pij}$ son las variables predictoras para el individuo ith y jth clúster; $\beta_{1j}, \beta_{2j}, \ldots, \beta_{pj}$ son los coeficientes del modelo en el j^{th} clúster a estimar.

La especificación del Nivel 2 se presenta en la ecuación 2.

$$\text{Level 2: } \beta_{0j} = \gamma_{00} + \gamma_{01} + \ldots + \gamma_{0p} + u_{0j} \quad (2)$$

Donde γ_{00} es el intercepto; $\gamma_{01}, \ldots, \gamma_{0p}$ son los coeficientes del Nivel 2 (efectos fijos); u_{0j} es el término del error o el efecto aleatorio relacionado a los puntos de corte.

La variable dependiente Y_k es un parámetro ordenado que capta la posesión de coches, con cuatro atributos categóricos: 0 coches, 1 coche, 2 coches y 3 o más coches. En nuestro caso, el conjunto de variables predictoras X_ij se refiere a las características sociodemográficas, el entorno construido de la ciudad, los atributos del sistema de transporte y las medidas de política de transporte aplicadas en la ciudad de Madrid.

Ocho de las variables explicativas utilizadas en el modelo son categóricas, por lo que es necesario elegir una referencia base para explicar adecuadamente los resultados del modelo. Para CHILD, SER, MC y PRIVATE, el caso de no ocurrencia es la referencia (No = 0). El nivel de referencia para las variables WORKER y PROFESSIONAL es 0 miembros. La referencia base para TRIPS es 0. El nivel de referencia de RENT es el grupo de ingresos anuales de 20 - 40 mil euros.

5. RESULTADOS DE LA MODELIZACIÓN Y DISCUSIÓN

A continuación, en primer lugar, se muestran los resultados de la modelización y, por último, se presenta el efecto sobre la propiedad de automóviles de las actuales políticas de transporte aplicadas en la ciudad de Madrid.

5.1 Modelo de propiedad del coche

Antes de calibrar el modelo de elección discreta, realizamos pruebas de multicolinealidad para comprobar la presencia de una fuerte correlación entre las variables explicativas, según Gujarati y Porter (2009). El análisis mostró dos problemas principales de multicolinealidad en nuestros datos. El número de permisos de conducir por hogar está muy correlacionado con el número de miembros del hogar, por lo que el primero se eliminó del análisis; por lo tanto, la densidad residencial fue la única variable de este tipo que se mantuvo en la modelización.

Los resultados del modelo que explica la propiedad de automóviles en la ciudad de Madrid se presentan en la Tabla 1. Como puede observarse, la mayoría de las variables explicativas que resultaron no estadísticamente significativas fueron finalmente eliminadas de la última versión del modelo. Para ello, realizamos múltiples pruebas de razón de verosimilitud (LR) durante el proceso de calibración, para comprobar que ciertas variables explicativas podían ser omitidas sin impacto en el ajuste global o en el poder explicativo del modelo. Los signos de los coeficientes del modelo se ajustan principalmente a los resultados esperados y a las contribuciones anteriores de la bibliografía. Como puede observarse, las variables sociodemográficas, del entorno construido de la ciudad, relacionadas con el sistema de transporte y de la política de transporte son estadísticamente significativas a la hora de explicar la propiedad del coche en el caso de estudio analizado.

Muchas variables sociodemográficas resultaron estadísticamente significativas a la hora de explicar las tendencias de la propiedad de automóviles. Como cabía esperar en un principio, el coeficiente de MEMBER (número de miembros del hogar) es positivo y estadísticamente significativo, lo que indica que cuantos más individuos viven en un hogar, mayor es la probabilidad de tener más coches. Según los resultados de la modelización, la probabilidad aumenta en torno al 10% por cada miembro adicional en el hogar. Además, como se ha señalado anteriormente, la presencia de niños en el hogar tiene un efecto positivo, pero este coeficiente sólo es estadísticamente significativo al 90%. Como se puede observar en la Tabla 1, el número de miembros del hogar con movilidad reducida aumenta la probabilidad de tener más coches. En particular, el número de coches por hogar aumenta en un 50% por cada persona adicional con movilidad reducida en el hogar.

Atributo	Variables		Coef.	Err. Std.	P>z
	MEMBER		0.101	0.023	0.000
	CHILD		0.091	0.047	0.054
	PRIVATE PARKING	Ref (0)	1.803	0.028	0.000
	TRANSIT_PASS		-0.552	0.018	0.000
	RM		-0.668	0.044	0.000
	WORKERS	(1)	0.555	0.026	0.000
	Ref (0)	(2)	0.648	0.060	0.000
		(3)	1.429	0.117	0.000
Características sociodemográficas del hogar	**GRADUATED**	(1)	0.249	0.027	0.000
	Ref (0)	(2)	0.079	0.063	0.213
		(3)	0.864	0.132	0.000
	INCOME	(40 - 50)	0.174	0.049	0.000
	Ref (20 - 40)	(50 - 60)	0.247	0.066	0.000
		(60 - 70)	0.355	0.072	0.000
		(70 - 80)	0.585	0.086	0.000
		(80 - 90)	0.671	0.094	0.000
	TRIPS	(2)	0.420	0.044	0.000
	Ref (0)	(3)	0.542	0.058	0.000
		(4)	0.654	0.047	0.000
		(5)	0.770	0.065	0.000
		(6)	0.886	0.053	0.000
Atributos de la red de transporte	**BUS_ST**		0.006	0.003	0.077
	METRO_ST		-0.053	0.022	0.016
Variables del entorno urbano	**DENSITY**		-0.001	0.000	0.000
	RESIDENTIAL DENSITY		-0.111	0.021	0.000
Variables relacionadas con la política	**SER**	Ref (0)	-0.397	0.046	0.000
	MC	Ref (0)	-0.427	0.092	0.000
	Cut1		-0.292	0.071	
	Cut2		2.528	0.073	
	Cut3		5.085	0.079	
	zt1259>INCOME	**var(_cons)**	0.053	0.008	0.000
	No. Observations	28,794			
	Log-Likelihood	28,313.1			
	AIC	56,668.1			
	BIC	56,944.4			

Tabla 1 Resultados de la modelización

El número de miembros que trabajan y que tienen un título universitario tiene una influencia positiva y significativa en el número de coches por hogar. Lo mismo ocurre con el nivel de ingresos. Como puede observarse, la variable que controla los ingresos medios del hogar (medidos en miles de euros) tiene coeficientes positivos y estadísticamente significativos y coincide con los resultados preliminares mencionados. Cuando el hogar se encuentra dentro de una ZT cuyo nivel de renta media anual se sitúa entre 40 y 50, entre 50 y 60, entre 60 y 70, entre 70 y 80 y por encima de 80 mil euros, el número de coches aumenta en un 19%, 28%, 42%, 79% y 95% respectivamente, en comparación con el caso base (renta de 20 a 40). Estos resultados están en consonancia con múltiples análisis realizados por diferentes autores (véase, por ejemplo, Dargay (2001), Zegras (2010) y Guerra (2015)).

Las variables del entorno de la ciudad también explicaron, de forma estadísticamente significativa, las tendencias de posesión de coches en los hogares. Tanto la densidad de población como la densidad residencial tienen una influencia negativa y estadísticamente significativa en la obtención de más coches. Según los resultados de la modelización, la probabilidad de poseer un coche disminuye un 11% por cada unidad de densidad residencial adicional (m2/hectárea) en el barrio donde se encuentra el hogar. En otras palabras, las zonas de alta densidad residencial reducen la probabilidad de tener un coche, probablemente porque hay menos espacio para aparcarlo. Este resultado está en consonancia con el meta-análisis realizado por Bassolas et al. (2019). Llegaron a la conclusión de que las zonas urbanas densas presentan una organización más jerárquica de la movilidad, lo que conduce a un uso más amplio del transporte público y de los modos activos y a un menor uso del vehículo privado, lo que afecta a las decisiones de propiedad del coche.

Los atributos relacionados con el transporte también tienen importantes implicaciones en las decisiones sobre la propiedad del coche. El número de abonos de transporte público adquiridos en un hogar tiene una influencia negativa y estadísticamente significativa (coeficiente = -0,552, valor p = 0,000) en el número de coches. Según los resultados de la modelización, por cada pase de viaje adicional en el hogar, la probabilidad de poseer un coche disminuye en un 43%. Además, los resultados de la modelización muestran una fuerte influencia del aparcamiento privado en la propiedad del coche, como ya se ha señalado en los resultados preliminares. Los atributos del sistema de transporte, especialmente la accesibilidad a la red de transporte público, también ofrecen resultados estadísticamente significativos. El número de estaciones de metro en el barrio donde se encuentra el hogar influye negativamente en la propiedad del coche (coeficiente = -0,053; valor p = 0,016). La buena accesibilidad a las estaciones de metro en Madrid hace más atractivo el uso del transporte público y proporciona un modo alternativo al coche privado para los desplazamientos urbanos, reduciendo así la propiedad del coche. Este resultado debe interpretarse teniendo en cuenta que Madrid cuenta con una extensa y densa red de metro que cubre razonablemente toda la ciudad. Los resultados relativos a la accesibilidad del autobús público están cerca de ser significativos (valor p = 0,077) e indicarían que cuanto mayor es el número de paradas de autobús en el barrio en el que se encuentra el hogar, mayor es el número de coches en los hogares. En este sentido, las paradas de autobús y los servicios de autobús también cubren razonablemente toda la ciudad, pero comparten las carreteras con otros modos motorizados y generan retrasos en los viajes y pueden disuadir a los usuarios de utilizarlo.

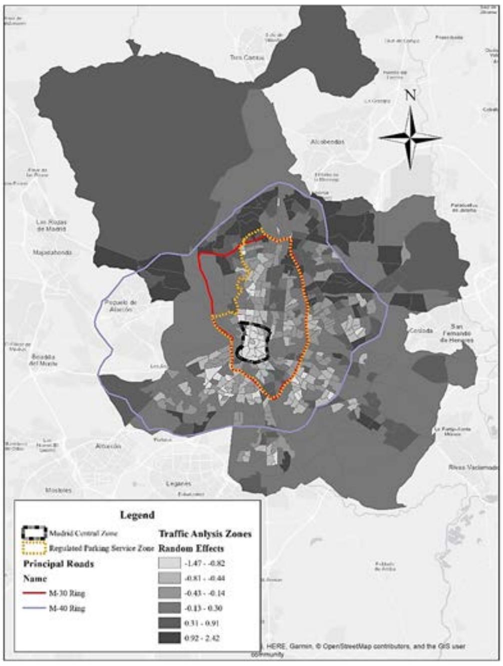
5.2 Impacto de las políticas de promoción de la movilidad sostenible

Ambas políticas de transporte sostenible (SER y MC) evidencian tener un impacto negativo en las tendencias de propiedad de automóviles en la ciudad de Madrid, tal y como muestran los resultados de la modelización (Ver Tabla 1). Este efecto es estadísticamente significativo (valor p = 0,000) incluso después de controlar las características de los hogares y los atributos de la ciudad, como la densidad urbana o la accesibilidad del transporte público. Las políticas del SER y de Madrid Central reducen en un 33% y un 35%, respectivamente, la probabilidad de poseer un coche, en comparación con las zonas donde no se aplican estas medidas. Este resultado parece razonable ya que estas políticas cobran o reducen las plazas de aparcamiento en la calle. En resumen, estas políticas parecen ser herramientas eficaces para desincentivar el uso del vehículo privado (impactando así en las decisiones de propiedad del coche) y para mejorar la sostenibilidad urbana.

Estimamos la heterogeneidad espacial de las tendencias de la propiedad de automóviles en los distintos barrios. Para ello, calculamos los efectos aleatorios para cada ZAT para el modelo nulo obteniendo un efecto aleatorio significativo (coeficiente = 0,4930 y valor p = 0,000). El Figura 2a muestra el efecto aleatorio estimado para cada ZAT. Como se puede observar, existe una gran variabilidad entre las distintas Zonas de Reparto. Por ejemplo, podemos observar los valores más bajos de los coeficientes aleatorios (que indican un menor número de coches por hogar) para casi todas las ZAT dentro de la ZBE Madrid Central, en comparación con otras ZAT fuera de Madrid Central. Del mismo modo, se observan los menores valores del efecto aleatorio obtenidos para los barrios situados dentro de la zona SER, en comparación con las ZAT de fuera de esta zona.

Además, analizamos el impacto de las dos medidas políticas sobre las tendencias de propiedad de automóviles controlando por los niveles de renta. El Figura 2b muestra el valor de los efectos aleatorios respecto a los coeficientes de pendiente de la variable de renta. Estos efectos aleatorios son estadísticamente significativos para el caso de Madrid, lo que implica que el efecto de la renta media anual sobre la propiedad de automóviles varía entre las zonas ZAT. Como se puede observar, los valores de estos efectos aleatorios cambian desde el centro a la periferia de la ciudad.

a. Efectos aleatorios en las ZAT



b. Efectos aleatorios generados por ZAT y renta media anual

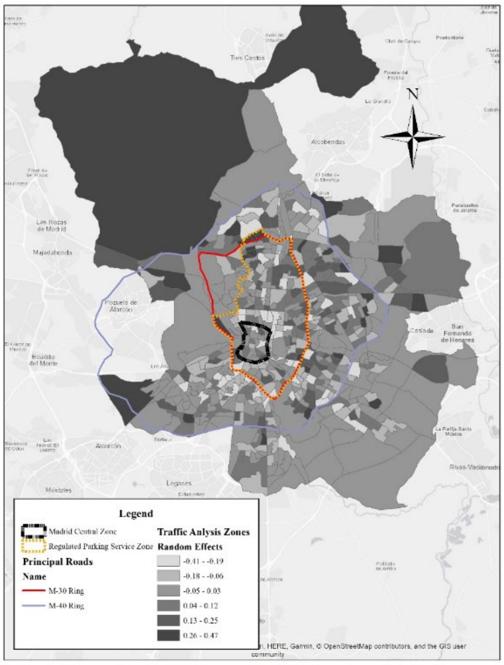
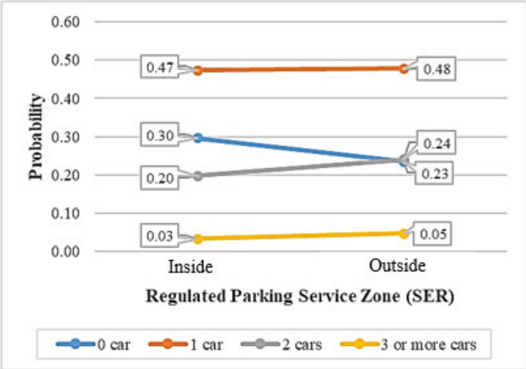


Figura 2 Efectos aleatorios

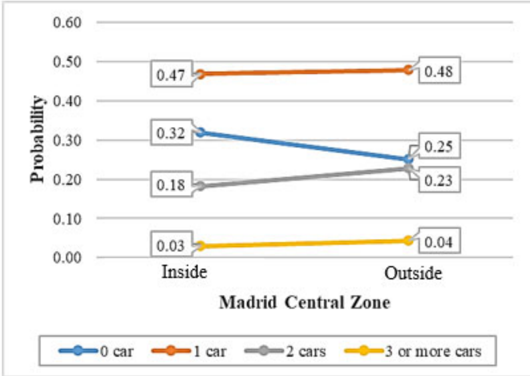
Hemos estimado los efectos marginales del modelo y hemos incluido estos valores en la Figura 3. Todos los efectos marginales resultaron estadísticamente significativos. La mayor diferencia se identifica en las probabilidades de tener las opciones "Sin coche" y "2 coches". Como puede observarse en la Figura 3a, tanto para las políticas SER como para las de "Madrid Central", la probabilidad de tener "Ningún coche" es en cierto modo mayor si el hogar está situado dentro de las zonas donde se aplican estas políticas. Esto parece razonable porque el control de la oferta de aparcamientos o las restricciones a la circulación de vehículos hacen menos atractivo el uso del coche privado, lo que repercute negativamente en la decisión de los residentes de comprar o poseer un coche (véase la Figura 3a y la Figura 3b).

Además, exploramos con más detalle la relación entre las políticas de transporte y el nivel de ingresos. Por ejemplo, en lo que respecta a la política del Servicio de Estacionamiento Regulado (SER), los mayores ingresos de los hogares reducen la probabilidad de no poseer ningún coche, mientras que aumenta la probabilidad de poseer uno o varios coches", en particular de poseer 2 coches. Un análisis comparativo muestra tendencias similares para las zonas TAZ situadas dentro y fuera de la zona SER. No obstante, las tasas de cambio son mayores para aquellos hogares situados en barrios en los que no se aplica la política cuando no está disponible (ver Figura 3c y Figura 3d). Los resultados son bastante similares para la política "Madrid Central LEZ"; sin embargo, la probabilidad de conseguir un coche dentro de esta zona es menor debido a sus fuertes restricciones (véase la Figura 3e y la Figura 3f).

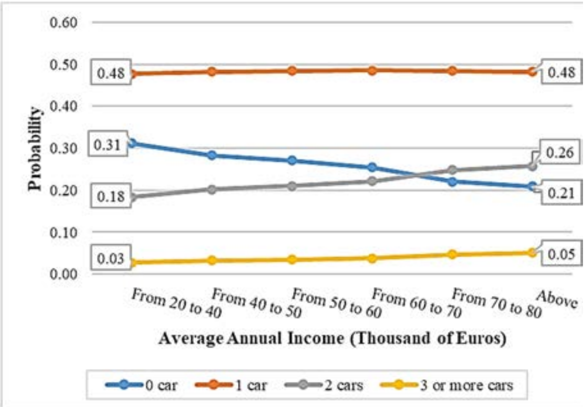
a. Servicio de Estacionamiento Regulado (SER)



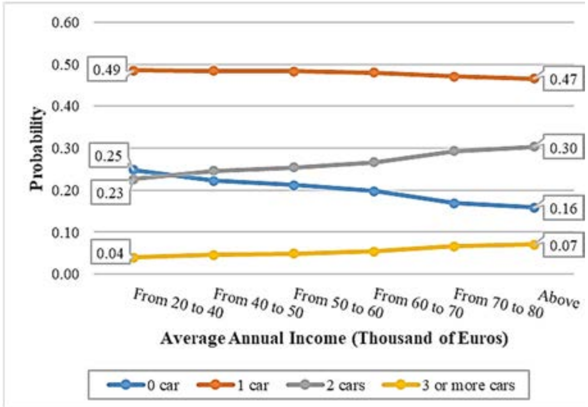
b. Madrid Central (MC)



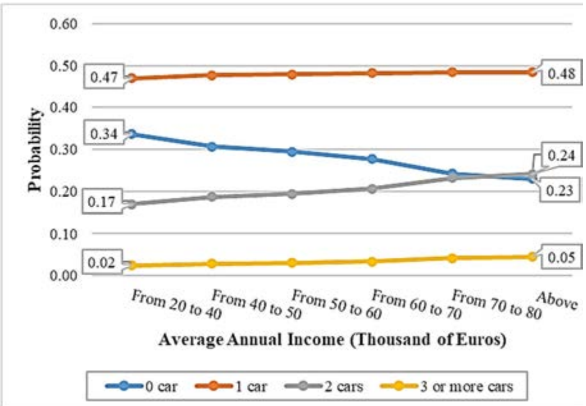
c. Comportamiento de los ingresos – En la Zona SER



d. Comportamiento de los ingresos – Fuera de la Zona SER



e. Comportamiento de los ingresos – En la MC



f. Comportamiento de los ingresos – Fuera de MC

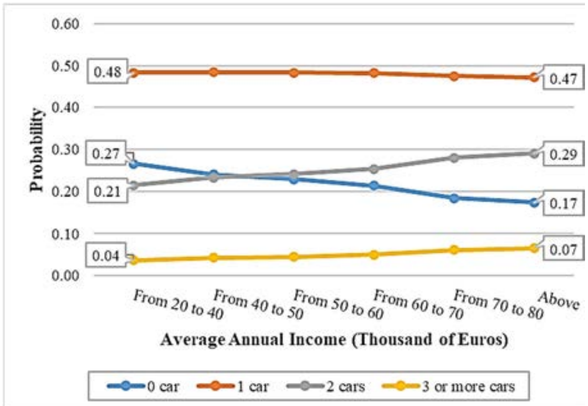


Figura 3 Análisis detallado de las políticas públicas en Madrid

6. CONCLUSIONES Y RECOMENDACIONES POLÍTICAS

Este estudio explora la propiedad de automóviles y cómo influye en ella la aplicación de políticas de transporte destinadas a mejorar la sostenibilidad urbana. Mediante la estimación de un Modelo Logit Ordenado Multinivel, se analizó el comportamiento del número de coches de los hogares, según las características sociodemográficas de los mismos, las variables del entorno construido de la ciudad, los atributos de la red de transporte y las variables relacionadas con las políticas.

La promoción de modos de transporte alternativos puede generar una reducción de la propiedad de automóviles. Esto es evidente en los resultados encontrados para variables como el número de abonos de transporte y las estaciones de metro. Para fomentar una ciudad sostenible, se han aplicado políticas que mejoran el transporte público y consiguen un modo de transporte alternativo para los ciudadanos con el fin de reducir la propiedad del coche. El uso de políticas de ordenación del territorio para reducir la propiedad de automóviles mediante la creación de ciudades compactas y la construcción de barrios de alta densidad puede desalentar la propiedad de automóviles y la dependencia del automóvil (Oakil, Manting y Nijland 2016). Los resultados demuestran que la alta densidad de población y la densidad residencial tienen un efecto positivo en la reducción de la propiedad de automóviles. Sin embargo, según Van Acker y Witlox (2010), las políticas de planificación urbana no deberían centrarse únicamente en medidas de aumento de la densidad y la diversidad, sino también en medidas indirectas a través de la propiedad del coche.

Nuestras conclusiones tienen varias implicaciones políticas. Las políticas actuales desarrolladas en Madrid han tenido un fuerte efecto en desalentar la propiedad del coche.

El cobro de las plazas de aparcamiento en la calle caracteriza al SER, y ha tenido un efecto positivo en la mitigación de las externalidades del transporte. La política se hizo a través de un marco regulatorio local en una cobertura específica. Como mejora, el SER puede ampliarse para aumentar los beneficios de la política. Además, la política puede explotar las oportunidades de aprovechar las tecnologías emergentes para mejorar la eficiencia. Las estrategias de MC pretenden reducir el acceso de vehículos en la zona mediante limitaciones de tráfico y aparcamiento. Estas estrategias han tenido un efecto positivo en la reducción del número de coches propios, por lo que puede considerarse un éxito.

Los resultados pueden utilizarse para fomentar algunas tendencias que son relevantes para la definición, mejora o aplicación de futuras políticas. La mejora de la sostenibilidad del transporte sigue siendo el objetivo de los responsables políticos, y hay que medir su impacto. Hay que seguir investigando para abordar algunas de las limitaciones de este documento. En primer lugar, las políticas de transporte no sólo tienen un impacto en la propiedad del coche, sino que también debe hacerse un análisis conjunto con otras opciones como el reparto modal, el horario de viaje y la ubicación residencial. En segundo lugar, las políticas evaluadas en el presente estudio se aplicaron durante un corto periodo de tiempo, por lo que el análisis de la propiedad de automóviles podría realizarse en el futuro con una perspectiva a largo plazo. Por último, en todo el mundo se han aplicado políticas de transporte más maduras, por lo que debe estudiarse su influencia.

AGRADECIMIENTOS

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SYSTEMATIC DESIGN OF WIRELESS CHARGING TRANSPORTATION NETWORK

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ABSTRACT

Many cities around the world encourage the transition to battery-powered vehicles to minimize the emissions of greenhouse gases. The standard plug-in electric vehicles have a limited amount of power stored in the battery resulting in frequent stops to refill the power. Wireless charging is an innovation of transmitting power through electromagnetic induction to portable electrical devices for energy renewal.

Online Electric Vehicle (OLEV) is a new technology that allows the vehicle to be charged while it is in motion, thus removing the need to stop at a charging station. Developed by the Korea Advanced Institute of Science and Technology (KAIST), OLEV picks up electricity from power transmitters buried underground.

This paper investigating bus routes to determine the optimum study area for planning out the costs of deploying a pilot service network by comparing the cost of initial investment for the three types of wireless charging: Stationary Wireless Charging (SWC), Quasi-Dynamic Wireless Charging (QWC), and Dynamic Wireless Charging (DWC), using OLEV technology for a bus service transit in the borough of Manhattan (MN) in New York City (NYC).

1. INTRODUCTION

In recent years, an expanding need to develop alternative solutions to traditional energy sources from fossil fuels becomes an imperative needed for sustainable cities. Thus, electric buses reduce fossil fuels uses and, therefore, provide a better living environment. Since transit is significant fuel consumption, the development of electric vehicles (EVs), especially electrical buses provided by effective wireless charging technologies, has become even a priority. Studies have shown the benefits and advantages of pure electric vehicles (EVs) compared to internal combustion (IC)-based cars or hybrid EVs in terms of their environmental effects (Jang et al., 2016). Nevertheless, these benefits may be offset by the limited amounts of energy stored in their batteries.

To make EVs even worse, charging with the fastest charger requires at least 30 minutes (Ulrich, 2012). To fill this gap, the use of Remote Charging Technology, also known as wireless charging (Costanzo et al., 2014), (Garnica et al., 2013), has been testing and implemented. Wireless charging is an innovation of transmitting power through electromagnetic induction to portable electrical devices to ensure optimized energy renewal.

In public transportation systems operation, exist three different types of wireless charging systems, to be specific, (a) Stationary Wireless Charging (SWC), the charging only happens when the vehicle is parked or idle, (b) Quasi-Dynamic Wireless Charging (QWC), when a vehicle is moving slowly or in stop-and-go mode the power is transferred, and (c) Dynamic Wireless Charging (DWC), the charging can be provided even when the vehicle is moving (Ulrich, 2012).

This paper compares the cost of initial investment for the three types of wireless charging (SWC, QWC, and DWC) using OLEV technology for a bus service transit in the borough of Manhattan (MN) (Figure 4), in New York City (NYC), the most populous city in the United States (U.S. Census Bureau 2010).

2. LITERATURE REVIEW

The public bus system helps to reduce traffic congestion and exhaust emissions (Song, 2013). Due to vehicle technology limitations, diesel-powered buses still dominate today's bus fleet. Various regulations related to the problem of battery size, cost, and life and onboard batteries have restricted the popularity of electric buses (Liu and Song, 2017).
Wireless charging technology is changing the form of energy transfer and utilization. Since its initial concept suggested by (Bolger et al., 1978), significant technological achievements have been made in developing wireless charging.

The development of wireless charging technology is surveyed (Esser, 1995; Wang et al., 2005; and Covic et al., 2007). To eliminate cables and dangerous sparking, wireless charging has been actively investigated in transit applications, such as charging for electric vehicles (Jang et al., 2016). Other focuses the charging strategy interacting with the power grid (Paul and Yamada, 2014), on e-buses were based on charging infrastructure comparison (Chen et al., 2018; Bi et al., 2015), and the Battery Management Systems (Ding et al., 2015; Hu et al., 2013; Liu and Song, 2017). (Ke et al., 2016) proposed a model for simulating the operation and battery charging schedule of plug-in e-buses and determined the minimum construction cost of an all plug-in electric bus transportation system.

The OLEV system is the first successfully commercialized EV wireless charging system (Jang et al., 2015; Lee et al., 2010; Shin et al., 2013).

Developed by the Korea Advanced Institute of Science and Technology (KAIST), OLEV picks up electricity from power transmitters buried underground. OLEV technology (KAIST, 2009) has its sights set on economizing and sustaining industrial and commercial electric vehicles' performance, with its current focus being bus transits. This is achieved by reducing the number of batteries required to operate the bus service, reducing the vehicle's cost and weight while always staying in service with its efficient, wireless charging technology.

The OLEV consists of shuttles (similar to conventional EVs) and a charging infrastructure containing a set of energy transmitters that can charge the bus's battery remotely utilizing an ingenious non-contact charging component while the buses are moving over the charging infrastructure.

3. MATERIALS AND METHODS

3.1 Characteristics of EV Types

The OLEV technology currently operates in several bus transits worldwide, including Seoul Grand Park and Gumi City transit lines in South Korea. There are three different categories of wireless charging systems (Figure 1) that OLEV can be used:

a) Stationary wireless charging (SWC),
b) Quasi-dynamic charging (QWC), and
c) Dynamic wireless charging (DWC).

SWC is only parked or idle charging, QWC is when a vehicle moving slowly or in stop-and-go mode, and DWC is supplied even when the vehicle is in motion. Each system's cost and benefit depend on various factors such as route and fleet size, service range, battery prices, and installation cost (Jang et al., 2016; Garnica et al., 2013).

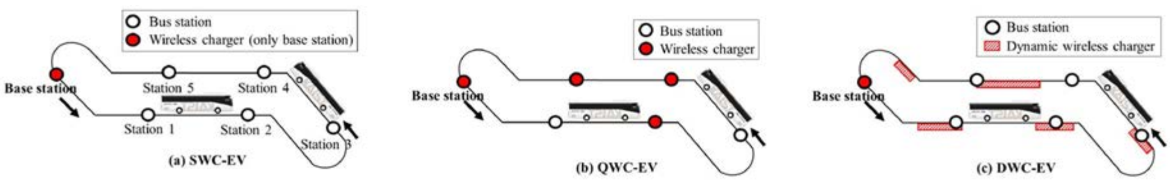


Figure 1. Charging allocation properties for each type of EV (Jang et al., 2016).

Figure 2. shows the OLEV serving as a campus shuttle on the KAIST campus, and the power track installed under the road.

(a) (b)

Figure 2. KAIST OLEV: one of the dynamic wireless charging EVs (DWC-EVs) (Jang et al., 2016). (a) under construction; (b) in operation.

3.2. Dataset Description

Two different datasets were used for the analysis. The first one is the drive-type network data taken from the Open Street Map (OSM) using the OSMnx (Boeing, 2017). The second one consists of General Transit Feed Specification (GTFS), which defines a standard format for public transportation schedules and associated geographic information from the Metropolitan Transportation Authority (MTA, 2020, March 18).

3.3. GTFS Data

The information was collected from the MTA data feeds for the NYC Manhattan Transit Bus transportation services. The downloaded data package contains eight text files: trips, stops, stop_times, shapes, routes, calendar_dates, calendar, and agency.

Open-source Python 2.7.13, an interpreted object-oriented, high-level programming language, was used to visualize GTFS data focusing on MN bus transit into Static Data Feeds (GTFS Schedule Data). Please refer to Correa et al. (2017) for more details on GTFS transit data. Additionally, Matlab programming is used to simulate a battery's state of charge (SoC) throughout a route to determine how well the allocation of charging units fits the model. Figure 3 shows the number of buses from bus lines M1, M2, M3, M4, and M72 arriving at bus stop # 400124 5 AV/E 72 ST, by each hour.

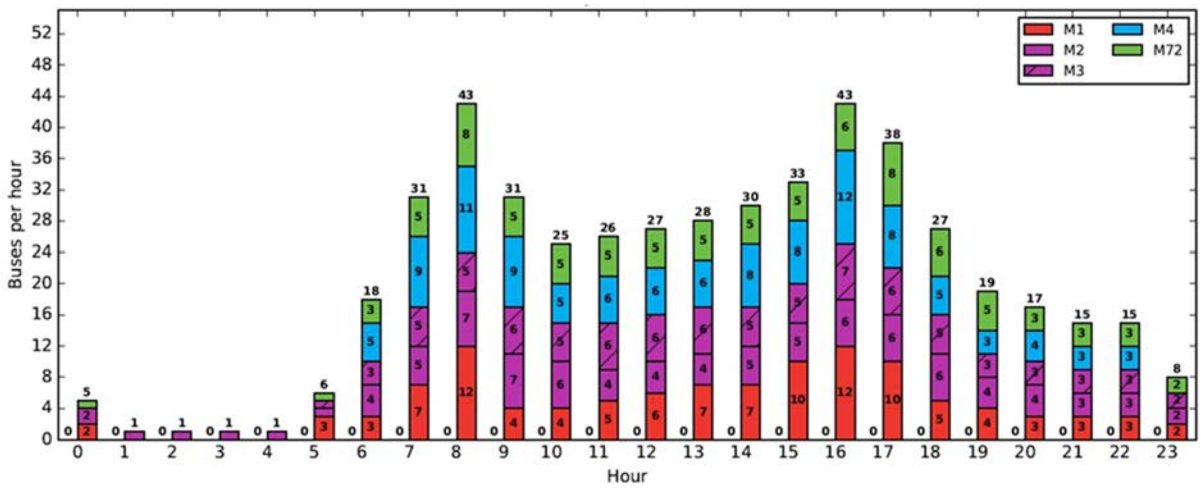


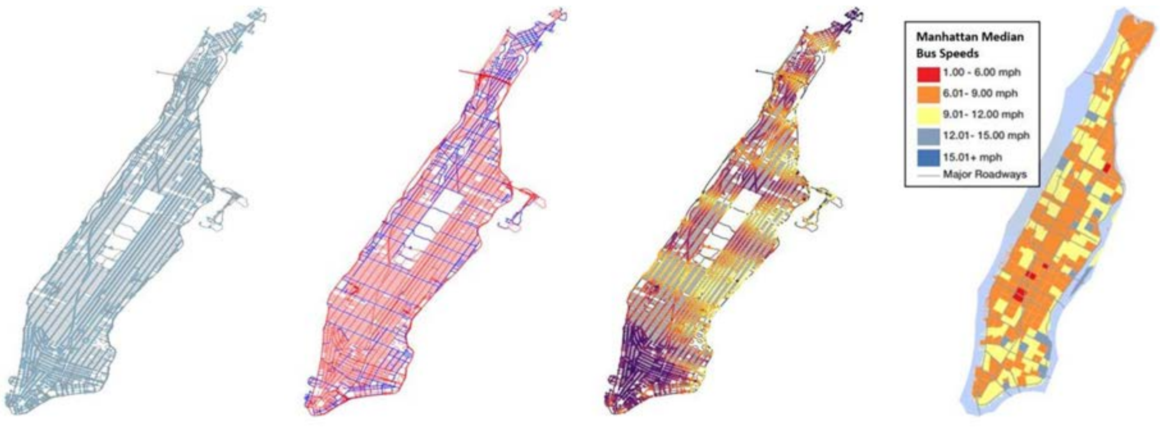
Figure 3. Visualization of GTFZ (Number of arriving buses to bus stop # 400124 at 5 AV/E 72 ST)

3.4 Network Data

Drive-type network data from MN was taken from OSM using the OSMnx (Boeing, 2017) to extract and clear the network. The network contains nodes for road intersections and joints, as shown in Figure 4. OSMnx downloads street network data that performs topological correction and simplification automatically to calculate accurate edges and nodes. The selected network types are "drive" to get drivable public streets and excluding service roads. (Figure 4a).

OSMnx analyzes networks and calculates network statistics, including spatial metrics based on geographic area or weighted by distance.

OSMnx allows classifying one-way and bidirectional streets (Figure 4b). For oneway streets, directed edges are added from the origin node to the destination node. For two-way streets, reciprocal directed edges are counted in both directions between nodes. This ensures that intersections are not considered dead ends. OSMnx also allows identifying the busiest nodes through the network, as is shown in Figure 4c.



(a) (b) (c) (d)

Figure 4. Study area: Manhattan Borough in New York City. Network Data

Visualization, (a) Network contains nodes for road intersections and joints.; (b) Network provides the single way in red and double way in blue; ((c) M22 bus) Network busiest nodes visualized from low (dark-violet) to high (light yellow); (d) Median bus Speeds of Manhattan.

4. DATA ANALYTICS: TOOLS AND METHODS

The quantity of charging on each power track required for a DWC system is a function of vehicle speed and the elapsed time spent on that power track. In the conventional station allocation problem, the vehicle speed is not related to the allocation.

Therefore, for optimum results, the system implementation should be in places where bus speeds are very low (bus stops, streets historically known for slow traffic). The median speed data shown in Figure 4d is established on GPS bus data time, which indicates the location of individual buses over time on their routes. Data was collected between 4 p.m. and 6 p.m. every typical weekday in 2017 (NYCDOT, 2018).

Based on the network and median bus speed information, we select three MN bus routes located within the low busiest node's area in MN in Figure 4c (dark-violet colored) as the best option for actual potential implementation because it will produce less disruption in the city than the other zones such as midtown.

In this project, information was collected from the Metropolitan Transportation Authority (MTA) data feeds for the NYC Manhattan Transit Bus transportation services. Initially, only three Manhattan bus routes: M8, M9, M22 (colored in green), were examined as the first analysis in the energy logistics (battery and charging infrastructure) cost for each system Figure 5).

(a) (b) (c)

Figure 5. Selected Routes. (a) M8 bus; (b) M9 bus; (c) M22 bus

After data processing, we tested the accuracy of the data obtained from GTFZ feeds, comparing bus stops of each selected route to the real bus stops in the city, using google street view, as is shown in Figure 6. This method allows us to eliminate potential bias in the data collected.

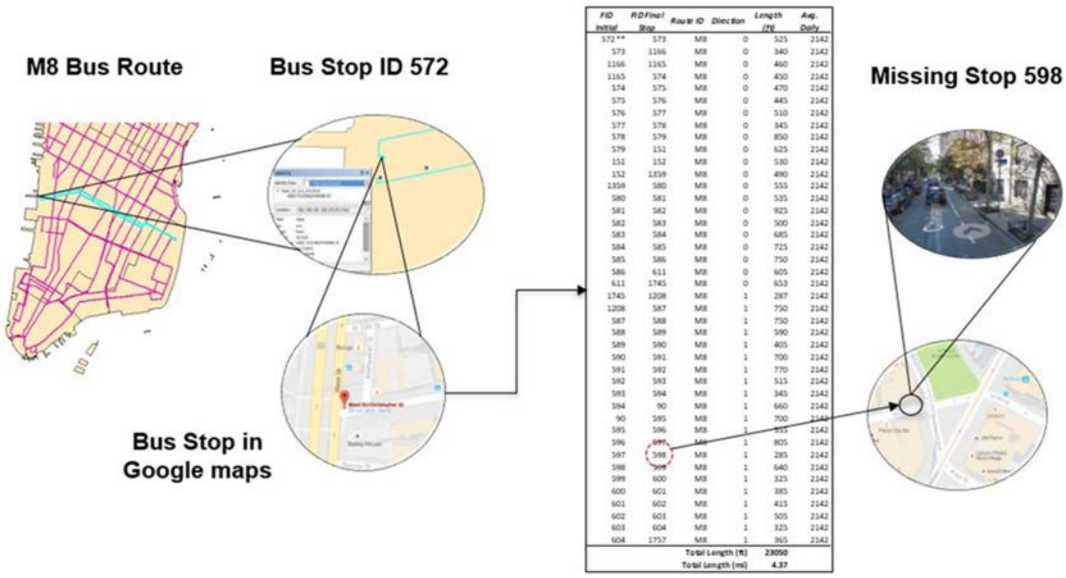


Figure 6. Comparison with real site data

5. COST ANALYSIS

For an EV-based transit system, the initial investment cost is fundamentally composed of two main components: the cost of the charging infrastructure and the cost of a fleet of vehicles.

The cost is divided into the batteries' costs, the vehicle units, and the other charging components. The energy logistics cost accounts for the majority of the total cost of an EV-based transit system.

Therefore, understanding the cost structure of energy logistics is critical for deciding on investments in EV-based transit systems.

In (Jang et al., 2016), there is a qualitative cost-benefit analysis for each wireless system, depending on the battery price and infrastructure cost, as seen in Figure 7. However, investment in the OLEV cannot only be made based on such analysis. Therefore, reports from current OLEV and EV bus transit operations, MTA data feeds, and tools from GIS software were utilized to develop a method for comparing the energy logistics costs for these different types of charging systems on a chosen Manhattan bus route.

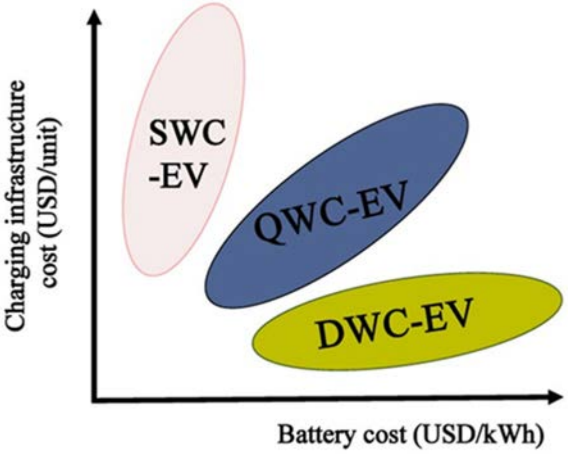


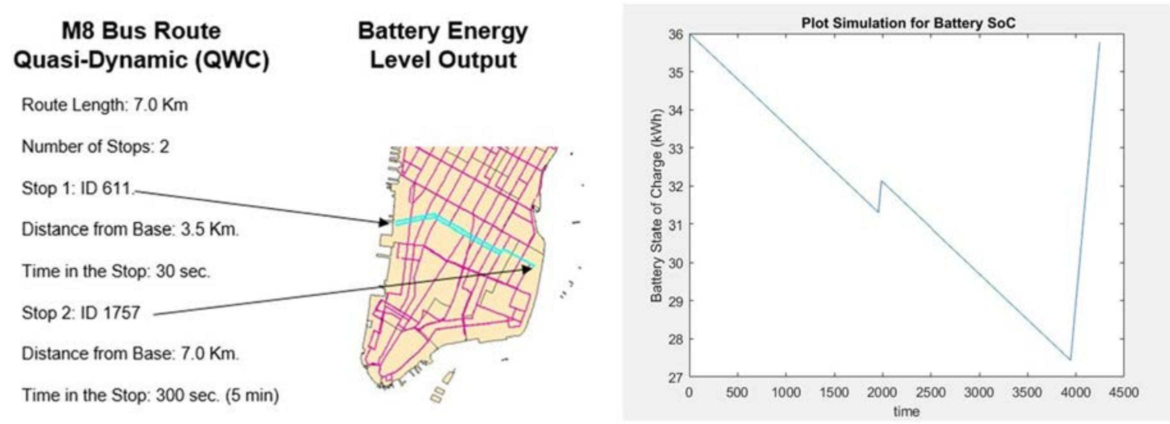
Figure 7. Qualitative analysis of the economic benefits of different EV charging systems (KAIST, 2009)

Allocation of chargers for each system is that SWC should be installed only at the station (base) where the vehicles rest between services; QWC - identify where to install the wireless chargers at minimum cost based on energy consumption and depletion between stops in a route; DWC - as the charging can be done while the vehicle is in motion, the vehicle speed should be considered determining the allocation of chargers along the route.

$$\text{SWC \& QWC: min } [(No.\ Buses) * (Cost\ of\ KWh) * (Service\ Batery\ Size)] + [(Cost\ of\ Charger) * (No.\ Chargers)] \quad (1)$$

$$\text{DWC: min } [(No.\ buses) * (Cost\ of\ KWh) * (Service\ Batery\ Size)] + [(Power\ track\ cost\ per\ meter) * (Power\ track\ lenght) + (Cost\ of\ Charger) * (No.\ Power\ track\ units)] \quad (2)$$

Once we determine the charging infrastructure's location and length, we can use equations (1) and (2) to optimize the minimum energy logistics cost for SWC, QWC, and DWC systems. The cost of battery per energy unit, charging unit, and power track per unit length can be found (KAIST, 2009).



(a) (b)

Figure 8. Simulation for Battery. (a) M8 bus details; (b) Battery energy level

Battery simulation for the M8 bus route Figure 8a is shown in Figure 8b. The energy level is within the upper and lower limits. We assume that the energy capacity of the battery is linearly proportional to the cost of the battery. This assumption is realistic, as an EV battery pack contains multiple battery cells, so the capacity is defined by the number of cells included in the battery pack. This method of linear cost calculation is also widely used in the industry.

6. RESULTS AND DISCUSSION

As shown in Table 1 and Figure 9, the data analysis conducted in this study evaluates the commercial fleet size with the cost structure for each system. Axis x and y represent the number of vehicles and the total investment cost, respectively, for the M8 bus route. The entire cost of the system is proportional to the battery's full size (cost of SWC increases linearly).

Beneath this assumption, the charger is installed only at the station base and is fixed just as if the number of Electric Vehicles grows. Thus, the energy logistics cost is linearly proportional to the fleet. In practice, more charging capacity would need to be added to the base station for the SWC system to avoid delays as busses wait to be charged, producing some non-linear discrepancies in the model.

For the DWC case, the increment rate of cost is less significant than that for the case of SWC. Therefore, if the smaller batteries are more economical, it produces a growing number of EVs that increase optimization.

Stationary (SWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	Base Station	Base Station	Base Station
E needed for service	140	140	140
Battery size (kWh)	233	233	233
No. of Evs	1.0	1.0	1.0
Battery cost per kWh	600	600	600
No. of chargers	1.0	1.0	1.0
Cost per charger	50,000	50,000	50,000
Length of Power Track			
No. of Power Tracks			
Power Track Cost (per m)			
	$ 190,000	**$ 190,000**	**$ 190,000**

Quasi-Dynamic (QWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	BS, 611, 1757	BS, 1720, 1769	BS, 1754, 1713
E needed for service	60	120	80
Battery size (kWh)	100	200	133
No. of Evs	1.0	1.0	1.0
Battery cost per kWh	600	600	600
No. of chargers	3.0	3.0	3.0
Cost per charger	50,000	50,000	50,000
Length of Power Track			
No. of Power Tracks			
Power Track Cost (per m)			
	$ 210,000	**$ 270,000**	**$ 230,000**

Dynamic (DWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	BS, 611, 1757	BS, 1720, 1769	BS, 1754, 1713
E needed for service (2/3 of bat. size)	24	80	54
Battery size (kWh)	40	133	90
No. of Evs	1.0	2.0	2.0
Battery cost per kWh	600	600	600
No. of chargers	5.0	3.0	3.0
Cost per charger	50,000	50,000	50,000
Length of Power Track	500		
No. of Power Tracks	*4		
Power Track Cost (per m)	600		
	$ 574,000	**$ 310,000**	**$ 258,000**

eff high 0.8 **eff low** 0.2

* x m at West/Christopher, y m at 9th/Broadway, z m at 8th/Mercer (4th charger @ Base Station).

Note: Prices and equations for logistics cost was taken from: (Jang et al., 2016)

Table 1. Cost Analysis of Wireless Network

The cost lines for SWC-QWC and QWC-DWC cross when the number of vehicles is three and seven, respectively, that means if less than three cars, SWC is the most economical; if the number of cars is between three and seven, QWC is competitive. If the number of vehicles is more significant than seven, DWC is the most efficient and economical. The lines with lower costs SWC for fleet <3, QWC for 3 < fleet < 7, and DWC for fleet > 7, regardless of the charging type, should be considered the lower bound for the wireless charging EV.

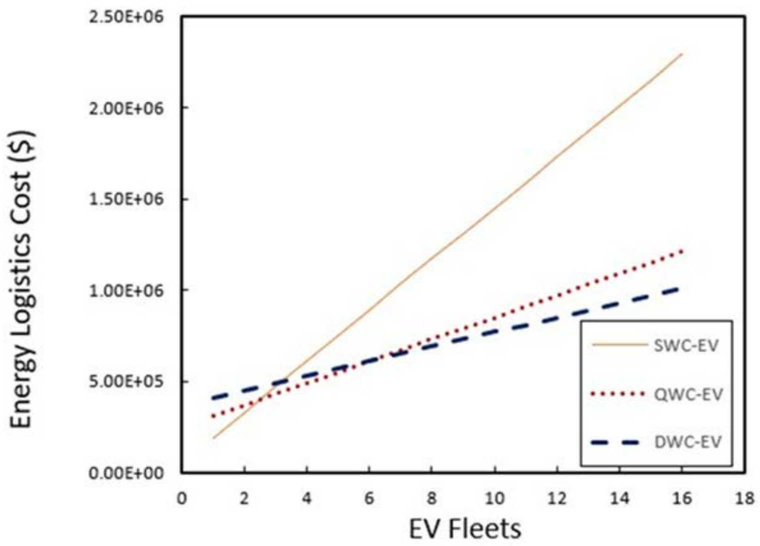


Figure 9. M8 Route Fleet-Scale Plot Analysis.

7. CONCLUSIONS AND FUTURE WORK

Wireless charging technology offers the possibility of eliminating the last remaining cord connections required to replace portable electronic devices. This technology has significantly improved during the past decades and leads to a vast number of applications.

In this article, we have investigated the implementation of wireless charging on bus routes and developed a cost analysis of initial investment for the three types of wireless charging: Stationary Wireless Charging (SWC), Quasi-Dynamic Wireless Charging (QWC), and Dynamic Wireless Charging (DWC), using OLEV technology. They are followed by a cost analysis of existing bus service transit, applying OLEV technology to deploying a pilot study in Manhattan, NYC.

The integration of wireless charging with existing transportation networks creates new opportunities as well as challenges for the development of sustainable cities. This study has shown the analysis of the potential implementation of wireless power charging to an actual bus route, reducing emissions, and improving traffic operations and planning.

This research would provide new possibilities of using OLEV technology, network, and bus route data to determine the optimum study area for planning out the costs of deploying a new electric bus service network. However, the implementation of power charging in networks is less explored and requires further investigation. Additionally, practical challenges in performing similar analyses of several NYC bus routes based on the route's EV history, ridership, and location can be considered the main directions for future research.

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NUEVAS FORMAS DE SEMAFORIZACIÓN EN LAS CIUDADES

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RESUMEN

Las ciudades aumentan, las formas de vida están cambiando y la población está en constante movimiento. Todo ello hace que para que una localidad desarrolle una mejora completa de su movilidad, se debe aplicar la Inter movilidad considerando todos los factores posibles como son las bicicletas, patinetes, car sharing, coches eléctricos, obras civiles, semáforos inteligentes, etc. que vayan a favorecer la movilidad en su conjunto.

Sin embargo, parece que, a día de hoy el cuello de botella parte del problema de los atascos que se producen en el centro de las grandes ciudades por los vehículos a motor, cuya cantidad diaria no sólo es difícil de disminuir, sino que sigue aumentando. Aun incluso cuando otros sistemas que se implanten logren reducir el número de vehículos en las calles de las ciudades, especialmente de las grandes, como por ejemplo la peatonalización o restricciones a los vehículos en las zonas más céntricas de las mismas, también seguirá siendo necesario minimizar los tiempos "improductivos" de los transportes que seguirán ocasionando acumulación no útil de los mismos en las calles.

Una forma de desbloqueo de los atascos, pasa por los sistemas de control de tráfico urbano (UTC) que permitirán el paso seguro y eficiente de los flujos de tráfico en intersecciones. Es decir, se trata de una comunicación en tiempo real entre el vehículo y la infraestructura bajo tres puntos de vigilancia: la densidad de tráfico, los espacios de aparcamientos y los llamados aparcamientos disuasorios, y el control de semáforos. Precisamente en este último punto, el control de semáforos, es en el que se pone el foco en esta ponencia. Se plantea y estudia en la misma un funcionamiento de semáforos, o bien sin semáforos físicos, o bien con semáforos inteligentes.

1. ANTECEDENTES Y DATOS ACTUALES DE LOS SEMÁFOROS

Se tienen los primeros registros del primer semáforo, el que fue instalado en la ciudad de Londres en 1868 utilizando un sistema de ruidos-alarma, parecido a lo que hoy en día serían los sistemas de comunicación de los barcos. Sin embargo, fue hacia 1920 cuando se instalaron en EEUU los primeros semáforos parecidos a los que hoy tenemos en las ciudades, utilizando el método de los tres colores (verdes, rojo y ámbar). Éstos aparecieron con la llegada de los vehículos motorizados pues hasta entonces ni las bicicletas, ni los carros tirados por caballos, ni los peatones necesitaban la señalización con semáforos para regular su paso en los cruces (SICE, 2019).

Por tanto, en la mayoría de los países desarrollados, la instalación del primer semáforo o ya ha cumplido o está a punto de cumplir el primer siglo de vida, y llevamos por tanto alrededor de cien años incrementando el número de semáforos en las ciudades proporcionalmente al mayor número de vehículos que hay cada día ocupando las calles.

Es el momento de empezar a disminuir su número hasta su desaparición y dejar sólo su imagen residual y simbólica, con la vista puesta en volver a disfrutar de ciudades del siglo XXI, pero sin semáforos.

Como ejemplos, se puede citar:

1. En la ciudad de Madrid, existen actualmente unas 130.000 Uds. de semáforos que regulan unas 2.200 intersecciones (Velloso, 2016).
2. Valencia es la ciudad de Europa con más semáforos por unidad de habitantes, con 1 Ud. por cada 750 ciudadanos (Landete, 2016).

2. CARACTERÍSTICAS ESTRUCTURALES DE LOS SEMÁFOROS

La instalación de semáforos supone una serie de características estructurales a tener en cuenta. En las ciudades, hoy en día no sobra precisamente espacio libre en las aceras y la visualización para los conductores resulta en muchas ocasiones demasiado densa. Mirando hacia el horizonte de muchas calles alargadas de las grandes ciudades, la vista alcanza en demasiadas ocasiones a una hilera continuada de semáforos.

La estructura de los semáforos debe cumplir la normativa vigente que exige una armadura para las partes luminosas y un soporte de tipo columna o forma de báculo. En general, hay que tener en cuenta que la distancia entre el suelo y la cabeza del semáforo suele ser de 450 cm, mientras que el brazo saliente sobre la vertical puede medir desde 350 a 550 cm dependiendo de la ubicación y del tipo de información que transmita. (software SABRE [Best Center, 2012]. En el Reporte NCHRP 796 (TRB, 2014), pág. 29 del documento)

Es decir, que cada semáforo ocupa un área visual aproximada de unos 16 m². Por tanto, si nos fijamos en una ciudad como Madrid, con más de 2.200 intersecciones reguladas por unos 130.000 semáforos, estaremos ocupando un área visual de 2.080.000 m² = 2 km².

Sin la presencia de semáforos, las ciudades quedarían más despejadas, con más espacios libres para peatones y también con una mayor visibilidad para los transportes. Además del ahorro que supondría su fabricación, mantenimiento y sustitución.

3. PROPUESTAS DE SUSTITUCIÓN DE LOS SEMÁFOROS

Dispuestos a eliminar los semáforos de las ciudades, ¿cómo los sustituimos? Aquí entrarían en juego los Sistemas de Control de tránsito Urbano que en cualquier caso deberán asegurar su funcionamiento ante fallos de la red eléctrica, cámaras, detectores-sensores, contadores, sistemas de bluetooth que conecten las vías con los propios vehículos en tiempo real, priorización de los transportes públicos de gran capacidad, y la implantación de leds sobre el asfalto, despejando así las infraestructuras.

El objetivo de las medidas a adoptar deberá consistir en sustituir el funcionamiento de los semáforos actuales consiguiendo los mismos objetivos funcionales de éstos, pero teniendo como finalidad que los flujos de tránsito sean más productivos y favorables.

La parada de los vehículos en las intersecciones incrementa además el gasto de combustible de los mismos al tener que arrancarlo desde parado, y esto produce una contaminación del lugar donde se encuentra, y además puede producir en algunos casos molestia a los vecinos con los ruidos ocasionados por los continuos movimientos de parada y arranque.

En el control de las señales de tránsito en las zonas urbanas, especialmente en las de mayor densidad de población, se debe tener en cuenta a todos los usuarios de la red, incluidos los peatones, los vehículos de motor de dos ruedas, el transporte público, los vehículos privados, bicis, patinetes, etc. Hoy día es cada vez mayor el número de dispositivos de movilidad que forman parte de la red viaria y que son por tanto susceptibles de coincidir en las distintas intersecciones. Es por ello que no sólo se puede configurar el sistema de circulación y de sustitución de los semáforos pensando en los vehículos de motor, sino que es absolutamente necesario contar con todos y cada uno de los usuarios, ya sean peatones o medios de transporte.

3.1 Procedimiento de sustitución

El procedimiento consiste en:

1. Se recogen los datos de flujos de tránsito en las intersecciones que estén interrelacionadas entre sí y que se quieran direccionar.
2. Se analizan los datos de estos flujos de tránsito por franjas horarias y días de la semana y del año. De modo que se pueda proceder a extrapolar sus datos.

3. Se recopilan los datos direccionales en las intersecciones, es decir, hacia dónde se producen en mayor y menor medida los movimientos de giro, cambios de dirección, etc.
4. Teniendo en cuenta los datos recopilados y analizados, se elaboran los planes de sustitución de semáforos mediante las propuestas que se indican en este documento más adelante.
5. Se elabora un plan de viabilidad medioambiental y también de viabilidad económica.
6. Se elabora también un plan de sensibilización con las propuestas tanto de los conductores como de los peatones, es decir, el grado de necesidad y satisfacción que puede proporcionar a los usuarios de la vía, sea cual sea su condición, en el caso de implantar estos nuevos métodos de gestión de la movilidad urbana.
7. Si los planes anteriormente citados, tanto los medioambientales, como los económicos y de satisfacción de los usuarios, son positivos, se hace uso de los modelos de simulación de los planes de sustitución de semáforos en programas informáticos y en vehículos modelo en tiempo real.
8. Se visualizan y se estudian los impactos y estrategias que hayan surgido de las simulaciones efectuadas.
9. Se corrigen los errores que hayan dado lugar y se vuelve a simular una vez corregidos.
10. Se implementan en la vía algunos de los sistemas propuestos de sustitución de los semáforos.
11. Pasado un tiempo de su instalación, se evalúa de nuevo su efectividad, el grado de satisfacción de los usuarios, y la forma en la que se han adaptado los usuarios al nuevo sistema implantado.

3.2 Instalación de semáforos en los vehículos.

En cuanto a los sistemas de sustitución de semáforos, por un lado, se propone que los vehículos lleven incorporados en sus sistemas de control de velocidad o también llamados velocímetros, un propio semáforo en sí, el cual, indique al conductor, que, en función de la dirección que lleven o hacia la que se vayan a dirigir, controlada por sistemas de GPS que ya se utilizan en la actualidad, les vaya informando previamente si su velocidad es la adecuada para que cuando lleguen al cruce en cuestión, éste lo puedan pasar en verde o por el contrario, que su velocímetro marque un color rojo si la velocidad que llevan no es la adecuada para llegar a la intersección con posibilidad de paso en verde.

De este modo se evita que los vehículos tengan que quedarse parados en una intersección, y, por el contrario, se proporciona la regularización de la velocidad en los metros previos a alcanzar dicho semáforo. Así, existirá una circulación en movimiento continuo sin paradas de vehículos proporcionando una mayor inter movilidad y flujo de tráfico.

Aquí hay que tener claro que, en la mayoría de los casos, el tiempo que los automóviles ganan circulando a alta velocidad, lo pierden cuando se detienen en los semáforos. Llegarían por tanto antes a su destino circulando de forma continua a una menor velocidad, no necesariamente siempre baja, sino la adecuada, y utilizando la comunicación que les transmitan los sistemas incorporados en su vehículo y en la red de calles y carreteras.

¿Cuántas veces se ve un semáforo verde y/o amarillo a lo lejos y se pisa el acelerador para evitar llegar a la altura del semáforo en rojo y de esta forma se pone en peligro la seguridad del propio conductor y del resto de usuarios? Con este sistema se evitaría precisamente que los vehículos acelerasen en los metros previos al paso por el semáforo y regulasen su velocidad durante todo su trayecto. Si se diera el caso de que no existe la posibilidad de llegar a la intersección con paso en verde, se podría mostrar una cuenta atrás de los segundos restantes para la siguiente fase en verde, de tal modo, que el conductor pueda regular el ritmo de circulación y evitar igualmente tener que detenerse antes del semáforo.

Para ello, es necesario, no solo que todos los vehículos, cualquiera que sea su formato y sus características, incorporen un pack de GPS + cámara de reconocimiento de señales de tráfico, sino que también, todos los semáforos estén conectados y que dispongan cada uno de ellos de un dispositivo sensor que reaccione en función del tráfico real en cada momento. De este modo, la comunicación de los vehículos con los semáforos y viceversa, facilitará el flujo de la movilidad urbana. Que los semáforos de una ciudad dispongan de dichos sensores, podría decirse que es decisión de un solo organismo. Sin embargo, esta propuesta no funcionará si no incorporan el pack todos los vehículos sin excepción y ello requiere de un compromiso y acuerdo de más partes y por tanto más tedioso.

Recordemos, además, que en la mejora de la movilidad y en todos los sistemas que se quieran implantar, no sólo tenemos que tener en cuenta a los automóviles, sino que también hay que contar con el resto de vehículos. ¿Cómo incorporamos este sistema a las bicis, patinetes, etc. que también forman parte de la movilidad urbana y cada vez con mayor intensidad? Este mismo pack de GPS + cámara deberá también ser incorporado a estos otros medios de transporte.

En este aspecto hay que apuntar que dos marcas tan destacadas del automóvil como Audi y Ford ya trabajan en proyectos que eliminarían de las ciudades los semáforos. Audi prueba en la ciudad alemana de Ingolstadt donde tiene su sede, un servicio de información de semáforos con tecnología V2I (vehículo a infraestructura). Los coches que formen parte del ensayo verán en la instrumentación la velocidad a la que deberían circular para llegar al siguiente semáforo estando abierto, lo que favorecerá incorporarse a lo que han llamado ola verde de la ciudad o Time To Green. Por su lado, Ford trabaja en su proyecto llamado Intersection Priority Management (IPM), se ha probado hace unos meses en las calles de Milton Keynes, en Reino Unido. Funciona básicamente así: conociendo la ubicación, dirección de viaje y velocidad de los coches, cada IPM de a bordo identifica un cruce próximo y la trayectoria de cada vehículo que se acerca a él; a continuación, sugiere la velocidad óptima para cada uno de modo que todos puedan atravesarlo con seguridad (Pedro Urteaga, 2019).

3.3 Semáforos sobre el asfalto

Si una de las propuestas de esta ponencia es precisamente eliminar los semáforos físicos de las vías, es decir, quitar sus estructuras metálicas en favor del espacio y la mayor visibilidad despejada en las ciudades, el sistema propuesto en el punto anterior, el 3.2., quedaría incompleto. Por eso es necesario ampliarlo con la siguiente propuesta.

Ésta consiste en trasladar la estructura del semáforo al asfalto. Se propone que la misma área de visibilidad del alcance de un semáforo actual, se traslade al suelo. De este modo, será el propio asfalto el que se ilumine en los colores que corresponda de verde, rojo y ámbar. El mismo sistema de control de semáforos se lleva al asfalto y se instalan tiras de luminarias led que estén permanentemente encendidas en cada uno de los tres colores con la misma base de funcionamiento actual. El conductor de cualquiera de los medios de transporte, divisará desde bastantes metros de antelación a su intersección, el color en el que está iluminada la vía por la que esté circulando. Por su parte, los peatones, identificarán directamente el color rojo de la vía, como el de permiso de paso para ellos. La alimentación de estas tiras led puede seguir siendo gestionada por las mismas tomas que ya alimentan a los semáforos actuales.

Esta propuesta del punto 3.3. es perfectamente compatible con la propuesta explicada en el punto 3.2. de modo que, con este nuevo formato de semáforos igualmente éstos estén conectados y dispongan cada uno de ellos también de un dispositivo sensor en combinación con los leds, que reaccione en función del tráfico real en cada momento.

4. VENTAJAS Y BENEFICIOS DE LOS NUEVOS FORMATOS DE SEMÁFOROS

Como se ha venido indicando en los puntos anteriores, la eliminación de los semáforos convencionales actuales y su sustitución por otros formatos, recoge una serie de beneficios que favorecen al conjunto de la movilidad urbana, y por tanto suponen una ventaja para todos los usuarios de las vías.

Se enumeran a continuación las ventajas identificadas:

1. Visibilidad más despejada para conductores y viandantes.
2. Más espacio físico libre en calles y aceras.
3. Ahorro de fabricación de estructura metálicas.
4. Reducción de los tiempos de trayectos.
5. Reducción y/o eliminación de tiempos de espera es las intersecciones.
6. Reducción del número de accidentes en cruces.

7. Mayor dinamismo del flujo de la movilidad.
8. Mayor información sobre velocidad, tiempos, y en definitiva conducción para los usuarios.
9. GPS mapeado para reducir las pérdidas en los trayectos desconocidos.

5. GRADO DE ACOGIDA DE ESTAS PROPUESTAS POR PARTE DE LOS USUARIOS

Se ha llevado a cabo una encuesta a usuarios de la vía, de cara a proporcionar y estudiar el grado de acogida de estas propuestas por parte de los mismos. La encuesta se ha realizado durante los meses de noviembre y diciembre de 2020, vía online, a través del portal de encuestas https://www.onlineencuesta.com, con el enlace https://www.onlineencuesta.com/s/65bac8c, el cuál ha sido distribuido a su vez por grupos de difusión y redes sociales de alcance variado con rango de visibilidad y acceso a la misma, no sólo en España sino también en varios puntos de Europa, como Alemania, países Balcánicos, Reino Unido y Sudamérica. El rango de alcance de esta encuesta encuadra diferentes franjas de edad, y, aunque no se puede determinar con claridad el perfil del encuestado, dada su distribución online y por lo tanto de alcance final desconocido, se trataría de personas de al menos clase social media con acceso a internet y sistemas informáticos.

1. ¿cuánta cantidad adicional estarías dispuesto a pagar por que tu vehículo incorporase estos sistemas de control?

		cantidad dispuesto a pagar			
nº de encuestados	franja edad	nada	50 € - 150 €	150 € - 350 €	> 350 €
10 personas	< 18	8	2	0	0
20 personas	18-30	6	13	1	0
25 personas	30-45	5	15	4	1
35 personas	45-65	12	16	5	2
20 personas	> 65	10	7	3	0

Tabla 1. Rango de edad encuestados y cantidad adicional dispuesto a pagar

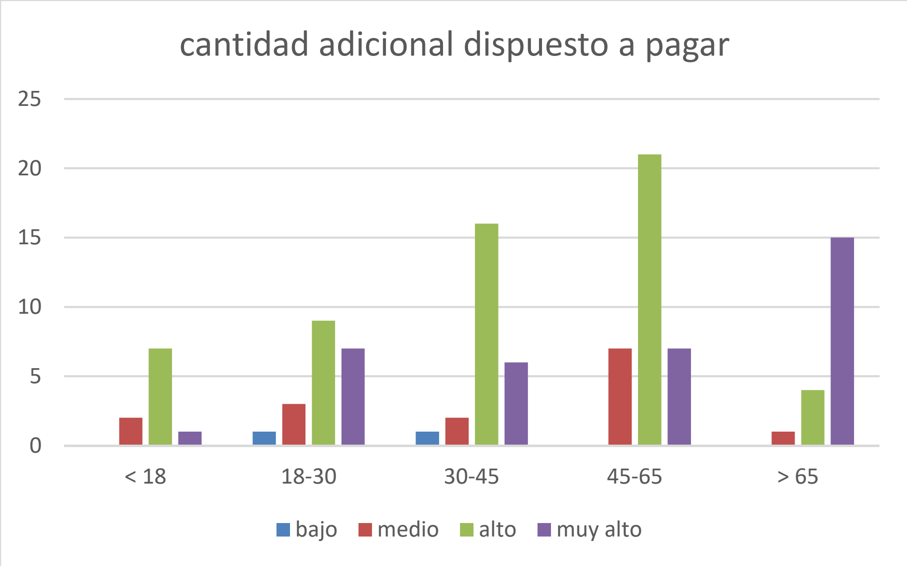

Figura 1. Cantidad adicional dispuesto a pagar porque su vehículo incluya los sistemas de control propuestos

La encuesta y/o gráfica refleja que hay un alto porcentaje de usuarios que no estaría dispuesto a pagar ninguna cantidad adicional al valor del vehículo por el hecho de que éste incorporase sistema de semaforización y sistemas de control de tráfico. Aun así, el porcentaje de los que sí estarían dispuestos a pagar hasta una cantidad máxima de 150 € adicionales es el más representativo.

2. ¿qué grado de dificultad consideras que tiene implantar estas propuestas a medio plazo?

		grado dificultad implantación			
nº de encuestados	franja edad	bajo	medio	alto	muy alto
10 personas	< 18	0	2	7	1
20 personas	18-30	1	3	9	7
25 personas	30-45	1	2	16	6
35 personas	45-65	0	7	21	7
20 personas	> 65	0	1	4	15

Tabla 2. Grado de dificultad que se considera para la implantación de las propuestas

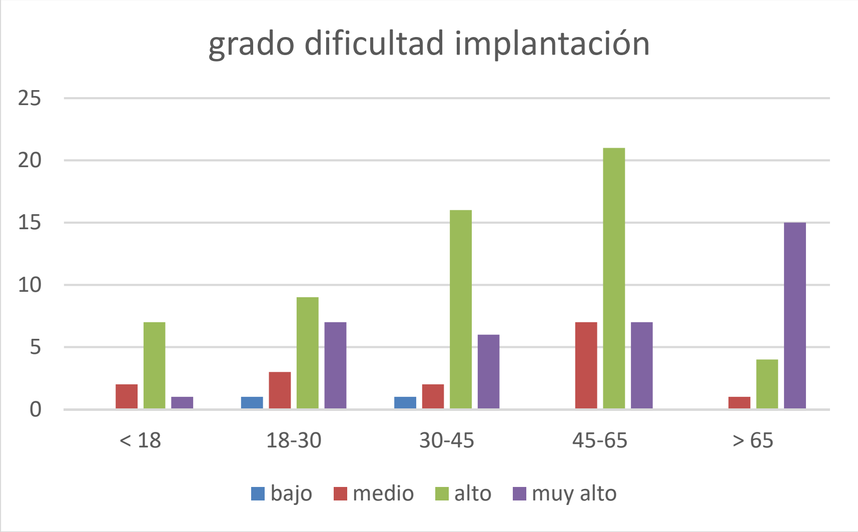

Figura 2. Grado de dificultad que se considera para la implantación de las propuestas

Los resultados de la encuesta reflejan que son los grupos de mayor rango de edad los que encuentran mayores dificultades a la hora de implantar estas nuevas propuestas en los vehículos. Siendo los jóvenes los más favorables a visualizar menos problemas en su puesta en marcha. Aun así, el grado de dificultad alto, es el más representativo en general.

6. CONCLUSIONES

Si la sociedad, en su globalidad, lleva alrededor de cien años incrementando el número de semáforos en las ciudades, resulta fácil entender que un cambio como el propuesto en esta ponencia, es una tarea tediosa. El grado de aceptación de la sociedad a un cambio, y más de este calibre, no suele ser ni fácil ni cómodo. En cualquier caso, la implantación de estos nuevos sistemas de control de tráfico requerirá de largos periodos de tiempo y tendrán que pasar años hasta que, no sólo se vayan implantando algunos de estos métodos en determinadas ciudades puntuales, sino que también los usuarios de la vía se familiaricen por completo con ello.

Como se ha dicho en un punto anterior de la ponencia, la implantación de estas propuestas, requiere de la implicación de variados organismos, como son los fabricantes de vehículos, de bicis, patines, etc. de organismos institucionales, de gobiernos y de los propios usuarios de las vías. Siendo el grupo de mayor aceptación a llevar a cabo estos cambios, el de las personas más jóvenes de la sociedad, tendrán que pasar décadas para que su implantación se convierta en una normalidad.

Sin embargo, está claro que todo cambio precisa de un inicio, y es ese punto de partida el que se debe poner en marcha cuanto antes, para que la cuenta atrás para su desarrollo e implantación, no se demore más en el tiempo.

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TRÁFICO Y SEGURIDAD VIAL
TRAFFIC AND ROAD SAFETY

ANALISIS EXPLORATORIO DE LA MOVILIDAD DE LOS VEHICULOS TIPO TURISMO REGISTRADOS EN LAS ITV EN ESPAÑA

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RESUMEN

Los kilómetros recorridos por los vehículos del parque, son un indicador clave para conocer los patrones de uso y desplazamientos de los vehículos, determinar los niveles de movilidad y emisiones de forma muy desagregada.

En España, una fuente de información de los kilómetros recorridos anualmente por los vehículos, son las lecturas del cuentakilómetros registradas en los centros de inspección técnica vehicular (ITV) y constituyen un recurso valioso para la construcción de indicadores de movilidad.

En este trabajo se presentan los resultados del análisis exploratorio de los datos de una muestra de los registros de kilómetros recorridos anualmente por vehículos tipo turismo, en su paso por las ITV, en España en un período de 5 años.

El análisis permite establecer relaciones entre el kilometraje con atributos del vehículo, tales como la antigüedad, cilindrada, la tara y el número de plazas, además de otros aspectos como la ubicación geográfica y la edad del conductor.

El tratamiento de parte de los datos contenidos en los registros de ITV tienen una aplicación directa en el campo de la investigación científica de accidentes de tránsito.

1. INTRODUCCIÓN

Para el estudio de la seguridad vial, es necesario contar con indicadores de exposición, para poder evaluar los niveles de movilidad de vehículos y personas. Se puede considerar como los indicadores de exposición más idóneos a: vehículos-kilómetros y pasajeros-kilómetros, producidos en un período de tiempo; estos indicadores pueden referirse con otros aspectos, tales como el tipo de vía, la ubicación geográfica, colectivos de usuarios, tipos de vehículos (Direccion General de Tráfico, 2011).

Uno de los parámetros para la estimación de la exposición, es el número de kilómetros recorridos por los vehículos (KV); pero la medición de los KV no resulta sencilla, por lo que se suele estimar en base a los siguientes métodos de recolección de datos: lectura del cuentakilómetros, encuestas de hogares, conteos de tráfico y el consumo de combustible (Transport Division, 2007).

(Góngora, 2012), establece que el método de lectura del cuentakilómetros, presenta la ventaja de ser un registro preciso, aunque demanda un uso muy intensivo de recursos y hay que contemplar la posibilidad de errores de lectura, anotación, transcripción y alteración del cuentakilómetros.

Los centros de Inspección Técnica Vehicular (ITV) registran datos de los vehículos inspeccionados, uno de ellos es la lectura del cuentakilómetros y además información adicional importante, relacionada con el uso, propiedad, prestaciones, averías, entre otras. A partir del 2011, en España, obligatoriamente se realiza la comunicación de los registros de ITV a la Dirección General de Tráfico (DGT), teniendo gran cantidad de información que no está disponible en otros lugares.

En este trabajo se realiza un análisis exploratorio de la movilidad de los vehículos tipo turismo de España, siendo por cantidad de vehículos, el segmento más importante, al conformar el 77% del total de parque de vehículos español. El análisis se lo realiza en base a la información de los registros de ITV, como un aporte al conocimiento de la movilidad de forma desagregada, considerando su importancia para la aplicación de políticas de gestión de tráfico y seguridad vial, enfocadas en colectivos específicos, contribuyendo a conseguir una movilidad segura y sostenible.

2. DATOS

Los datos facilitados por la DGT, constan de alrededor de 6 millones de registros de pruebas de ITV, correspondientes a vehículos de turismo, en un amplio período que incluye inspecciones con fechas del año 1985 hasta julio de 2015. Cada registro contiene 36 variables, con la información referente a los campos: identificación del vehículo, datos técnicos, titularidad, historial de inspección e historial de defectos.

Considerando que desde el 2011 es obligatorio la comunicación de los registros de revisiones técnicas a la DGT, y que a partir de 2013 el registro de vehículos de la DGT se conecta telemáticamente con todas las estaciones de ITV, se tiene que para años anteriores la información no es de buena calidad.

La misma presenta principalmente problemas de datos faltantes, datos registrados con valor de cero y valores incoherentes. En el presente trabajo se han considerado los datos del período 2011-2015, los cuales contienen, por tanto, información de una calidad aceptable.

3. METODOLOGÍA

En este trabajo, la primera actividad ha sido la preparación de los datos, necesaria en vista de los problemas encontrados con los datos suministrados; a continuación, se realiza un análisis exploratorio de la movilidad, utilizando metodología estadística de tipo descriptiva, y finalmente para relacionar la movilidad con la ubicación geográfica, se aplica un análisis clúster.

3.1 Preparación de los datos

Los datos suministrados se han sometido a un proceso de preparación, para lo cual se ha seguido la metodología indicada en la Figura 1. Los criterios de preparación, se han ejecutado mediante la aplicación de algoritmos generados en el lenguaje R (Hastie et al., 2009).

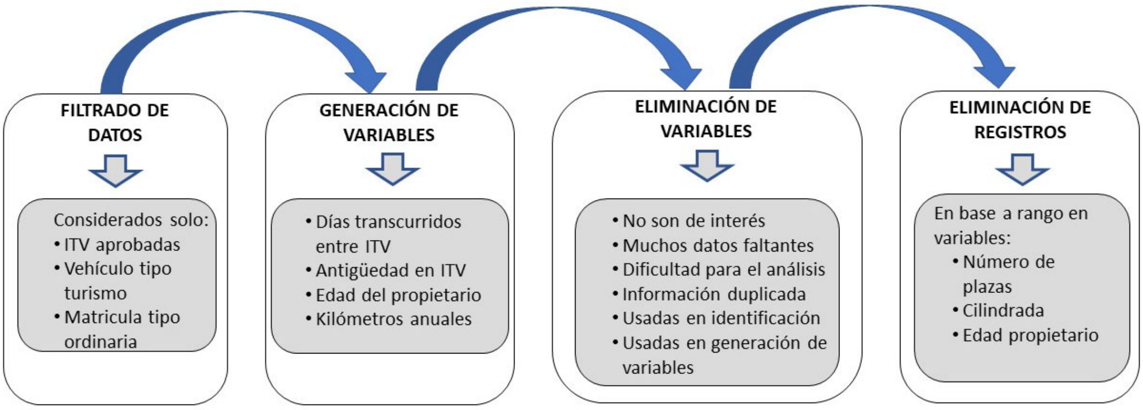

Figura 1: Metodología de preparación de los datos

3.2 Generación de variables

En este estudio se consideran cuatro variables de interés: días transcurridos entre ITV, la antigüedad del vehículo, los KV anuales y la edad del propietario, teniendo claro que el propietario registrado no será el conductor del vehículo en el 100% de los casos, pero se realiza la suposición razonable de que conductor y propietario coinciden en la mayoría de los casos. Las variables consideradas no se encuentran de manera directa en la base de datos, pero pueden ser estimadas partiendo de variables existentes.

Los días transcurridos entre ITV consecutivas, se establecen por la diferencia entre las fechas de revisión ITV y de la revisión ITV anterior, según Ecuación (1).

$$\textit{Días transcurridos entre ITV} = \textit{fecha de ITV} - \textit{fecha de ITV anterior} \qquad (1)$$

La antigüedad que tiene el vehículo, en el momento de pasar por ITV, se determinan por la diferencia entre las fechas de revisión ITV y de la primera matrícula registrada del vehículo, según Ecuación (2).

$$Antigüedad\ del\ vehículo = fecha\ de\ ITV - fecha\ de\ primera\ matrícula \quad (2)$$

La edad del propietario, en el momento de pasar por ITV, se establece por la diferencia entre las fechas de revisión ITV y de nacimiento del propietario, según Ecuación (3).

$$Edad\ del\ propietario = fecha\ de\ ITV\text{-}fecha\ de\ nacimiento \quad (3)$$

Para la determinación de los KV anuales que recorren los vehículos, se realiza la diferencia entre las lecturas de kilómetros registrada en la revisión ITV y en la revisión ITV anterior, este valor se lo divide entre los días transcurridos entre ITV, con lo que se tiene un valor de KV diario, que se lo multiplica por 365, para obtener los KV en términos anuales. Ver ecuación (4).

$$KV\ anuales = (kilómetros\ en\ ITV - kilometros\ en\ ITV\ anterior)/Días\ transcurridos\ ente\ ITV \cdot 365 \quad (4)$$

3.3 Análisis exploratorio de la movilidad

A partir de la base de datos preparada (BD_tur11-15), se hace el seguimiento de los KV a través de los registros consecutivos de inspecciones ITV, que permitirá varios análisis (cumplimiento de normativa, estimación y/o predicción de kilómetros anuales por tipos de vehículos, caracterización de vehículos de uso intensivo, etc.) siendo el objetivo de este trabajo la caracterización de los kilómetros anuales de vehículos turismos según variables de interés.

Como señala (Wilson et al., 2013), no es factible un análisis a nivel de vehículos individuales, pero si es posible un estudio de la distribución del KV a nivel de población de vehículos y establecer relaciones con atributos del vehículo. En este trabajo se consideran datos de un período de tiempo relativamente corto (5 años).

Con base a la información disponible, se han establecido relaciones entre los KV anuales con atributos como la cilindrada, la tara, el número de plazas y la antigüedad, además de otros aspectos como la ubicación geográfica y la edad del conductor y además se han comparado la evolución temporal en los diferentes años del período 2011 – 2015.

3.4 Análisis Clúster

Siendo uno de los objetivos la obtención de la relación entre el KV anual de turismos con aspectos geográficos, se ha formulado la hipótesis que la movilidad sigue unos patrones espaciales además de los temporales. Para obtener los patrones espaciales se recurrió al análisis clúster con el objetivo de encontrar grupos similares, pero que sean diferentes con las observaciones de otros grupos. El enunciado de la hipótesis es: hay diferencias entre las regiones del territorio español que se traducen en los KV anuales, caracterizados por los atributos de cilindrada, tara, antigüedad del vehículo y edad del conductor.

Para este propósito se utilizan algoritmos de minería de datos, que combina el método K-medias (K-means) con el método de agrupamiento jerárquico (hierarchical clustering), que evita especificar anticipadamente el número de agrupamientos (clústers).

4. RESULTADOS

La base de datos conformada ITV-Tur11-15 contiene ocho variables cuyos valores descriptivos se muestran en la Tabla 1.

Variable	Min	Max	Mean	S.D.
Cilindrada del motor (en cm^3)	852	6292	1765	384,12
Capacidad de ocupantes (variable discreta)	4	9	NA	NA
Edad del propietario (en años)	18	80	50,29	13,51
Días transcurridos entre ITV	201	3360	502,1	183,92
Provincia de matriculación (variable categórica)	NA	NA	NA	NA
Antigüedad del vehículo (en años)	1	39,96	12,37	4,20
Tara del vehículo (en kg)	620	2960	1219	224,85
Kilómetros recorridos anualmente	2000	39998	9754	5174,22

Tabla 1: Variables base de datos ITV-Tur11-15. Elaboración propia.

El análisis de la relación entre los KV anuales con la antigüedad de los vehículos, muestra un comportamiento similar al comparar los datos de los 5 años en estudio. Se observa que los vehículos recorren menos KV anuales con la antigüedad del vehículo, con un punto de inflexión en el rango de 4 a 6 años.

En la Figura 1 se puede apreciar que el punto de inflexión define dos comportamientos distintos en la movilidad de turismos: hasta 6 años de antigüedad y los de más de 6 años de antigüedad. La tasa de disminución de kilómetros medios anuales es mayor en los vehículos turismos más jóvenes que la que muestran los más antiguos. Además, los vehículos con antigüedad inferior a los 4 años, presentan aproximadamente el doble de KV en comparación a los que se encuentran el rango de 10 a 12 años, y aproximadamente el triple de KV que los vehículos con antigüedad superior a los 20 años.

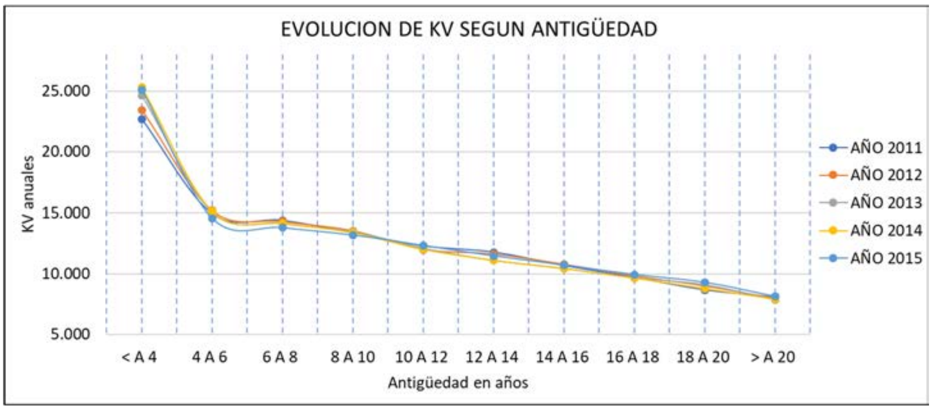

Figura 1: Evolución de los KV anuales según antigüedad del vehículo. Elaboración propia. Fuente: BD_tur11-15.

En la Figura 2, se muestra la relación entre la cilindrada de los vehículos y KV anuales y se observa que los vehículos con cilindrada superior a los 1600 cm^3, son los que mayor KV presentan, siendo aproximadamente un 30% superior a los vehículos de cilindrada inferior a 1200 cm3, que muestran el menor valor medio de KV. Esta información es relevante y muestra un patrón de movilidad diferente según la composición del parque de turismo en los que a cilindrada se refiere. Según las estadísticas de matriculaciones publicadas (Direccion General de Tráfico, 2015), los vehículos de mayor cilindrada constituyen aproximadamente el 27% del parque de turismos y los vehículos de cilindrada en el rango de 1200 a 1600 cm3 representan aproximadamente el 54%.

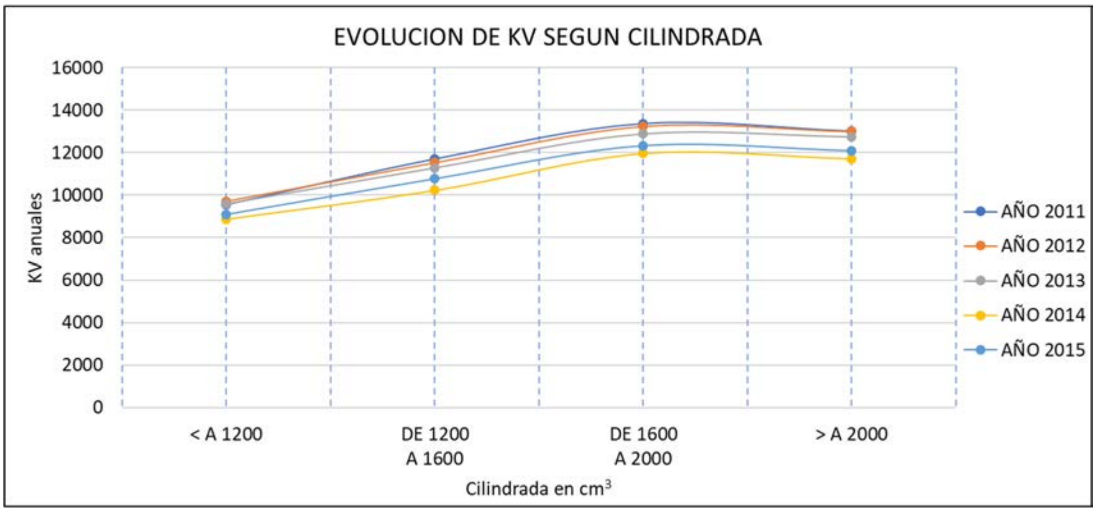

Figura 2: Evolución de los KV anuales según cilindrada del vehículo. Elaboración propia. Fuente: BD_tur11-15.

En la serie histórica han crecido más las matriculaciones de los vehículos más grandes, aunque en los últimos años se observa un repunte de los más pequeños cuyos cambios tecnológicos permiten obtener de éstos unas prestaciones notables. Ver Figura 3.

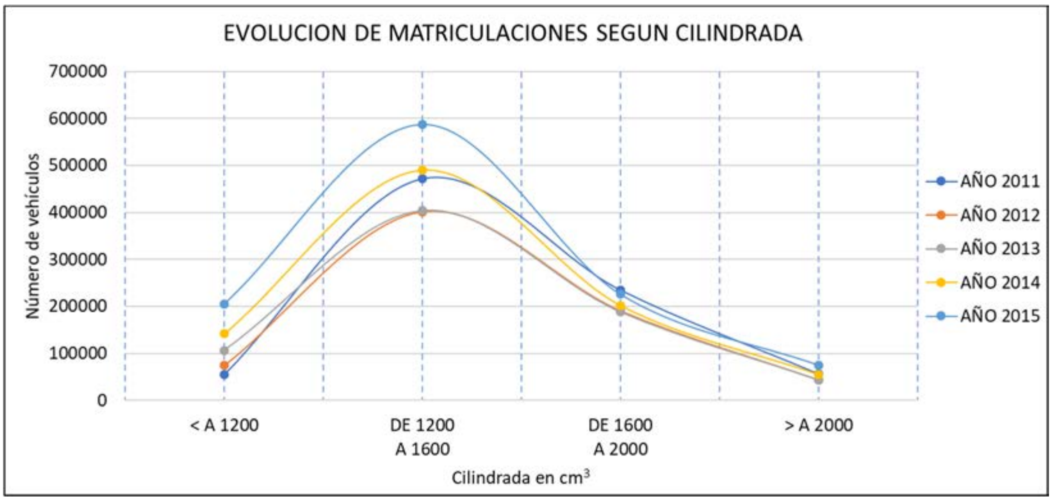

Figura 3: Evolución de matriculaciones según cilindrada. Elaboración propia. Fuente: DGT.

En la Figura 4 se muestra el resultado para la relación entre los KV anuales y la tara de los vehículos en los 5 años del estudio y se puede apreciar que los vehículos de tara más alta, son lo que más KV presentan. Este resultado es lógico, considerando que los vehículos de tara más alta, presentan motores de mayor cilindrada y de mayor uso en grandes recorridos.

Se observa un comportamiento distinto entre los turismos según los intervalos definidos a partir de 2000 kg, en donde los registros de los vehículos de los años 2011 y 2012 indican una disminución de los KV con el aumento de la tara, en cambio los registros de los años 2013 y 2015 muestran un pequeño incremento que refleja de otra manera que la movilidad los vehículos decrece con el factor edad del vehículo y requiere profundizar en el análisis de las relaciones subyacentes.

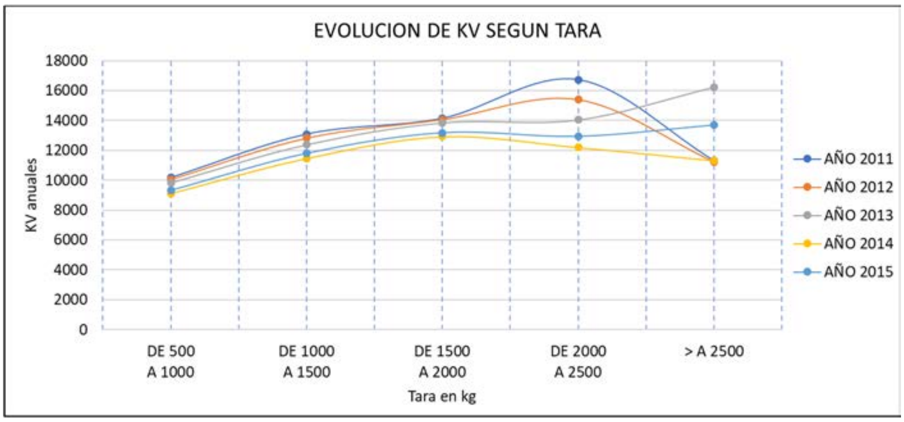

Figura 4: Evolución de KV anuales según tara del vehículo. Elaboración propia. Fuente: BD_tur11-15.

La relación de los KV anuales con la edad de los conductores, se muestra en la Figura 5. El patrón general que se puede extraer es que la movilidad de los conductores se reduce con la edad y este patrón tiene una tasa de cambio mayor a partir del rango de 55 a 60 años: los conductores realizan alrededor de 1000 KV anuales menos, por cada incremento de 5 años. Los conductores en el rango de los 25 y 30 años muestran valores de KV ligeramente superiores a los demás y el resto hasta 60 años tienen patrones de movilidad similares.

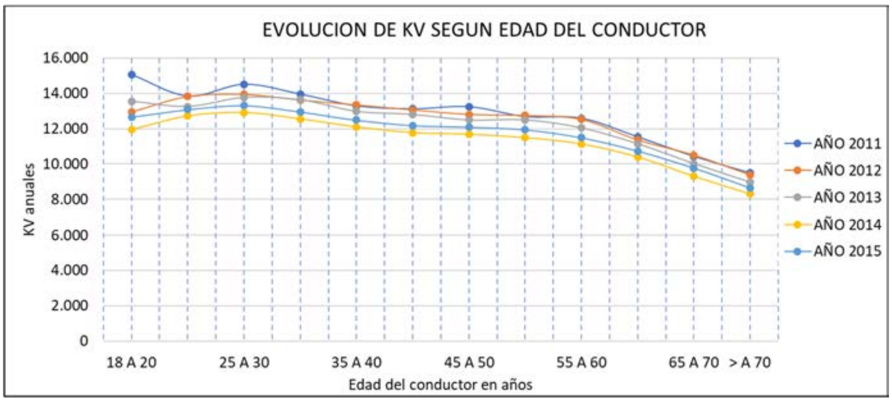

Figura 5: Evolución de KV anuales según edad del conductor. Elaboración propia. Fuente: BD_tur11-15.

En relación con la evolución de la obtención de permisos de conductores con la edad, el segmento más relevante es el que se encuentra en el rango de 35 a 40 años, que son aproximadamente 5 veces más que los conductores en las franjas más jóvenes y las de mayor edad y se corresponde con el grupo de conductores que tienen un comportamiento de movilidad muy parecido al resto de grupos de hasta 60 años de edad. Ver Figura 6.

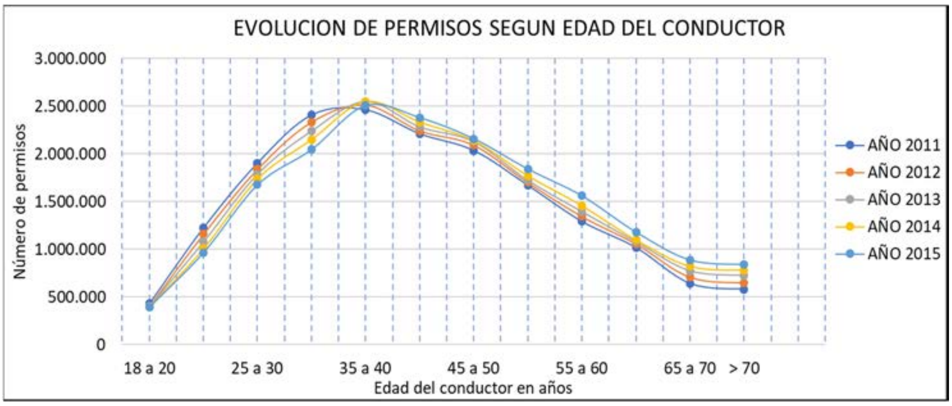

Figura 6: Evolución de conductores con permiso clase B. Elaboración propia. Fuente: Censo de conductores. DGT.

En lo que concierne al número de plazas, la Figura 7 permite observar que a medida que el vehículo tiene más plazas, más KV anuales presentan, es así que los vehículos de 9 plazas recorren alrededor de un 35% más de KV anuales, en comparación con los vehículos de 4 plazas, y un 20% más que los vehículos de 5 plazas.

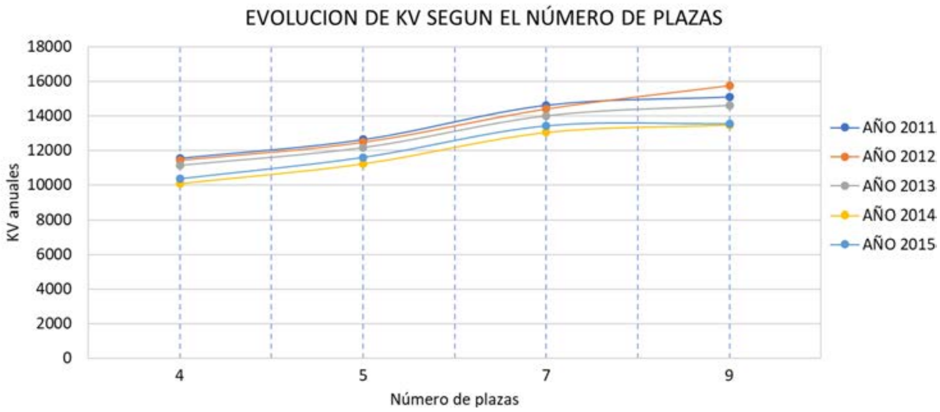

Figura 7: Evolución de KV según el número de plazas. Elaboración propia. Fuente: BD_tur11-15.

Si se asume que los vehículos de mayor número de plazas se utilizan en desplazamientos fuera de los centros urbanos, se puede justificar este resultado. Los vehículos de 5 plazas, representan el 90% del parque de turismos, pero son los vehículos que tienen más de 5 plazas los recorren más KV anuales, según los registros de ITV.

Para el estudio de la movilidad por regiones, a través del análisis clúster, en primer lugar, se aplica el agrupamiento jerárquico para generar un árbol, utilizando el método de “euclidean distance” para medir de similitud entre las observaciones.

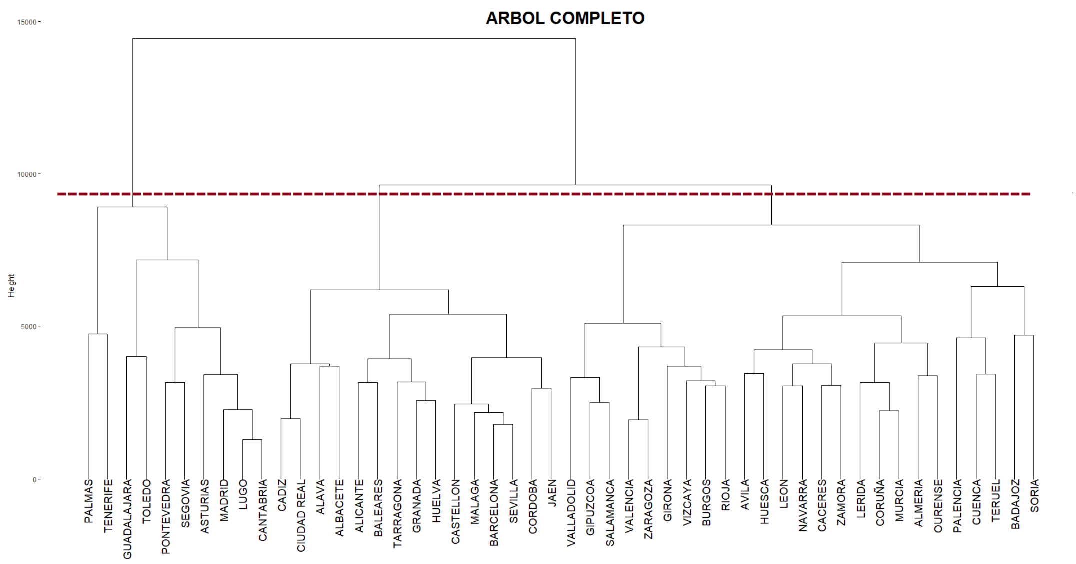

Figura 8: Árbol jerárquico generado con datos de KV de las provincias de España. Fuente: BD_tur11-15.

Para medir la diferencia entre grupos de observaciones, se utiliza el método “complete linkage clustering”, el cual calcula todas las diferencias en pares, entre los elementos del grupo 1 y los elementos del grupo 2, y toma en cuenta el máximo valor de estas diferencias, como la distancia entre los grupos, tendiendo a producir grupos más compactos. El árbol generado, se corta en un número de agrupamientos que se elige de forma visual del árbol generado (Figura 8), estableciéndose 3 agrupamientos.

Los grupos encontrados, se ilustran en la Figura 9, en la cual, al existir varias variables involucradas en la generación del clúster, ha trazado los puntos de acuerdo con las dos componentes principales, de las variables usadas en la generación, es decir las que explican la mayor varianza.

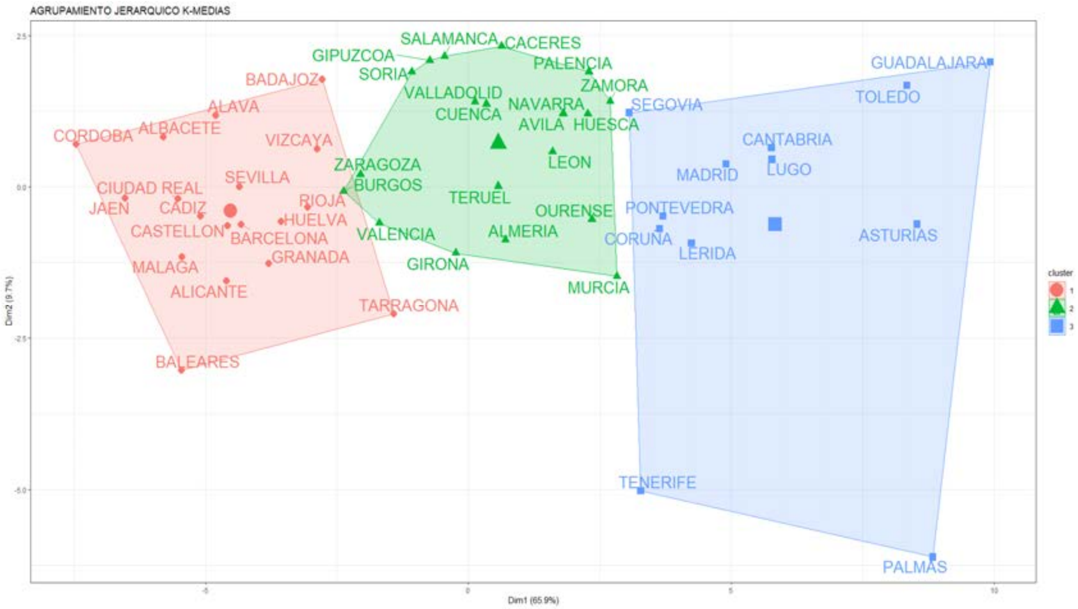

Figura 9: Agrupamientos por método Jerárquico K-medias. Elaboración propia. Fuente: BD_tur11-15.

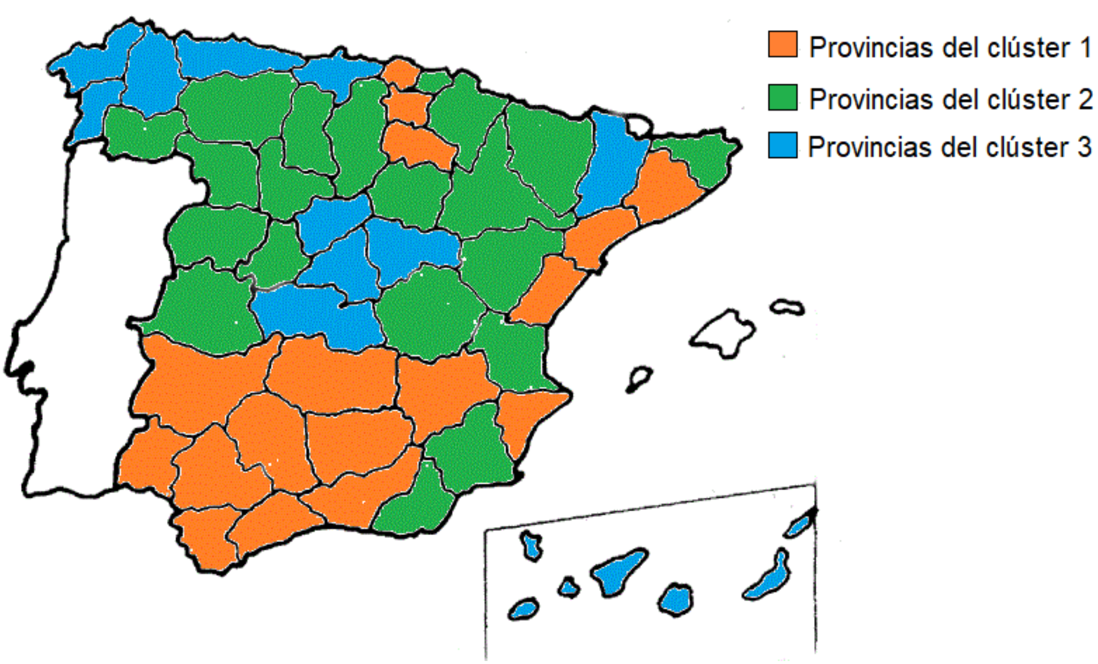

Figura 10: Correspondencia geográfica de los clústeres de provincias. Elaboración propia. Fuente: BD_tur11-15.

Para una mejor comprensión de estos resultados, la Figura 10 muestra la correspondencia geográfica de los agrupamientos de provincias obtenidos en los clústeres, pudiendo observar lo que se detalla a continuación:

- Las provincias incluidas en el clúster 1, geográficamente se encuentran formando tres agrupamientos de provincias colindantes, un grupo formado por las provincias de Vizcaya, Álava y La Rioja; un segundo grupo formado por las provincias de Castellón, Tarragona y Barcelona; y un tercer grupo formado por las provincias de Badajoz, Ciudad Real, Albacete, Alicante, más las provincias de la Comunidad Autónoma de Andalucía, con la excepción de Almería.
- En el segundo clúster se sitúan las provincias de Cáceres, Valencia, Ourense, Guipúzcoa, Navarra, Cuenca, más las provincias pertenecientes a las Comunidades Autónomas de Aragón y de Castilla y León, con la excepción de la provincia de Segovia.
- Las provincias incluidas en el tercer clúster, muestran dos agrupamientos de provincias colindantes, un primer grupo formado por las provincias de Pontevedra, La Coruña, Asturias y Cantabria, que son provincias de la costa norte del país; y un segundo grupo, formado por las provincias Segovia, Guadalajara, Madrid y Toledo, en el centro del país. Además, se puede observar que las islas de Palmas y Tenerife, también se incluyen es este clúster.

Considerando que los niveles de movilidad que presenta una región, está relacionada con la riqueza de la misma, se ha relacionado los agrupamientos obtenidos, con el PIB per cápita de las diferentes zonas del país (Instituto Nacional de Estadística, 2015), encontrando las siguientes relaciones relevantes:

- Las provincias pertenecientes al clúster 1, de la zona sur del país, pertenecen a las comunidades autónomas de Andalucía, Extremadura, Valenciana y Castilla La Mancha, teniendo un PIB per cápita inferior a 18.500 Euros/habitante, con excepción de la provincia de Alicante que pertenece a la comunidad Valenciana, con un PIB superior a 20.500 Euros/habitante y las pertenecientes a Cataluña con un PIB superior a los 27.500 Euros/habitante.
- Las provincias que forman parte del segundo clúster, en su mayoría forman parte de comunidades autónomas que tienen un PIB superior a 18.000 Euros/habitante, con excepción de Cáceres y Almería, las cuales pertenecen a comunidades autónomas con PIB de 16.000 Euros/habitante y 17.000 Euros/habitante, respectivamente.
- Las provincias incluidas en el clúster 3, ubicadas al norte del país, se distribuyen entre las comunidades autónomas de Galicia, Cantabria y Asturias, las mismas que tiene un PIB per cápita similar, alrededor de 20.500 Euros/habitante. Las provincias del centro del país constan de Madrid (PIB superior a los 31.000 Euros/habitante) y de las provincias de Guadalajara, Toledo y Segovia, pertenecientes a comunidades autónomas con PIB inferior a los 21.000 Euros/habitante.

Los niveles de movilidad de los clústeres establecidos, se representan por el valor de la media de los KV anuales; en la Tabla 2 se muestra la relación con la cilindrada del motor, en la Tabla 3 se muestra la relación con la tara del vehículo, y en la Tabla 3 y Tabla 4, se muestra la relación con la edad del propietario y la edad del vehículo, respectivamente.

CLUSTER	RANGOS DE CILINDRADA EN cm^3			
	MENOR_A1200	DE1200_A1600	DE1600_A2000	MAYOR_A2000
1	8135	9655	11569	11449
2	8247	10170	12272	12221
3	9656	11554	13186	12713

Tabla 2: Media de KV anuales de los clústeres con relación a la cilindrada. Elaboración propia.

CLUSTER	RANGOS DE TARA EN kg			
	HASTA1000	DE1000_A1500	DE1500_A2000	DE2000_2500
1	8349	10998	12402	11985
2	8709	11753	13330	13175
3	10094	12772	13824	14367

Tabla 3: Media de KV anuales de los clústeres con relación a la tara. Elaboración propia.

CLUSTER	EDAD DEL PROPIETARIO EN AÑOS								
	18 a 20	20 a 25	25 a 30	30 a 35	35 a 40	40 a 45	45 a 50	50 a 55	55 a 60
1	8363	12441	12422	11984	11457	11126	11016	11081	10675
2	8931	13518	13657	13254	12353	12097	11929	11740	11342
3	9731	14240	14103	13891	13349	13138	12983	12815	12256

Tabla 4: Media de KV anuales de los clústeres con relación a la edad del propietario. Elaboración propia.

CLUSTER	ANTIGÜEDAD DEL VEHÍCULO EN AÑOS								
	< 6	6 a 8	8 a 10	10 a 12	12 a 14	14 a 16	16 a 18	18 a 20	>20
1	15391	13369	12656	11465	10669	9999	9129	8363	7449
2	15644	14470	13783	12381	11582	10817	9839	8931	7847
3	16174	14861	14047	13015	12120	11392	10676	9731	8427

Tabla 5: Media de KV anuales de los clústeres con relación a la antigüedad del vehículo. Elaboración propia.

Al examinar los valores de KV anuales presentados, se observa en el clúster 1, los valores más bajos de KV y en el clúster 3 los valores más altos de KV, lo cual va en concordancia con los valores del PIB per cápita, indicados anteriormente.

4. CONCLUSIONES

La aplicación de la metodología de preparación de los datos, ha permitiendo contar con una base (BD_tur11-15) apropiada para aplicación en los análisis de movilidad, así como establecer variables de interés que no se encontraban registradas de manera directa.

A través de un análisis exploratorio de la movilidad, utilizando estadística descriptiva, se ha establecido la existencia de patrones de movilidad (representada por los KV anuales) con la edad del conductor y con los atributos del vehículo: antigüedad, cilindrada, tara, número de plazas.

El uso de minería de datos, a través del método de agrupamiento jerárquico combinado con K-medias, y considerando la forma en la que se reparten los KV anuales por los atributos del vehículo, en las diferentes provincias de España, ha permitido establecer 3 grupos de provincias, estos grupos además se encuentran distribuidos geográficamente en bloques de provincias colindantes y se observa coincidencia con los valores de PIB per cápita de las diferentes regiones.

Los resultados muestran información relevante, de interés en estudios de movilidad, con una metodología de análisis, que puede ser aplicada a otros tipos de vehículos.

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EVALUATION OF THE EFFICIENCY OF TRAFFIC LIGHTS TURNING RED IN CASE OF EXCEEDING SPEED LIMIT WITH PREVIOUS PANELS INDICATING THE SPEED

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ABSTRACT

A usual traffic calming measure (TCM) to reduce vehicle speed in urban areas is the traffic lights that turn red when a vehicle exceeds the speed limit. These traffic lights can detect if an approaching vehicle exceeds the speed limit and, if so, stop it by means of a red light. It is generally employed in interurban roads rather than in big cities, where the presence of traffic lights is common. In a rural road crossing a small village, they are deployed to reduce the risk of accidents to vulnerable road used when vehicles arriving at high speeds tend to conflict with pedestrians attempting to cross the road.

The aim of this paper is to analyze the efficiency of this TCM, preceded by panels indicating the vehicles' speed, by controlling the vehicles' speed in the A-132 road that crosses through the village of Azazeta in the province of Álava/Araba (Spain). Different sequence of the TCMs can be found in each direction approaching the village; in A direction, warning traffic lights, the panel indicating the speed and the traffic light turning red; and in B direction, the panel, the warning traffic lights and the traffic lights turning red.

However, similar results were obtained in both directions for average speeds and percentile 85 of the speed distribution at the traffic lights, and speed was reduced as motorists faced the TCMs. However, although average speed was below speed limit (50 km/h), the percentile 85 was over it, implying that more than 26% of drivers did not respect the red light. Moreover, after the traffic lights turning red, motorist speed up and higher values were measured at the midpoint of the urban segment, the place where pedestrians use to cross from one side of the village to the other one, although no pedestrian crosswalk is available.

1. INTRODUCTION

Traffic calming measures (TCMs) are a usual solution for reducing vehicles' speed in urban areas. TCMs are defined as the combination of mainly physical measures that reduce the negative effect of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users (Lockwood, 1997). Their main aim is the reduction of vehicles' speed and volumes in an area because speed is directly related to the probability of death for pedestrians involved in a crash, as shown in Table 1 (TRB, 2010; Tefft, 2011) despite the multiple factors that are involved in a highway crash (Llopis-Castelló et al. 2019; Ziolkowski, 2019).

Collision speed (km/h)	80	65	50	32
Chance of pedestrian death (%)	100	80	40	5

Table 1: Chance of pedestrian death if hit by a motor vehicle.

There are a wide variety of possibilities for TCMs but they are generally classified in the following groups (Kveladze and Agerholm, 2018; Gonzalo-Orden et al. 2016; Ziolkowski, 2018; Pérez-Acebo et al. 2020a):

- Vertical deflection: Speed hump, speed bump, speed cushion, rumble strip, raised intersection, raised crosswalk, road lump and table.
- Horizontal deflection: Curb-extension, chicane, gateway, traffic circle, raised median island.
- Physical obstruction: Semi and diagonal diverter, right-in and right-out island, raised median through intersections, street closure
- Signs and pavement markings.

In urban areas, calmed road segments are achieved due to the succession of traffic calming measures in the area. Nevertheless, an important problem is observed in the transition from and interurban area to an urban area, i.e. at the beginning of the urban area (Gonzalo-Orden et al. 2018; Pérez-Acebo et al. 2021a). The problem is increased in rural roads crossing small villages that are not bypassed. When drivers arrive to a short urban area, as the ones that can be found in rural roads crossing small villages, they do not usually reduce their speed conveniently, maintaining high speeds allowed in the interurban area and, hence, increasing the risk for pedestrians in the village (Table 1).With the aim of reducing the speed of the vehicles during the short segments of these villages, traffic calming measures are placed at the entrance to indicate that drivers are entering an urban area, even for a short period of time, and, to force them to speed down. Typical solutions at the border between non-urban and urban areas are raised crosswalks, signs with speed limits, panels displaying vehicle speed, radars (which could fine if drivers exceed speed limit), etc., and their efficiency is being analyzed (Gonzalo-Orden et al. 2018; Daniels et al. 2019).

A common solution in Spain is traffic lights turning red if the speed limit is exceeded. The traffic lights detect an approaching vehicle, measure its speed and, if it is higher than the speed limit, they try to stop it by turning red immediately. Consequently, in theory, drivers speed down in front of a red light and, when speed is reduced below the limit, the lights turn yellow again. Few studies can be found in the literature about this type of TCM. Generally, papers are focused on traffic offenses involving red lights and how red light cameras can be efficient on crashes (Llau et al. 2015; Baratian-Ghorghi et al. 2016). Pérez-Acebo et al. (2021a) analyzed the efficiency of traffic lights turning red in case of exceeding speed limit and they showed that better results were obtained if the traffic lights were combined with a crosswalk.

The aim of this paper is to measure the efficiency of traffic lights turning red in rural roads crossing villages with a short urban segment, preceded by panels indicating the speed. The case study took place at the A-132 road and at the village of Azazeta, in the province of Álava/Araba (Spain). The traffic lights were placed at the entrance of the village on both directions and before them panels indicating the instantaneous speed of each vehicle were also posted. It was aimed to observe the speed reduction achieved combining both TCMs (the traffic lights and the panels) at the centre of the village.

2. METHODOLOGY AND CASE STUDY

As explained before, the village of Azazeta and the A-132 running trough it were selected as a case study for analyzing the efficiency of traffic lights turning red in case of exceeding speed with previous panels indicating the drivers' speed. The A-132 road belongs to the Regional Government of Álava/Araba, one of the 3 provinces of the Basque Country. Due to the special legal status of the Basque Country, all the roads in each of the provinces belong to the regional government of the province, even those connecting to other regions and countries. Consequently, the Spanish Government does not manage any road in the Basque Country (Pérez-Acebo et al. 2020b; 2021b).

The A-132 road is included in the Basic Network (orange network), which is the second level of importance in the province. Table 2 shows all the road network categories in which the road network of the province is divided (DFA/AFA, 1990; Hernández et al. 2021). The A-132 road goes from Vitoria-Gasteiz (the capital of the province of Álava/Araba) to Estella, in the Region of Navarre.

When entering in the Region of Navarre, as that stretch from the border to Estella belongs to the Regional Government of Navarre, the road changes its name to NA-132-A. In the segment in the province of Álava/Araba, there is the mountain pass of Azazeta, and at the bottom of it, after crossing it coming from Vitoria-Gasteiz, the village of Azazeta is located.

Road Network level	Lenght (km)
Preferential interest network (red)	145.7
Basic network (orange)	146.42
Provincial network (green)	200.91
Local network (yellow)	534.23
Neighborhood network (grey)	373.02

Table 2: Length (km) of the road network in the province of Álava/Araba.

At the mountain pass, there is a permanent counting station, measuring passing vehicles continuously and, hence, provided values are real. The obtained values, shown in Table 3, represent the traffic flow for a 17.5 km-long segment, including the entire mountain pass and the village of Azazeta.

Table 3 shows the values of the Average Annual Daily Traffic (AADT), the percentage of heavy vehicles and the Average Annual Daily Traffic of Heavy Vehicles (AADTHV), in both directions. In Spain, a vehicle needs to weight more than 3,500 kg to be considered as a heavy vehicle (MFOM, 2003; Pérez-Acebo et al. 2020b). As seen, the total traffic volume and the percentage of heavy vehicles increase each year.

Years	AADT (vehicle/day)	% of heavy vehicles	AADTHV (heavy vehicle/day)
2019	3510	8.6	302
2018	3453	5.1	280
2017	3411	6.2	213
2016	3352	6.0	221
2015	3239	5.9	192
2014	3202	5.8	187

Table 3: Traffic volume values at the permanent counting station of Azazeta (190) for the last years.

The A-124 crosses the village of Azazeta, in a segment of approximately 240 m, dividing the urban area in two approximately similar parts (Figure 1).

There is not any pedestrian crosswalk between the two parts. Nevertheless, the Regional Government of Álava/Araba wanted to reduce the speed of vehicles crossing the village because inhabitants cross the road to access the other part of the village.

With this aim, various traffic calming were introduced to speed down the traffic. Moreover, in the direction from Vitoria-Gasteiz to Estella, vehicles have just gone down the mountain pass and their speed tends to be high. Consequently, the TCMs were necessary to calm down the urban area of this short road segment.

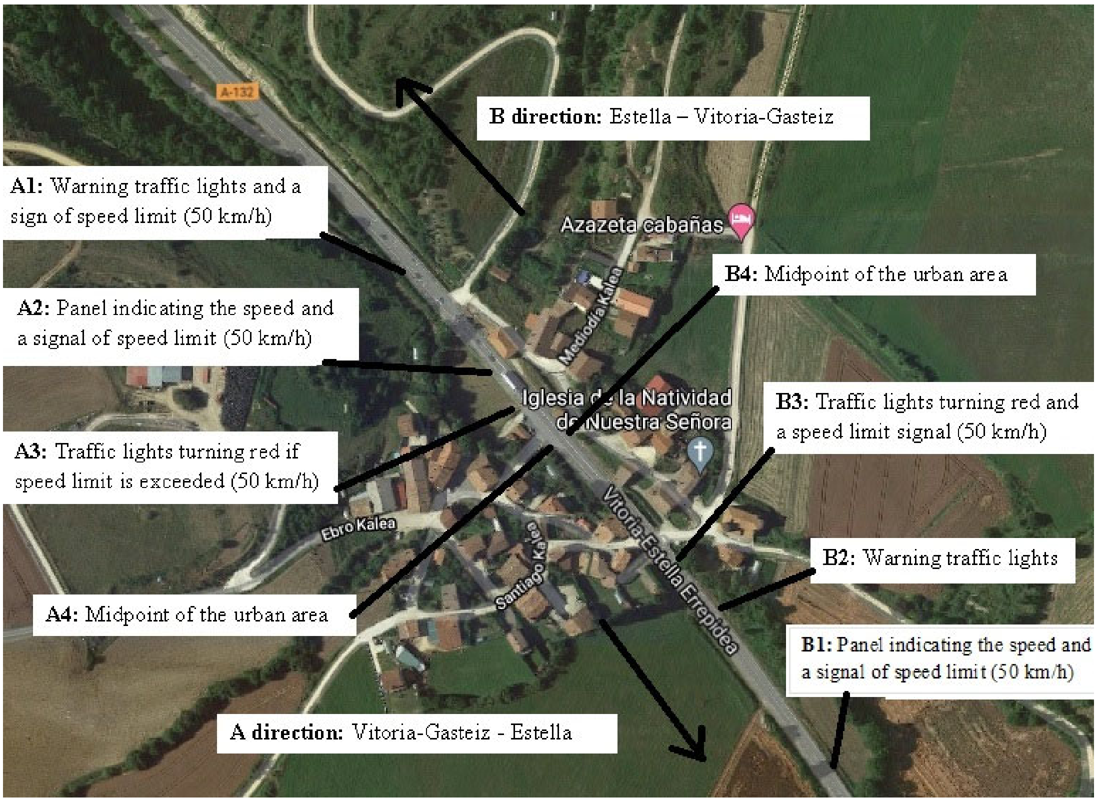

Figure 1: Aerial photo of the village of Azazeta and locations of the TCMs.

Traffic lights turning red if speed is exceeded and some previous panels indicating the speed of each vehicle were placed in both directions. In each direction, the sequence of the TCMs is as follows:

Vitoria-Gasteiz – Estella direction (north – south) (Figure 2):

- Point A1: Traffic lights warning about the presence of traffic lights and a signal with a speed limit of 50 km/h.
- Point A2: A panel indicating the speed of each vehicle (with a speed limit of 50 km/h).
- Point A3: Traffic lights turning red if speed limit is exceeded.
- Point A4: Mid-point of the urban segment, where pedestrian cross the road.

Estella - Vitoria-Gasteiz (south - north) (Figure 2):

- Point B1: A panel indicating the speed of each vehicle (with a speed limit of 50 km/h)..
- Point B2: Traffic lights warning about the presence of traffic lights.
- Point B3: Traffic light turning red if speed limit is exceeded and a signal reminding the speed limit (50 km/h) some meters before.
- Point B4: Mid-point of the urban segment, where pedestrian cross the road.

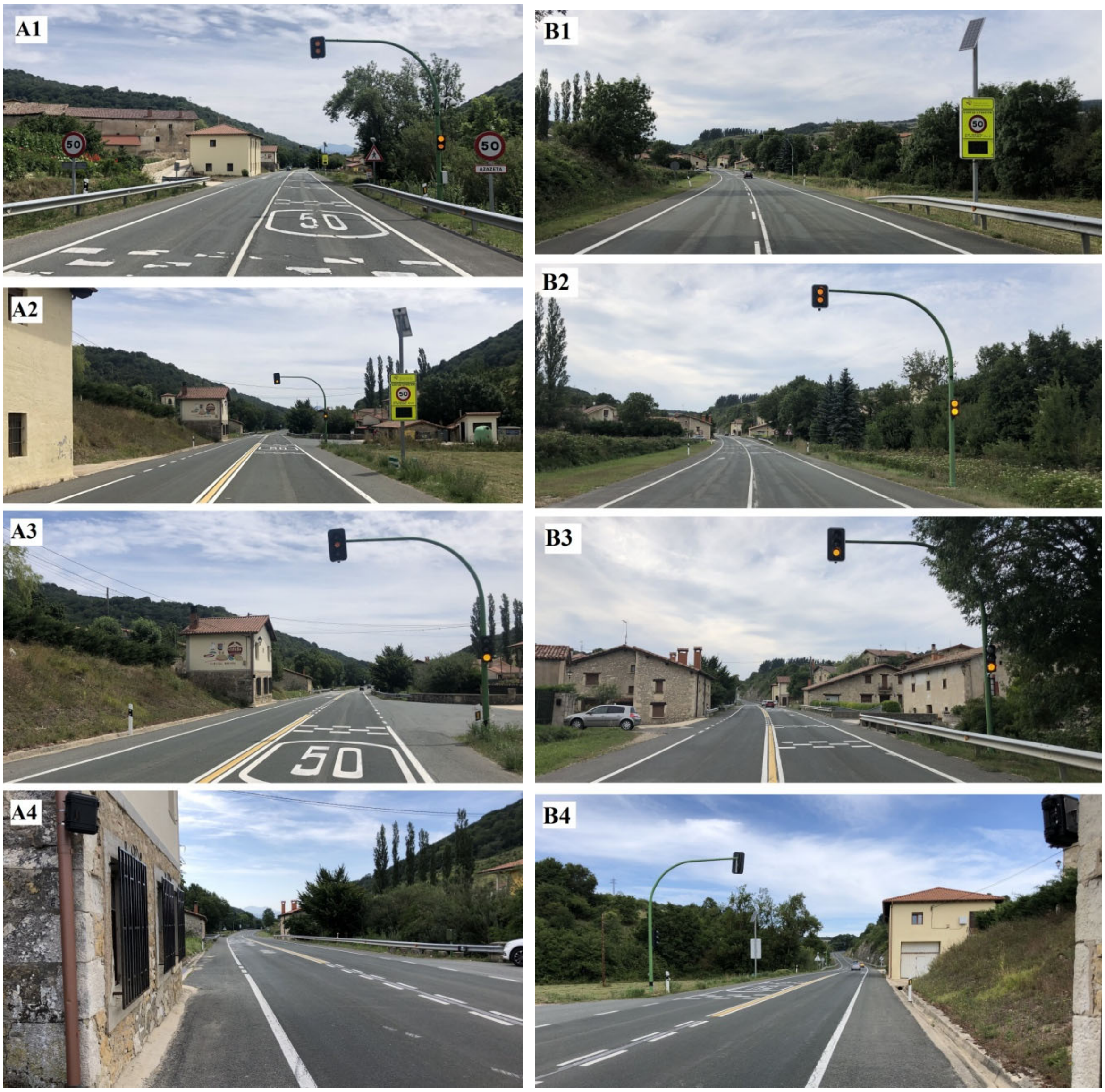

Figure 2: Traffic calming measures in direction A (points A1, A2, A3, and A4) and in direction B (points B1, B2, B3, and B4).

As seen, the sequence is not identical in both directions. While in north-south direction, there are traffic lights warning about the presence of more traffic lights and then the panel indicating the speed appears, in the other direction the panel is placed before the warning traffic lights. Additionally, Point A4 and B4 represents the same point, the midpoint of the urban area and the different name for it means the direction of the measured traffic volume.

Speed measurements were taken on August 6, in 2019. This type of small villages has a higher population in summer because many people spend their holidays in these small villages, leaving the big cities. A fixed radar was placed in point A4/B4 to measure the speed at the midpoint of the urban area, where inhabitants tend to use to cross the road in spite of the lack of an adequate pedestrian crosswalk. Moreover, warning signals (triangular) indicating that pedestrian could eventually cross the road are placed between A1 and A2 and between B2 and B3.

Therefore, this point represents the place where the effect of the traffic calming measures must take place in case pedestrians want to cross the road. Furthermore, at this place, vehicles coming from any of the two urban areas access to the main road, the A-132.

Additionally, from 11:00 am to 2:00 pm, a gun radar was employed to measure the speed of vehicles in points A1 and A3 from a hidden place, not to disturb vehicles' speed. Speeds shown to the vehicles in the panel of point A2 were also recorded and, hence, a complete speed profile of the vehicle was possible to obtain. Similarly, from 3:30 p.m. to 6:30 p.m., the same gun radar was used to measure the speed of vehicles in point B2 and B3 from a hidden place and the speed indicated in the panel in B1 was also registered.

The aim of this study was to show how the speed is reduced at the traffic lights turning red in the case of exceeding speed limit in two different configurations (with the panel indicating the speed nearer or further from the traffic light), know the speed profile of the vehicles approaching the traffic lights and how the reduced speed is maintained after the traffic lights, at the place where pedestrian would cross the road.

3. METHODOLOGY AND CASE STUDY

More than 1700 vehicles were controlled at the midpoint of the urban area (A4/B4) in both directions, and 334 vehicles in direction A and 257 in direction B. Table 4 presents the average speed of the vehicles, V_{ave}, the percentile 85th of the speed, V_{85} (which is the speed not reached by 85% of vehicles or, from another point of view, the speed achieved or exceeded by 15% of the vehicles), the maximum speed V_{max}; and the minimum speed, V_{min}. Moreover, Table 4 also includes the number of vehicles exceeding the speed limit (50 km/h), and the percentage of vehicles exceeding this limit from the total of measured vehicles.

Direction	Vitoria-Gasteiz – Estella				Estella – Vitoria-Gasteiz			
Points	A1	A2	A3	A4	B1	B2	B3	B4
V_{min} (km/h)	27	27	19	7	35	26	10	4
V_{ave} (km/h)	56.33	49.9	46.2	53.4	68.7	59.0	46.5	55.0
V_{85} (km/h)	67	59	55	65	83	72	56	66
V_{max} (km/h)	105	92	79	99	103	95	84	103
Total number	334	334	334	361	257	257	257	807
Vehicles V>50 km/h (units)	216	122	88	588	231	180	79	569
Vehicles V>50 km/h (%)	64.7	36.5	26.3	61.2	89.9	70.0	30.7	70.5

Table 4: Measured values of selected variables at control points in both directions.

As observed, in the Vitoria-Gasteiz – Estella direction, the average speed at A3 (the point of the traffic light turning red) was 46.2 km/h, and the V_{85} is 55 km/h, implying that 26.3 % of the vehicles did not respect the speed limit and the red light, and continued their way. Fortunately, a decrease on the speed can be seen from point A1 to point A3 (Figure 3a).

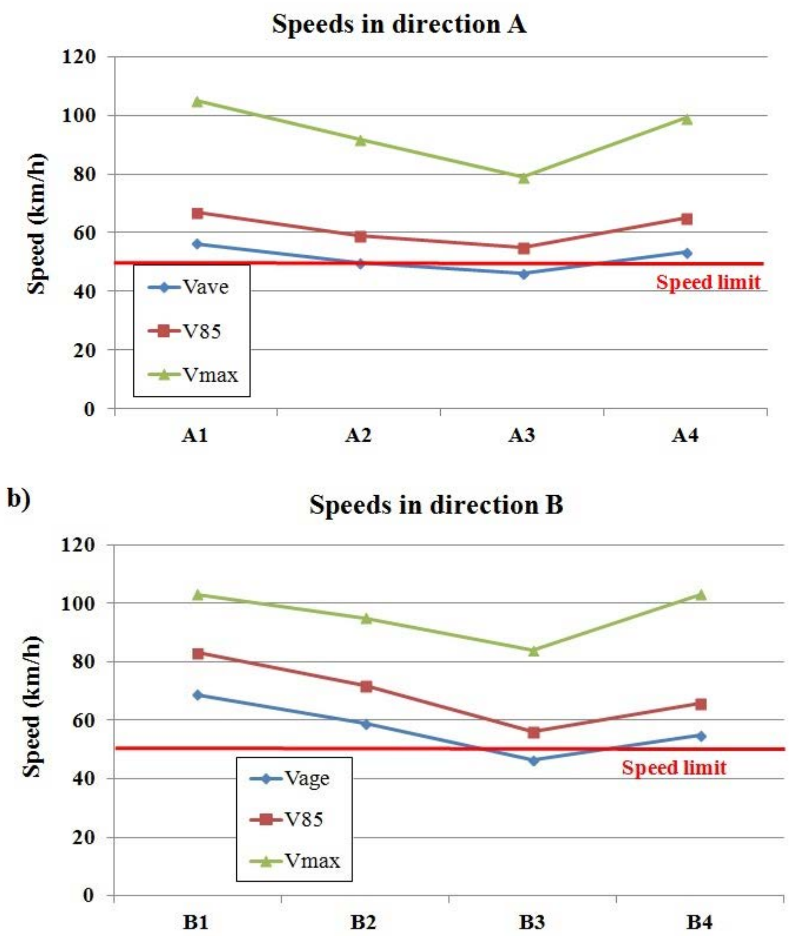

Figure 3: Speeds at each controlled point, a) in direction A; b) in direction B.

It shows that the first traffic lights warning about the presence of traffic lights serves as a first warning but even the average speed is over the speed limit at this point. Motorists speed down at the next point, where the panel indicates their speed, and the V_{ave} is below the speed limit, but not the V_{85} (36.5 % of the vehicles did not respect the limit). Finally, as commented, the better values are obtained at point A3, with the traffic light turning red, as drivers drive more carefully due to the possibility of a fine. Nonetheless, at point A4, the midpoint of the urban area, the place where pedestrian could appear, motorist speed up as they feel they are not controlled. Even the average point at this point (A4) is over the speed limit, with 61.2 % of vehicles faster than allowed (Figure 3a). In Figure 4a, the cumulated distributions of speeds at each point in A direction are shown.

In the other direction, Estella – Vitoria-Gasteiz, similar results were obtained (Table 4, Figure 3b). Speed is reduced from point B1 to B3, reaching the lowest value at B3, where the traffic light that can turn red if speed is over 50 km/h is placed. At B1, where the panel shows the speed to drivers, high speed values were registered despite the speed limit of 50 km/h: the average speed is over 68 km/h and the V_{85} is 83 km/h. Fortunately, lower values were measured in B2 and in B3, the average speed was below the speed limit, 46.5 km/h, and the V_{85} was 56 km/h.

The percentage of drivers not respecting the red light was 30.7 % in B3. Once again, at point B4 motorist speed up and an average speed of 55 km/h was observed, V_{85} was 66 km/h and 70.5% of vehicles did not respect the speed limit. In Figure 4b, the cumulated distributions of speeds at each point in B direction are shown.

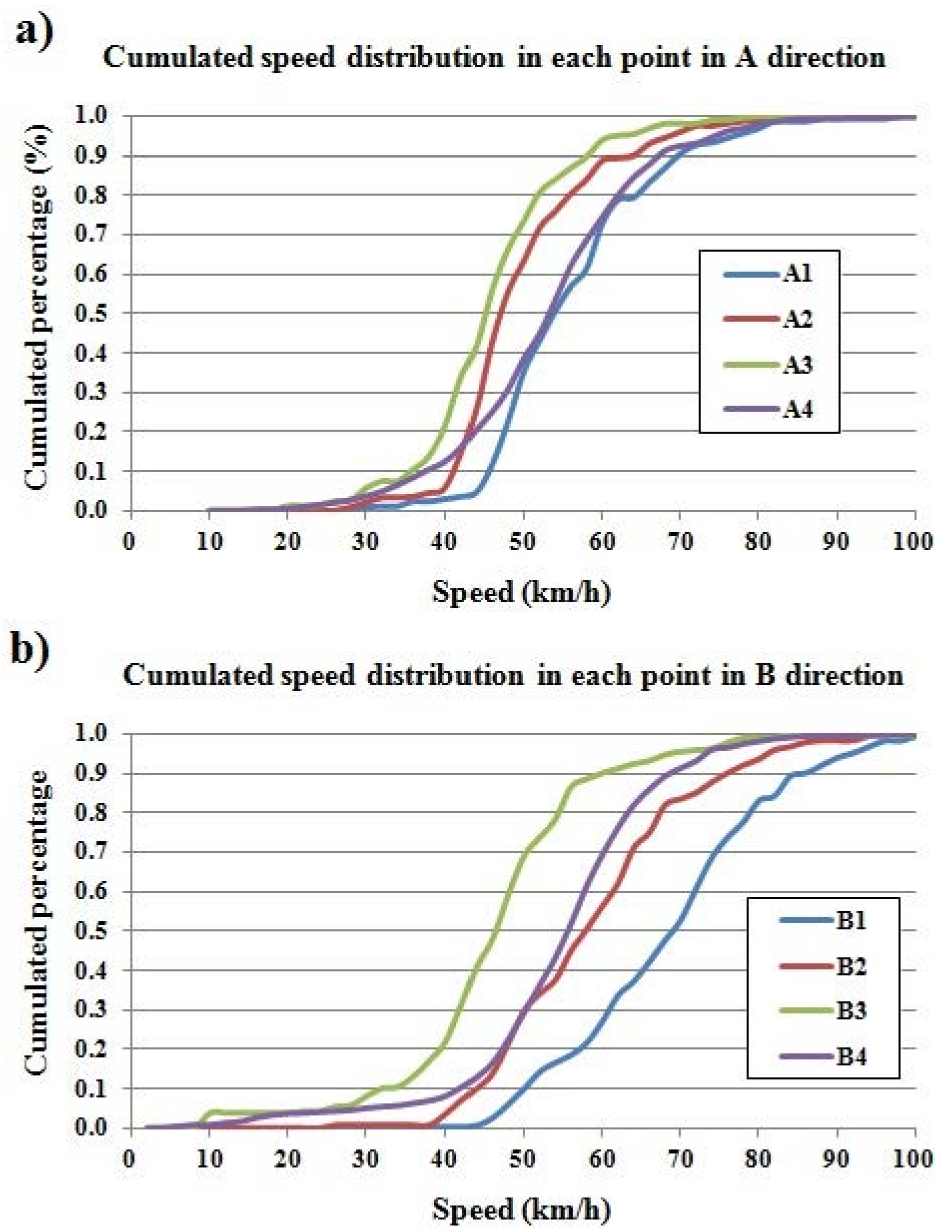

Figure 4: Cumulated speed distribution at each point, a) in A direction, b) in B direction.

If values obtained at the midpoint of the urban area are compared (A4 and B4), similar values are obtained. Average values of 46.2 and 46.5 km/h and V_{85} values of 55 and 56 km/h were measured in direction A and B, respectively. Consequently, the order of the sequence (panel and warning traffic lights or warning traffic lights and panel) obtained similar results at the subsequent traffic light turning red in case of exceeding speed limit and at the midpoint of the urban area.

However, it must be noted that higher values were recorded in B1 than in A1, but it could be due to the fact that B1 is further from the urban area than A1, which is very near from the start of the urban area. Although panels show the driving speed to motorist, they understand that they are still far from the urban area and they may think that they have time to speed down.

Moreover, the fact that values obtained in A4 and B4 are similar and higher than in A3 and B4 indicates that drivers tend to accelerate as they feel that they have passed the traffic light turning red and that, despite being in an urban area, the controlled area (at the traffic lights) is finished. Drivers' experience show them that the traffic lights could be the place where the radar of the police could be located (controlling the speed or not violating a red light), but not after passing them. These values also show that although drivers can respect the speed limits at the TCMs but, after them, they forget their effect.

Finally, if we compared the values obtained at the traffic lights of Azazeta with a similar study in Ábalos (Region of La Rioja, Spain) (Pérez-Acebo et al. 2021a) some conclusions can be deduced. In Ábalos, traffic lights turning red in case of exceeding speed limit were placed after warning traffic lights but without panel indicating the speed. However, in one direction the traffic light included a pedestrian crosswalk, and in the other one without pedestrian crosswalk. Table 5 compares the measured speed values in Azazeta and Ábalos.

Location	Azazeta (Álava/Araba)		Ábalos (La Rioja)	
Point	A3	B3	A2	B3
Placed TCM	Traffic lights turning red	Traffic lights turning red	Traffic lights turning red	Traffic lights turning red and pedestrian crosswalk
V_{ave} (km/h)	46.2	46.5	50.5	30.5
V_{85} (km/h)	55	56	60	42
V_{max} (km/h)	79	84	85	80
Total number	334	257	261	1411
Vehicles V>50 km/h (units)	88	79	224	255
Vehicles V>50 km/h (%)	26.3	30.7	58.8	18.1

Table 5: Speed values in traffic lights turning red in Azazeta and in Ábalos (from Pérez-Acebo et al. 2021a).

As seen, the presence of a crosswalk help reducing the vehicles' speed, reinforcing the effect of the traffic light turning red in case of exceeding the speed limit. As seen, the introduction of a panel indicating the speed helps also improving the efficiency of the traffic lights, better if it is located just before the traffic light (as in A3 in Azazeta) and not at the beginning of the sequence as in B3 in Azazeta. Nonetheless, the best effect is achieved if the pedestrian crosswalk is placed with the traffic lights, because drivers would respect more the speed limit.

Apart from the possible fine if the limit is not respected, a pedestrian could appear, wanting to cross the road and that possibility contributes to a higher speed reduction (or a higher percentage of drivers respecting the speed limit).

4. CONCLUSIONS

The study analyzes the efficiency of traffic lights turning red if the speed limit is exceeded preceded by panels indicating the vehicles’ speed. Traffic lights that turn red if the approaching vehicle exceed speed limit are a usual traffic calming measure in rural roads crossing short urban segments. The selected village, Azazeta, is crossed by the A-132 road (Vitoria-Gasteiz – Estella), managed by the Regional Government of Álava/Araba, and traffic lights turning red, panels indicating the speed and warning traffic lights in a different sequence. While in A direction (Vitoria-Gasteiz – Estella), the sequence is warning traffic lights, the panel, and the traffic lights turning red, in B direction (Estella – Vitoria-Gasteiz), the sequence is the panel, warning traffic lights and traffic lights turning red. In both directions a speed reduction is observed as drivers pass each traffic calming measure, achieving the lowest speed at the traffic lights turning red, with a similar average speed (slightly over 46 km/h), below the speed limit (50 km/h), but the percentile 85 of the speed distribution is over the speed limit (55 and 56 km/h in A and B direction, respectively), indicating that 26.3% and 30.7% of drivers did not respect the red light. Moreover, after the traffic lights turning red, drivers speed up and higher speeds are measured at the midpoint of the urban segment in both direction. Additionally, obtained results were compared to other traffic lights turning red in Ábalos (La Rioja) and the lowest speeds were obtained when combining the traffic lights with a pedestrian crosswalk.

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ESTUDIO DE ACCIDENTES DE CICLISTAS EN ESPAÑA

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RESUMEN

El uso de la bicicleta en España es aún reducido, pero se ha incrementado de manera significativa, como medio de vida saludable por la práctica deportiva entre los ciudadanos y también como modo de transporte en las ciudades en las que se ofrecen infraestructuras específicas o adaptadas, lo que se extiende también a áreas periurbanas para ir al centro de estudios o al trabajo, es un hecho constatado por diversos estudios. Se desconoce el tamaño y evolución del parque de bicicletas y la venta de unidades y que ha experimentado un gran crecimiento en los últimos años.

En el año 2018, se produjeron 102.299 accidentes en España, de los que 37.892 se produjeron en carretera y 64.407 en ámbito urbano. De este total, en 7.598 accidentes estuvieron implicados ciclistas, de los que 2.143 fueron accidentes en carretera mientras que 5.465 fueron en urbano. Entre 2003 (año de referencia de la importante mejora de la mortalidad general en accidentes de tráfico y a partir del cual se invierte la tendencia de accidentes con ciclistas) y 2018, el número de accidentes con bicicletas aumentó el 236%, mientras los accidentes totales lo hicieron el 2%.

Los datos relacionados con la accidentalidad de ciclistas ponen de relieve la necesidad de estudios rigurosos para la comprensión del fenómeno y los factores de influencia que motiven la aplicación de medidas de intervención adecuadas. En este trabajo se presenta el análisis de la evolución de los accidentes con lesionados ciclistas y la identificación de patrones accidentológicos de ciclistas con técnicas estadísticas de análisis clúster, de los microdatos de las Bases Generales de Accidentes (BGAs) de los años 2000 – 2015.

Entre los patrones identificados se destaca el bajo uso del casco entre ciclistas en ámbito urbano y sobre todo entre mujeres y jóvenes, lo que puede motivar acciones especialmente dirigidas para campañas de concienciación y control entre los colectivos identificados.

1. JUSTIFICACION DEL TRABAJO

El uso de la bicicleta en España es aún reducido, se viene incrementando de manera significativa en los últimos años, como medio muy atractivo para incrementar el ejercicio físico de muchos ciudadanos y como modo de transporte, especialmente en ciudad. Los poderes públicos están fomentando el uso de este medio, ofreciendo infraestructuras especiales o mejor adaptadas, tanto en entornos urbanos como en áreas periurbanas. Se desconoce el tamaño del parque de bicicletas y su evolución, aunque las ventas de este tipo de vehículos reflejan un gran crecimiento. En el año 2018, se produjo un notable incremento de las ventas si se consideran como referencia las 800.000 unidades del año 2011, y el mercado muestra una gran estabilidad, por encima del 1.000.000 de unidades. En la Unión Europea, las ventas oscilan entre 20 y 21 millones de bicicletas en los últimos años.

En la medida que se incrementa el uso de la bicicleta, el riesgo de accidentes con implicación de estos vehículos y el correspondiente balance de víctimas, tiende a crecer, y, si bien su número sigue siendo muy reducido en relación con los accidentes y víctimas totales, la proporción entre ellos crece especialmente desde el año 2004, con mayor tasa de incremento en zona urbana, debido a la evolución del número de heridos leves y graves en estos accidentes.

Entre 2010 y 2018, el número de víctimas mortales entre lesionados ciclistas, pasó de 67 a 58 que representa una reducción del 13%; mientras que el número de heridos graves se incrementó en un 124% (de 467 a 620) y el número de heridos leves en un 124% aumentando de 2.962 a 6.633, correspondiendo las mayores tasas de variación de heridos graves y leves al ámbito urbano.

En términos relativos, en 2010 el número de víctimas mortales en accidentes con ciclistas representó un 2,7% de las totales por accidente de tráfico mientras que en el año 2018 este porcentaje fue del 3,2%.

En los países de la UE este fenómeno es análogo, aunque el mayor uso de la bicicleta en algunos países hace que los valores sean distintos a los españoles. En función de los datos europeos disponibles en el periodo 2005-2016; el porcentaje de víctimas mortales de ciclistas en relación a los totales pasó de un 7% a un 8% en el conjunto de la UE; el cambio para España fue del 1,8 al 3,2%, en Holanda fue de 20 a 19%, en Dinamarca del 12 al 15% y en el Reino Unido de 5 a 6%. República Checa y Noruega experimentaron incrementos de 6 puntos porcentuales y representan los valores más altos de la UE.

Los anteriores datos nos indican que la contribución de los accidentes con ciclistas implicados al balance general de accidentes y víctimas de tráfico puede seguir creciendo en España y, por tanto, se trata de un colectivo que debe ser estudiado en profundidad.

Este estudio, realizado por un equipo investigador del INSIA de la UPM, en el marco de la Cátedra Universidad-Empresa Eduardo Barreiros y financiado por la Fundación Eduardo Barreiros, tiene como finalidad contribuir al conocimiento de los factores de mayor influencia en los accidentes con ciclistas implicados y de ofrecer conclusiones de interés para la adopción de medidas orientadas a reducirlos. Aparicio et al. (2020).

2. DATOS ESTADISTICOS DE ACCIDENTES Y VÍCTIMAS CICLISTAS.

2.1 Evolución de los accidentes con implicación de ciclistas

En el año 2018, se produjeron 102.299 accidentes en España, de los que 37.892 se produjeron en carretera y 64.407 en ámbito urbano. De este total, en 7.598 accidentes estuvieron implicados ciclistas de los que 2.143 fueron accidentes en carretera mientras que 5.465 fueron en urbano.

En el periodo de 1993 a 2018 los accidentes de tráfico con implicación de bicicletas presentan un comportamiento de ascenso notable hasta los casi 7.600 del último año y ha sido espectacular desde 2004. Figura 1.

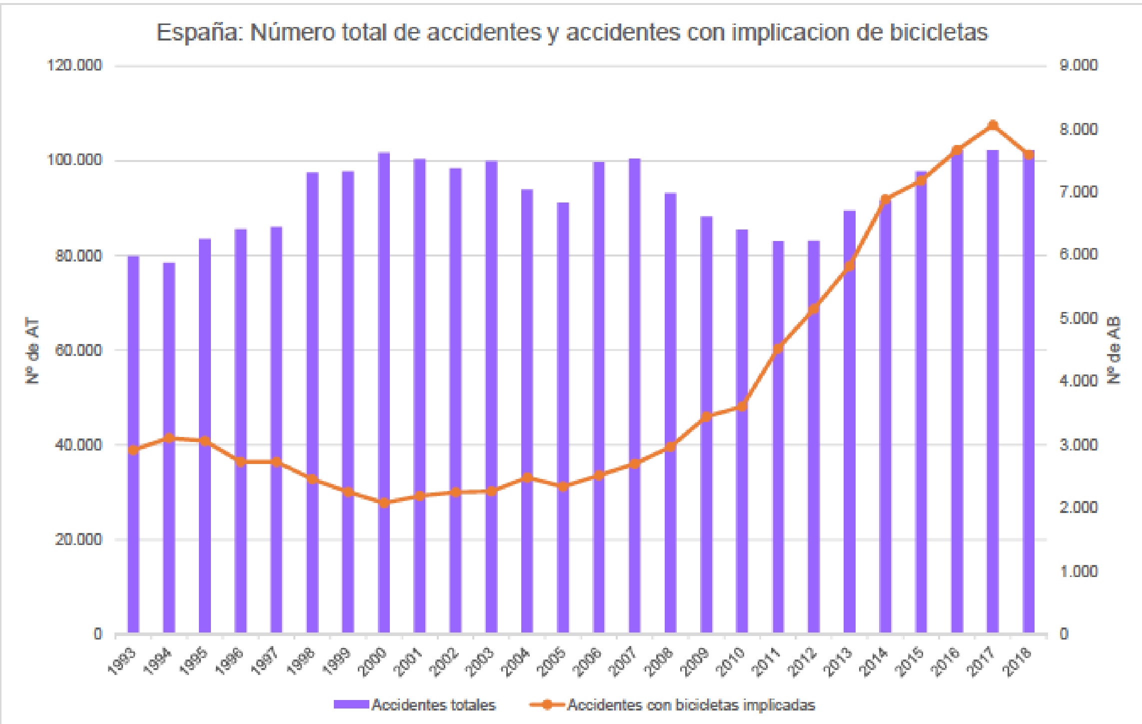

Figura 1: España: accidentes totales y con bicicletas implicadas. 1993-2018. (Fuente: DGT)

Entre 2003 (año de referencia de la importante mejora de la mortalidad en carretera y a partir del cual se invierte la tendencia de accidentes con ciclistas) y 2018, el número de accidentes con bicicletas aumentó el 236%, mientras los accidentes totales lo hicieron el 2%.

El mayor aumento de accidentes con bicicletas se observó en zona urbana que alcanzó el 272% frente al aumento del 23 % de los accidentes totales en la misma zona. Los accidentes con bicicletas en zona interurbana aumentaron: en 168% frente al descenso del 20% que experimentó el conjunto de la accidentalidad cuando se consideran todos los vehículos.

En formato de número Índice (Año 1993=100) los accidentes con bicicletas se han multiplicado por 3 en ciudad y prácticamente por 2 en carretera. Desde 2010, la evolución de este índice referido al total de accidentes muestra el ascenso de los accidentes en ciudad y un comportamiento muy estable en torno al índice 100 en carretera.

La implicación de bicicletas en accidentes de tráfico (en % del total de vehículos implicados) tiene tendencia creciente tanto en carretera como en ámbito urbano desde el año 2000 hasta 2014, a partir del cual se produce un estancamiento.

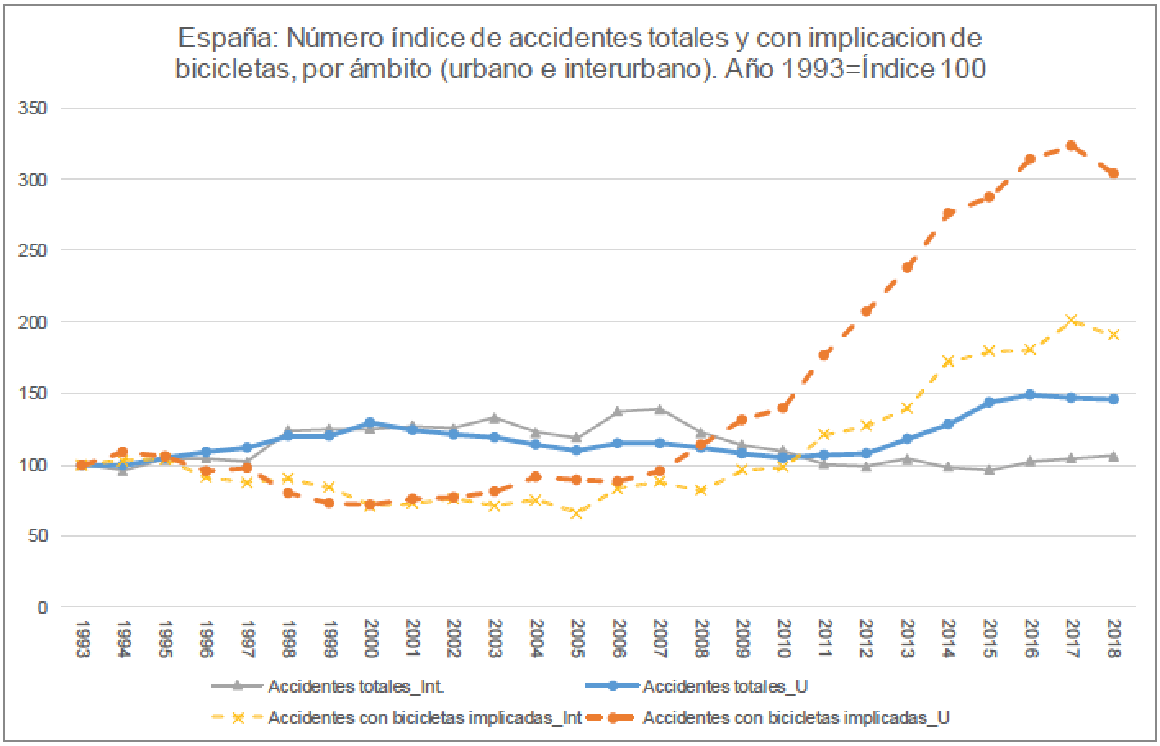

Figura 2: España: Número índice de accidentes totales y con implicación de bicicletas. Año 1993=Índice 100. (Fuente: DGT).

Desde el año 2000, la implicación de bicicletas en accidentes de tráfico en carretera pasó del 1,1% al 3,6% y en vías urbanas del 1,3% al 5,0 % en 2018. La implicación de bicicletas en accidentes en vías urbanas fue superior al de carretera en la serie completa de años y su tasa de crecimiento es más acelerada que la de vías interurbanas.

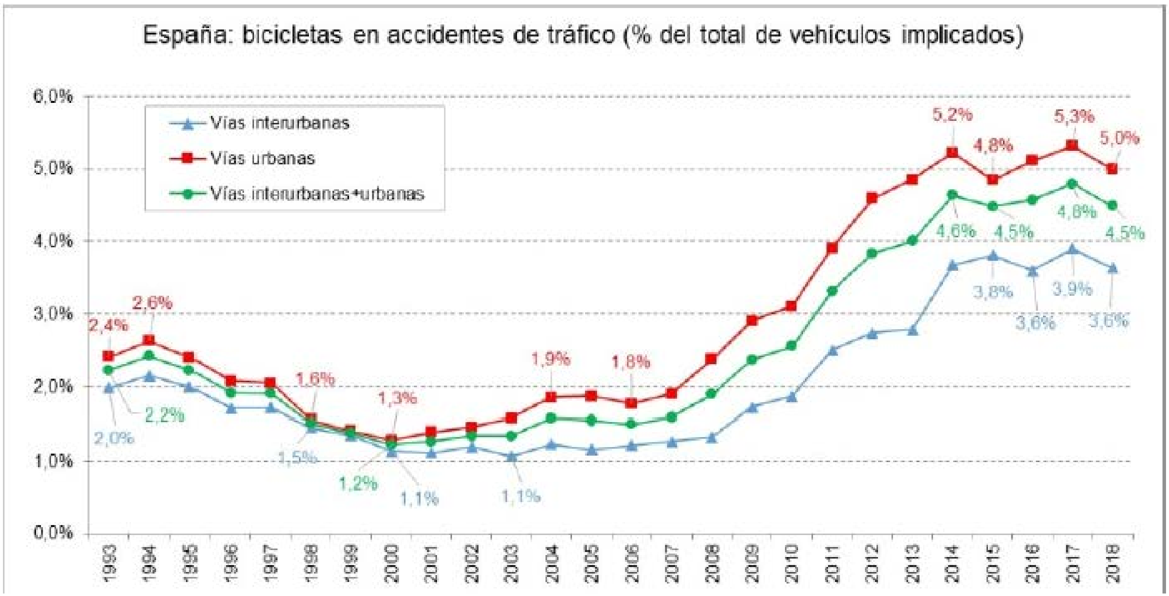

Figura 3: España. Bicicletas implicadas, en accidentes de tráfico en % del total de vehículos implicados. Según ámbito de ocurrencia. 1993-2018. (Fuente: DGT).

1.2 Evolución de los lesionados ciclistas

En el periodo 1993-2018 el número de conductores de bicicletas muertos en carretera presenta una tendencia decreciente, con fluctuaciones en todo el período. El valor máximo fue de 118 en 1994 y el mínimo de 37 en 2011, a partir del cual los valores fluctúan entre 40 y 50. En zona urbana, se aprecia un estancamiento y los valores fluctúan entre 20 y 40, con valor máximo de 39 en 1993 y el mínimo de 10 en 2015. Sin embargo, en 2016 y 2017 la serie ha recuperado los niveles de 1993.

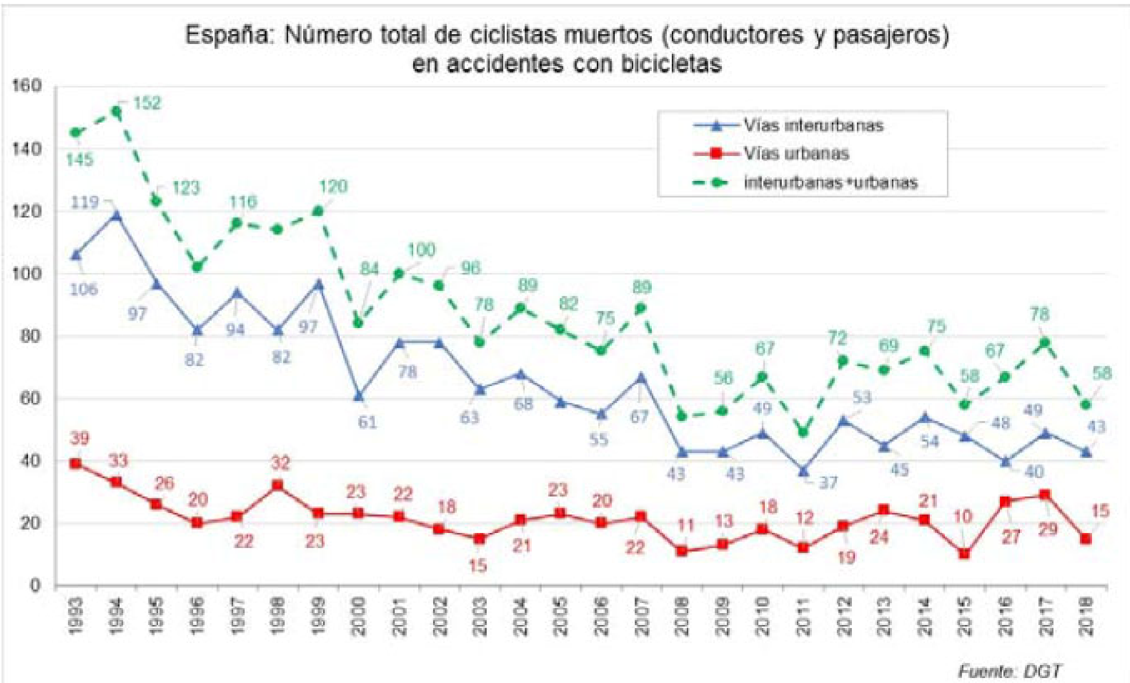

Figura 4: Total de fallecidos en accidentes con bicicletas por zona de ocurrencia España 1993-2018. (Fuente: DGT).

El 99% de las víctimas son conductores de la bicicleta. Las cifras de muertos en carretera son significativamente más elevadas que en zona urbana.

De media, el 75% de víctimas mortales se producen en accidentes en carretera, mientras que el 25% en calles urbanas. El peso porcentual de víctimas mortales en accidentes en carretera con bicicletas relativo al total de víctimas en esos accidentes, ha bajado desde el máximo de 83% en 2015 al 74% en 2018, pero solo ha cambiado en 1 punto porcentual en todo el periodo. En urbano el peso ha cambiado del 27% al 26% en todo el período.

El porcentaje de víctimas mortales en accidentes de tráfico con implicación de bicicletas en el periodo 1993-2018 según zonas (en términos relativos al total de víctimas fatales en accidentes de tráfico), ha aumentado en zona urbana hasta el 5,7% frente al 3,4% en interurbano en el año 2018.

La evolución desde 1993, de ambos números en paralelo en la Figura 5 muestra el descenso claro e importante de las muertes totales, frente al estancamiento de la mortalidad de ciclistas y hasta un repunte en los últimos años, que coloca el último registro al nivel de la década del 2000 y pone de manifiesto la atención que merece este colectivo en particular. Como ya se dijo, el año 2003 marcó un hito para la mejora de la política de seguridad vial española con un descenso acumulado del 67% de la mortalidad hasta el año 2018, por la mejora en ámbito interurbano fundamentalmente con una reducción del 71% y una aportación del ámbito urbano del 47%. En el mismo período la mortalidad en accidentes con ciclistas experimentó sólo el 25,6% de mejora. Las víctimas mortales en urbano en el año 2018 igualaron las de 2003 (15 ciclistas muertos) mientras que las habidas en carretera bajaron el 31,7%.

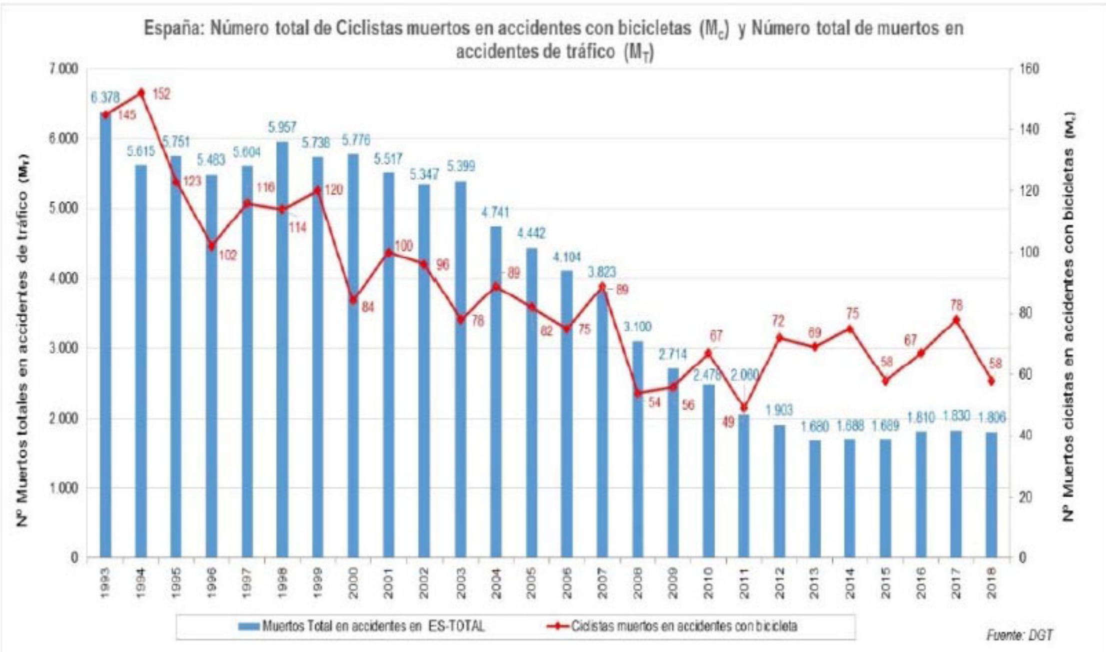

Figura 5: Total de muertos en accidentes de tráfico y en accidentes con bicicletas implicadas. (Carretera+urbano). España 1993-2018. (Fuente: DGT).

En la Figura 6 se muestra la evolución del indicador Muertos por accidente (en los totales (AT) y en los que han estado implicados bicicletas (AB). (Valor índice 100=año 1993) y se aprecia la evolución favorable hasta 2014 en ambos casos, con un estancamiento en ambas series hasta el último año.

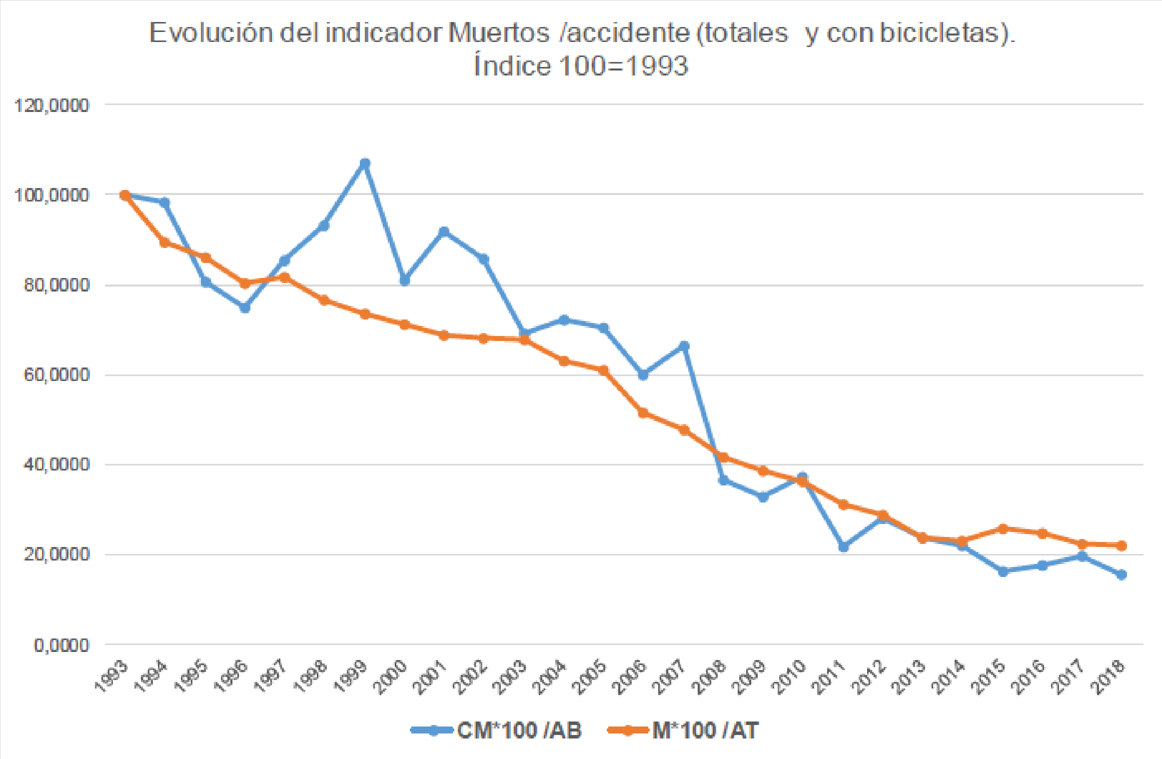

Figura 6: España: Indicador Muertos por accidente (totales y con implicación de bicicletas). 1993-2018. Valor índice 100=año 1993. (Fuente: DGT).

En la Figura 7 se muestran los valores absolutos de los heridos graves en accidentes de tráfico con ciclistas y su peso porcentual de las producidas en accidentes totales. La evolución de ambas es creciente en prácticamente todo el período con un importante aumento de su peso porcentual: la incidencia de ciclistas heridos graves en 2018, ha multiplicado por más de 4 veces el valor de 2001.

En la Figura 8 se muestran los valores absolutos de los heridos leves en accidentes de tráfico con ciclistas y su peso porcentual de las producidas en accidentes totales. La evolución de ambos es creciente desde 2001 en el que se produjo el valor mínimo de 1,3% y no ha parado de crecer: hasta alcanzar el valor máximo de 5,5% en 2017, en el que ha multiplicado por más de 4 veces el valor mínimo indicado. En el año 2018 el peso porcentual ha descendido sólo 4 décimas.

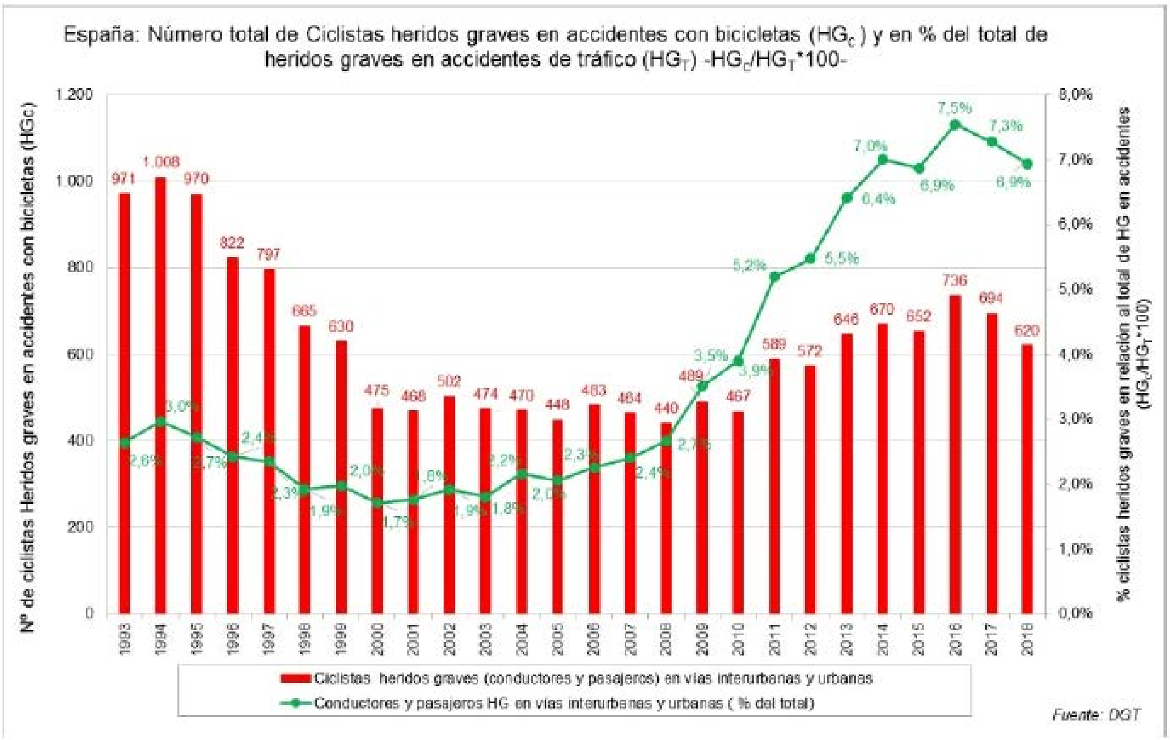

Figura 7: España. Número de ciclistas heridos graves en accidentes con bicicletas (HGC) y su porcentaje en relación al total de heridos graves en accidentes de tráfico (carretera+urbano) (HGT). 1993-2018. (Fuente: DGT).

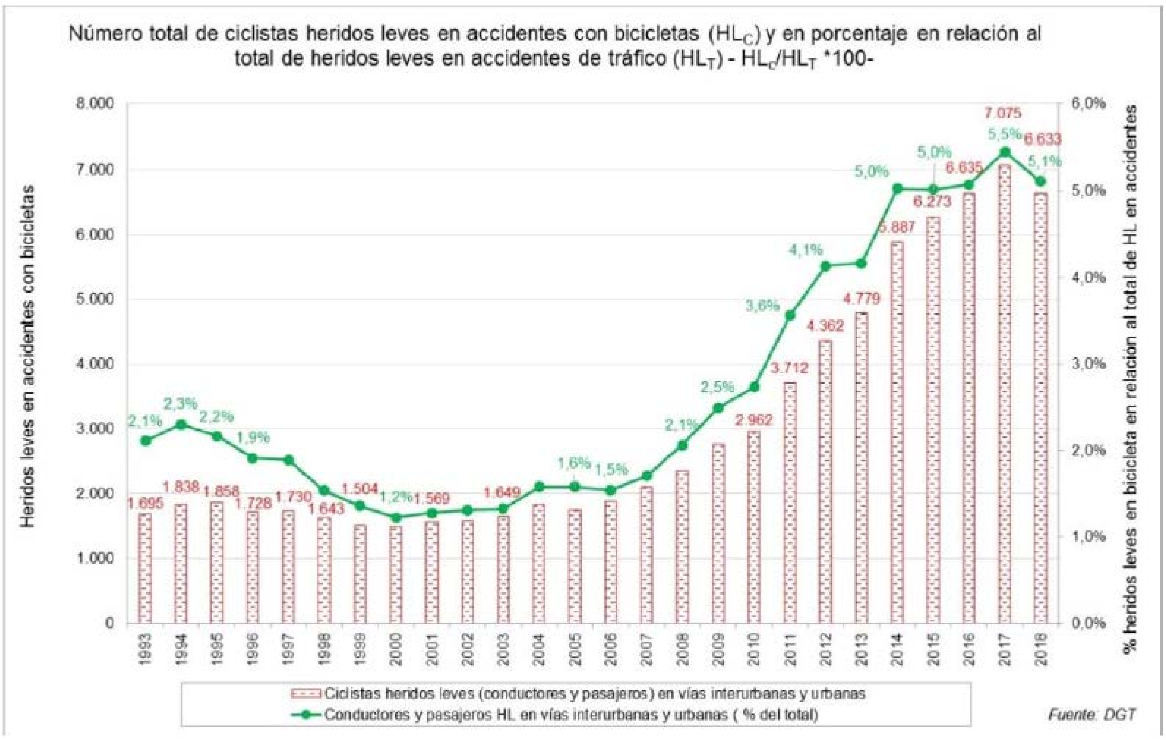

Figura 8: España.Total de ciclistas heridos leves en accidentes con bicicletas (HLC) y su porcentaje en relación al total de heridos leves en accidentes de tráfico (carretera+urbano) (HLT). 1993-2018. (Fuente: DGT).

2. IDENTIFICACIÓN DE PATRONES ACCIDENTOLÓGICOS DE CICLISTAS

Las variables de la base de datos creada para estos modelos fueron: género, edad, grado de lesividad, infracción del conductor/ciclista, infracción de velocidad e infracción administrativa. El periodo analizado corresponde al periodo 2000 a 2015.

2.1 Técnicas estadísticas de análisis clúster

Para la identificación de patrones de accidentalidad de bicicletas se han aplicado técnicas estadísticas de análisis de conglomerados o clúster y dentro de esta categoría, se han seleccionado los mapas autoorganizativos (Self organizing Maps- SOM) por su rapidez de interpretación. Los mapas SOM forman parte del campo de Machine Learning y ponen de manifiesto las asociaciones multivariante más frecuentes que explican la ocurrencia de accidentes. Las primeras referencias al SOM se encuentran en los artículos de Kohonen (1982), Kohonen (1990), Kohonen (1995), Kohonen (1998), y en los trabajos Von der Malsburg (1973), Rumelhart y Zipser (1985) y Willshaw & Von Der Malsburg (1976) sobre aprendizaje competitivo (competitive learning).

La metodología Self-Organizing Maps (SOM) de clúster ha sido aplicada a diferentes campos, siendo su aplicación en el ámbito de los accidentes de tráfico, más limitada. Hu et al. (2004) propusieron un modelo probabilista para predecir los accidentes de tráfico mediante la monitorización 3D de los vehículos. Para ello, se usó un modelo SOM difuso, con el objetivo de aprender patrones de actividad para las rutas de muestra. En el artículo de Chen et al. (2006), se aplicó SOM con el propósito de revelar patrones de tráfico regionales específicos. Por su parte, Liu (2009) desarrolló un modelo analítico para aprender acerca de la asignación de responsabilidad en accidentes de tráfico en Taiwan. Tiwari et al. (2017) aplicaron las técnicas de SOM, así como otras herramientas de Data Mining, para analizar los accidentes de tráfico con el objetivo de analizar los diferentes tipos de atributos que contribuyen a que se produzca el accidente, entre ellos el tipo de vehículo (bicicleta entre otros). Por último, debe mencionarse el trabajo realizado por Giacomo et al. (2012), quienes estudiaron accidentes de peatones aplicando técnicas de clúster, con el fin de identificar patrones que pudiesen ayudar a diseñar medidas preventivas y asignar recursos para los problemas identificados en los accidentes de tráfico mortales de Israel entre 2003 y 2006 y en especial dirigidas a los usuarios más vulnerables de la carretera, entre los que se encuentran los ciclistas.

3. RESULTADOS

El mapa de calor de la implicación de ciclistas en razón de género y en accidentes según la zona de ocurrencia del accidente se muestra en la Figura 9. La variable sexo toma valor 1 cuando el ciclista es varón y 0 cuando es, los nodos aparecen de color rojo y azul respectivamente.

En el mapa de la Figura 9 se observa que predomina el género masculino, solo un 15% de los ciclistas implicados son mujeres ciclistas y requiere estudios que consideren la exposición de cada colectivo.

Las mujeres ciclistas, en general, han estado mayoritariamente implicadas en accidentes ocurridos en vías urbanas (alrededor del 84%).

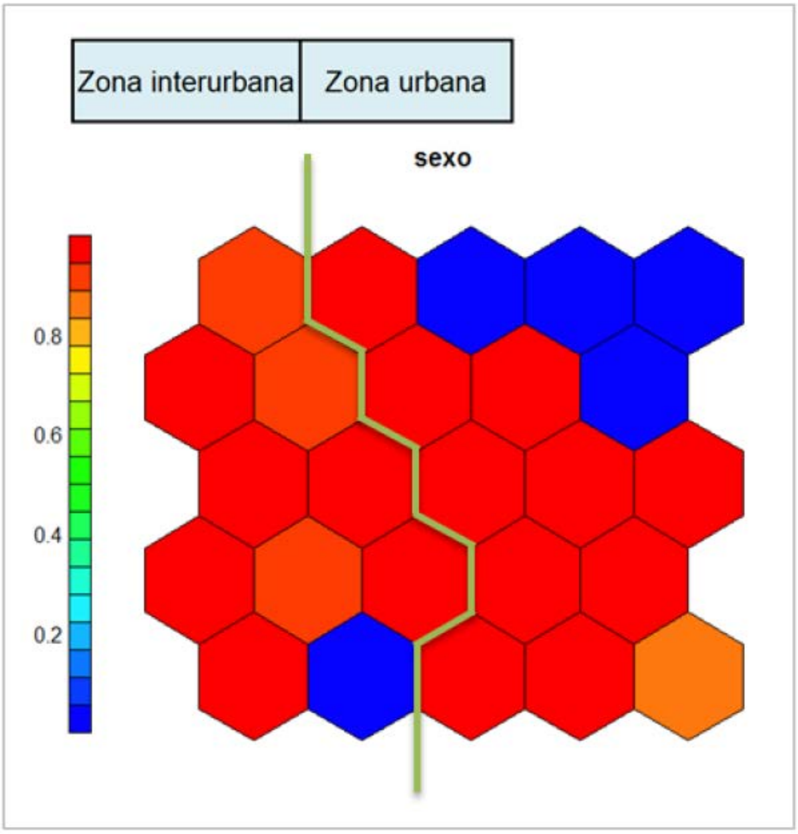

Figura 9: Mapa de calor para "sexo" en el mapa SOM. (Fuente: Elaboración propia a partir de las BGAs).

En el mapa de calor de la variable lesividad (Figura 10), se puede observar cómo en el área derecha, que corresponde a la zona urbana, la lesividad de los ciclistas es, en general, menor en comparación con la que se observa en la zona interurbana. En color azul lesividad baja (valores próximos a 0); en verde cuando la lesividad es media (valores próximos a 0,5); y en color rojo cuando la lesividad es alta (valores próximos a 1).

Dentro de la zona urbana también hay un nodo de alta lesividad, el nodo naranja C53, que alberga en torno a 500 ciclistas. Sin embargo, el nodo de alta lesividad que está incluido en la zona interurbana, nodo rojo C41, contiene más de 1.000 ciclistas.

En los accidentes ocurridos en zona interurbana la lesividad es, en general, mayor con más heridos graves y muertos en relación a los accidentes ocurridos en zona urbana, donde predominan fundamentalmente los heridos leves.

También es importante señalar que los accidentes mortales, a pesar de que predominen en la zona interurbana, son un parte pequeña en comparación con el resto de accidentes que sufren los ciclistas, tal y como se muestra en la escala del mapa de lesividad, donde el nivel 1 (muertos) no llega a estar representado, y el valor máximo del vector de peso es de 0,75 como se muestra en la Figura 10.

En relación a la lesividad, se observa que, en general, las mujeres presentan una lesividad media leve, siendo complicado sacar conclusiones sólidas acerca de la lesividad de los varones, dado que su presencia está muy distribuida a lo largo del mapa, debido a su elevada presencia en el estudio en comparación con su contraparte femenina.

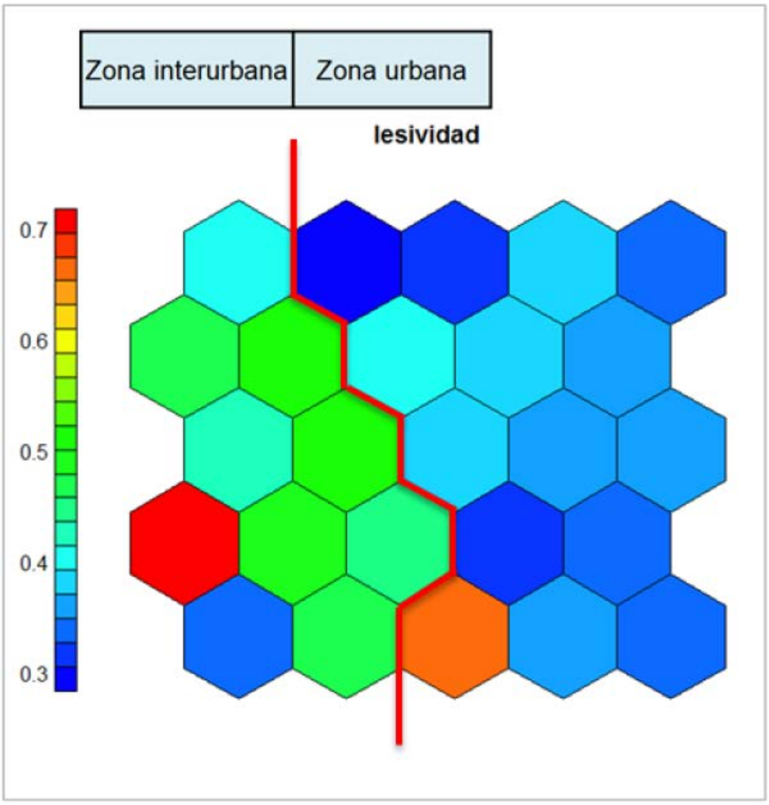

Figura 10: Mapa de calor para “lesividad” en el SOM. (Fuente: Elaboración propia a partir de las BGAs).

Otros mapas SOM con la edad indican que, entre los ciclistas más mayores (50-64 años y mayores de 65), se observa una escasa presencia de mujeres, frente a este colectivo entre los varones. Este patrón está en consonancia con el detectado en la conducción de turismos, donde se observa que la presencia de mujeres disminuye en las edades más avanzadas.

En la Figura 11 aparecen representado en azul los porcentajes de ciclistas de cada nodo que estaban usando el casco. De todos los ciclistas involucrados en accidentes observados en este análisis, de media el 26,5% estaban usando el casco y el resto no. De media el 40% de los ciclistas lo usaba cuando se produjo el accidente en una vía interurbana y sólo el 14% cuando se produjo en vía urbana.

En el nodo C51, se identifican 2.967 ciclistas, con el mayor porcentaje de uso del casco 66% frente al 34% que no usaban casco en el momento de ocurrencia del accidente en una carretera.

A primera vista en el mapa con los porcentajes, se observa que a la izquierda del mapa el porcentaje de ciclistas que usan casco es significativamente mayor. Si lo comparamos con el mapa SOM con la variable "zona", se ve claramente cómo la zona de ciclistas con mayor porcentaje de uso de casco coincide con la parte del mapa en la que predominan los accidentes ocurridos en zona interurbana.

Se resaltan algunos ejemplos de grupos que requieren algún tipo de atención: 1) en el clúster C52 hay 582 accidentes ocurridos con ciclistas mujeres de edad media, que han resultado con severidad media y entre las que el 59% no usaban el casco, 2) en el clúster C41 se clasifican 1.201 accidentes en los que el 48% de los ciclistas (mayoritariamente varones de edad media) no usaban el casco y han resultado con severidad alta, 3) los clústers C22, C32 y C43 presentan los porcentajes más altos de no uso de casco en medio interurbano (86, 83 y 72% respectivamente).

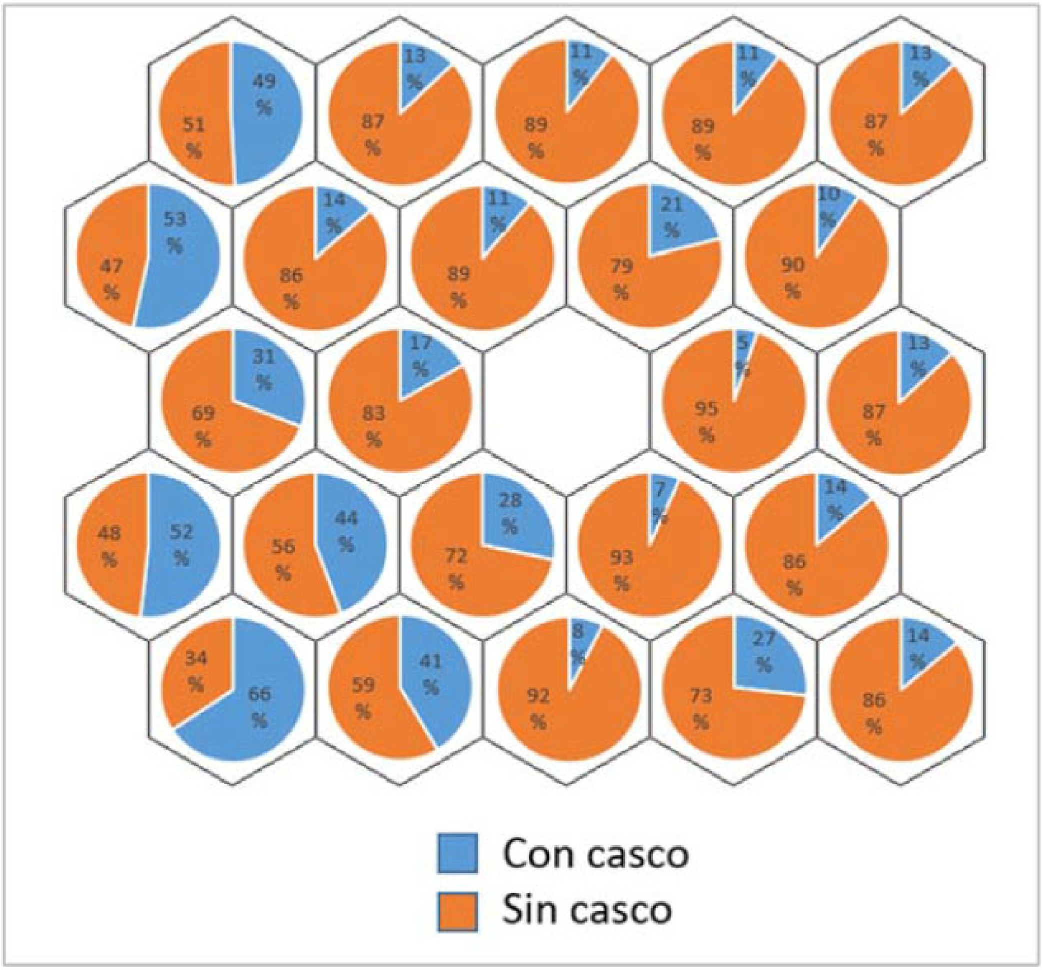

Figura 11: Mapa de uso del casco (en porcentaje) en el mapa SOM. (Fuente: Elaboración propia a partir de las BGAs).

3.1 Aceptación o rechazo de las hipótesis de trabajo

A continuación, se transcriben 3 de las 10 hipótesis formuladas en el proyecto de investigación seleccionadas para el análisis con los mapas SOM en éste trabajo.

- H(a). "Los ámbitos de uso de las bicicletas: urbano e interurbano, así como de diferentes infraestructuras en cada uno de ellos (vías convencionales, vías de alta capacidad, intersecciones, etc.) ejerce influencia en los patrones accidentológicos de los ciclistas".

Para verificar o rechazar la H(a) se han realizado el estudio de la evolución temporal de la accidentalidad por tipo de vía y zona de los datos contenidos en las BGAs, así como el ajuste de mapas SOM para la identificación de los patrones de accidentes según la zona. Hay mayor severidad en accidentes en vías interurbanas.

Los resultados parciales de los resultados mostrados contribuyen a la verificación de la hipótesis H(a). Otros mapas SOM y los patrones multivariantes encontrados permiten concluir que se ha verificado la hipótesis H(a).

- H(b). "Los diferentes colectivos de ciclistas: grupos de edad y género, presentan, también patrones accidentológicos diferentes".

La verificación o rechazo de la hipótesis H(b) se ha abordado mediante el estudio estadístico de las BGAs y la identificación de patrones por sexo y rangos de edad con los mapas SOM. Hay más ciclistas varones y mayores en accidentes interurbanos que mujeres y más mujeres de hasta 50 años en accidentes urbanos.

Los resultados parciales de los resultados mostrados contribuyen a la verificación de la hipótesis H(b). Otros mapas SOM y los patrones multivariante encontrados permitenconcluir que se ha verificado la hipótesis H(b).

- H (c). El uso de medios de protección adecuados, especialmente del casco, ejerce influencia en la severidad de las lesiones en caso de accidente.

Para esta hipótesis (H(c) la variable uso – no uso de casco se abordó en el estudio estadístico de las BGAs y en la identificación de patrones mediante los mapas SOM. Los patrones complejos de SOM indican que el tipo de vía y zona influyen en esta variable de comportamiento de los ciclistas.

Hay diferencias entre entorno urbano-interurbano. Los mapas SOM identifican comportamientos multivariantes y el sexo y la edad son factores relevantes en el patrón de uso-no uso de casco. Su no uso resulta en accidentes más severos. Se considera verificada la hipótesis H(c).

4. CONCLUSIONES

La implicación de bicicletas en accidentes de tráfico (en % del total de vehículos implicados) tiene tendencia creciente tanto en carretera como en ámbito urbano. La implicación de bicicletas en accidentes en vías urbanas fue superior al de carretera en la serie completa de años y su tasa de crecimiento es más acelerada que la de vías interurbanas, lo que es un indicador de su mayor uso en las ciudades por la incorporación de la bicicleta como medio de desplazamiento cotidiano.

Aunque el porcentaje de víctimas mortales en accidentes de tráfico con implicación de bicicletas en el periodo 1993-2018 según zonas (en términos relativos al total de víctimas fatales en accidentes de tráfico), ha aumentado en zona urbana hasta el 5,7% frente al 3,4% en interurbano en el año 2018.

La reducción observada en la mortalidad total (-67% entre 2003 y 2018) es mayor que la de ciclistas (-25,6% en el mismo período) y marca una línea de trabajo enfocada en este colectivo para una mayor contribución a la mejora de la seguridad vial en España.

A través de los mapas SOM se han identificado patrones de accidentes de ciclistas, y se concluye que la zona de ocurrencia y el sexo son factores relevantes en la identificación de patrones en accidentes y severidad de lesiones de ciclistas.

La lesividad de los ciclistas en accidentes urbanos es menor que la que se observa en la zona interurbana.

El porcentaje de mujeres ciclistas es reducido respecto al de hombres tanto en zona interurbana como urbana, siendo esta diferencia mayor en vías interurbanas.

El no uso de casco deviene en mayor lesividad y hay diferencias en el uso en entorno urbano e interurbano que requiere medidas de vigilancia adecuadas.

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IMPACT ON URBAN MOBILITY OF PREVENTIVE MEASURES AGAINST COVID-19 DURING THE STATE OF ALARM. THE PARTICULAR CASE OF A MEDIUM-SIZED CITY

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RESUMEN

La gran Pandemia mundial, como consecuencia de la COVID-19, no sólo ha afectado a nuestra salud sino a toda nuestra forma de vivir la vida. El Gobierno ha propuesto distintas medidas con el objetivo de reducir su expansión entre las que se encuentran el mantenimiento de una distancia mínima interpersonal, el uso de mascarilla en espacios cerrados y la higiene constante.

Estas imposiciones, unidas a la posibilidad de teletrabajar ofertada por algunas empresas y a la responsabilidad personal han modificado los patrones de comportamiento en cuanto a la movilidad urbana se refiere.

La población ha tendido a reducir sus viajes, priorizando determinados destinos y, en algunos casos, modificando su elección modal habitual hacia modos individuales en vez de colectivos. Este cambio de tendencia es factible en ciudades de tamaño pequeño y mediano en las que las distancias a recorrer no son relativamente excesivas y los usuarios tienen la opción de desplazarse a pie o en bicicleta en vez de usar el autobús o decantarse por el uso del vehículo privado.

El objetivo de este artículo es analizar la variación en el flujo de tráfico desde un estadio prepandémico al estadio actual en una ciudad de tamaño medio. Para ello, se han tomado mediciones mediante un radar, en la ciudad de Burgos, en una serie de puntos de referencia situados en vías de zonas de alta y baja demanda de tráfico y se han comparado con datos de IMD y velocidad obtenidos en esas mismas secciones respetando la estacionalidad, los días y las horas de la toma de datos para comprobar la variación sufrida.

El análisis de los resultados ha permitido comprobar que las medidas impuestas, como el teletrabajo y las medidas de distanciamiento social, han tenido repercusión en la movilidad, reduciendo la intensidad de tráfico de la ciudad de Burgos y hacen reflexionar sobre si estos resultados obtenidos se mantendrán a lo largo del tiempo o evolucionarán hacia los valores prepandémicos.

1. INTRODUCCIÓN

La pandemia mundial del coronavirus SARS-CoV-2, conocido como COVID-19, ha tenido, y sigue teniendo, un gran impacto en la vida cotidiana a nivel mundial. Ha conseguido alterar los patrones de comportamiento referentes a la vida laboral, vida familiar y al modo de desplazarnos o de hacer compras intentando evitar riesgos en todo momento (Eisenmann et al., 2021; Hörcher et al., 2021; Fischer and Winters, 2021; Cazelles et al., 2021; Barbieri et al., 2021; Aloi et al., 2020).

En la primavera de 2020, con objeto de reducir la propagación del COVID-19, se cerró la educación y el sector del ocio y restauración. El teletrabajo y el comercio on line pasaron a formar parte de nuestro día a día y la mascarilla y el gel hidroalcohólico se alzaron como accesorios indispensables para reducir la propagación del virus (Abboah-Offei et al., 2021).

Las medidas de presión impuestas durante el estado de alarma se fueron suavizando durante los distintos intentos de desescalada lo que derivó en distintos repuntes de los casos que llevaron a sufrir distintas olas de contagios como justifican Cazelles et al. (2021). En el caso particular español, se sufrieron hasta un total de cinco olas de contagio, con picos en los meses de marzo, septiembre y octubre de 2020 así como enero y abril de 2021 (RNVE, 2021).

La posibilidad de teletrabajo ofertada por algunas empresas y la responsabilidad personal han llevado a la población a reducir sus viajes, priorizando determinados destinos y, en algunos casos, modificando su elección modal habitual hacia modos individuales en vez de colectivos.

Este cambio de tendencia es especialmente factible en ciudades de tamaño pequeño y mediano en las que las distancias a recorrer no son relativamente excesivas y los usuarios tienen la opción de desplazarse a pie, en bicicleta o patinete en vez de usar el autobús o decantarse por el uso del vehículo privado.

El miedo de los usuarios a sufrir contagios en el transporte público o la propia percepción de inseguridad ha derivado en una reducción a nivel mundial del transporte público colectivo (Barbieri et al., 2021). Ese traspaso hacia modos de transporte no colectivos ha suscitado muchísimo interés en la comunidad científica.

Desde Bohman et al. (2021) que desarrolló su investigación en Suecia, país que no sufrió medidas de confinamiento estricto hasta múltiples estudios realizados por todo el mundo como los de Basu and Ferreira (2021), Jiao and Azimian (2021), Souch et al. (2021) en Estados Unidos, Fischer and Winters (2021) en Canadá, Dingil and Esztergár-Kiss (2021) y Nikitas et al. (2021) y Dingil and Esztergár-Kiss (2021) en el Reino Unido, Eisenmann et al. (2021) y Anke et al. (2021) en Alemania, Borkowski et al. (2021) y Wielechowski et al. (2020) en Polonia, Cazelles et al. (2021) en Francia, Aloi et al. (2020) y Orro et al. (2020) en España o Campisi et al. (2020) y Barbarossa (2020) en Italia.

Muchos de estos estudios han detectado que la migración hacia otro modo de transporte es dependiente de los grupos socio demográfico y que, por tanto, han presentado como variables destacables el sexo, edad, el poder adquisitivo, el puesto de trabajo, el nivel de estudios y el lugar de residencia contribuyendo a la estigmatización del transporte público (Bohman et al., 2021; Borkowski et al., 2021; Hasselwander et al., 2021; Fischer and Winters, 2021; Barbieri et al., 2021; Campisi et al., 2020; Dingil and Esztergár-Kiss, 2021). En Burgos, por ejemplo, donde la mayor parte de los usuarios del transporte público está compuesto por jóvenes, ancianos y mujeres de edad media, el 41% de los burgaleses reconoció que había reducido su uso de los autobuses urbanos durante los últimos meses (MOOVIT, 2021).

Por tanto, como algunos autores han remarcado, estamos ante una gran oportunidad para modificar la movilidad urbana hacia alternativas más sostenibles e incluso podría ser el momento de evolucionar hacia una ciudad planificada de manera más sostenible (Basu and Ferreira, 2021; Eisenmann et al., 2021; Awad-Núñez et al., 2021; Fischer and Winters, 2021; Campisi et al., 2020; Nikitas et al., 2021).

Algunas ciudades, han aprovechado las desescaladas para promover acciones en favor de una reorganización urbana llegando a restringir el tráfico rodado en determinadas calles para permitir el distanciamiento social (Barbarossa, 2020). Este tipo de iniciativas ha conseguido promover los desplazamientos andando, en bicicleta (también en bicicleta de préstamo) y patinete eléctrico, devolviendo la ciudad a los usuarios más vulnerables. Según MOOVIT (2021), Burgos sería una de las tres ciudades españolas en las que más se usa ha usado la micromovilidad en la primera mitad de 2020.

Parece presumible pensar que no toda la migración del transporte público se haya producido hacia modos de transporte sostenibles en contra de las políticas de sostenibilidad que defienden las ciudades europeas. Toda la inversión, tanto económica como humana, realizada en los últimos años, en favor de la potenciación de soluciones eco-responsables, puede llegar a perderse como consecuencia de la sensación de desprotección e inseguridad sufrida al desplazase en transportes públicos colectivos (Orro et al., 2020; Campisi et al., 2020).

Sin embargo, distintos autores han confirmado que tanto en los periodos de confinamiento estricto como en los periodos posteriores, el uso del automóvil se ha visto reducido en base al descenso de los niveles de contaminación ambiental experimentados (Crowley et al., 2021; Querol et al., 2021; Griffiths et al., 2021; Aloi et al., 2020).

El presente artículo tiene por objeto analizar qué es lo que ha sucedido con el tráfico rodado en la ciudad de Burgos una vez alcanzada la "nueva normalidad" justo antes de levantarse el estado de alarma.

Puesto que la nueva ordenanza municipal de tráfico de Burgos (AYTO BURGOS, 2020) entró en vigor en el 24 de enero de 2020, y comparte con la MPR (2020) las limitaciones de velocidad a 30 km/h en calzadas de una vía para cada sentido de circulación, también se ha aprovechado para comprobar qué es lo que está sucediendo con las velocidades en las vías urbanas burgalesas.

2. METODOLOGÍA Y CASO A ESTUDIO

Como ya se ha argumentado, algunos autores han comprobado que se ha producido en algunas ciudades un traspaso de usuarios del transporte público hacia, principalmente, el vehículo privado. Sin embargo, también se ha detectado que en algunos casos el volumen total de vehículos que circulan por las vías urbanas ha descendido. Por tanto, este artículo se centra en averiguar qué es lo que ha sucedido con el tráfico en la ciudad Burgos, ciudad de tamaño medio de 180.000 habitantes situada en la parte norcentral de la península ibérica.

Para ello, se han tomado mediciones mediante un radar móvil en distintos puntos de referencia de la ciudad en los que Gonzalo-Orden et al. (2018) ya habían tomado medidas antes de la pandemia en 2018 (valores prepandémicos) y así comprobar la variación experimentada tras la vuelta a la nueva normalidad (valores en pandemia). Las mediciones fueron tomadas respetando la estacionalidad y la variabilidad semanal. Es decir, se tomaron medidas en el primer cuatrimestre de 2021 los mismos días de la semana y mes en los que se habían realizado en el estudio anterior para así poder compararlos.

Los puntos de medición se dividieron en cuatro tipologías diferentes:

- Tipo 1: hace referencia a vías urbana de alta capacidad
- Tipo 2: hace referencia a zonas de conexión urbana
- Tipo 3: hace referencia a zonas de carácter residencial y zonas de paso
- Tipo 4: Hace referencia a zonas residenciales principalmente periféricas.

A continuación, se detallan los distintos puntos medidos.

2.1 Tipo 1

Esta zona a estudio comprende la Avenida de Caja Círculo (carretera del cementerio) (Fig.1). Se trata de una vía de alta capacidad de dos carriles para cada sentido de circulación que no ha experimentado reducción en su velocidad como consecuencia de la entrada en vigor de la nueva ordenanza de circulación burgalesa.

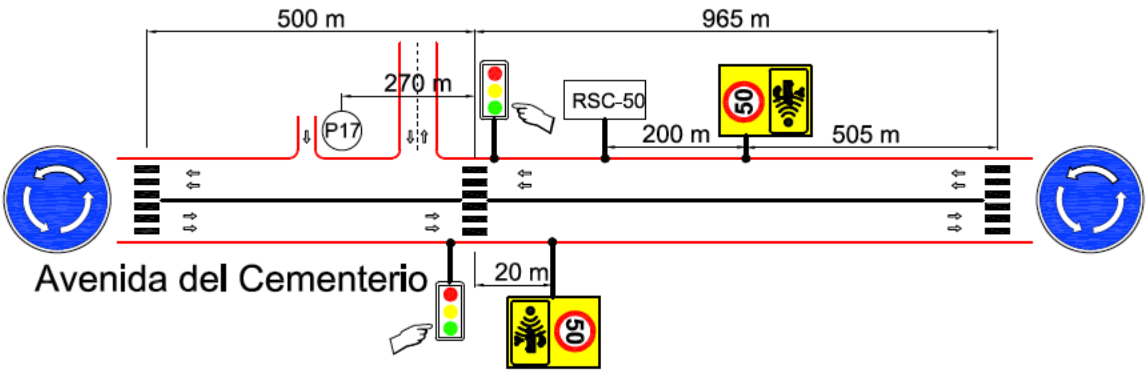

Figura 1: Puntos analizados en zonas tipo 1.

2.2 Tipo 2

La zona a estudio comprende la Av. Arlazón (Fig. 2), Av. Palencia (Fig.3) y la calle Pozanos (Fig.4). Los puntos medidos tanto la Av. Arlanzón (Fig. 2) como la Av. Palencia (Fig. 3) han visto reducida su velocidad a 30 km/h, respecto a la situación de 2018, por tratarse de tramos de un solo carril para cada sentido de circulación.

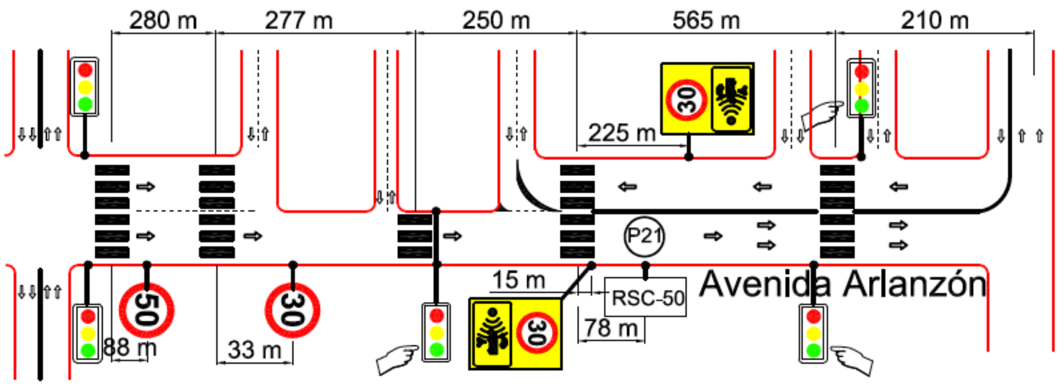

Figura 2: Puntos analizados en Avenida Arlanzón (Zona tipo 2).

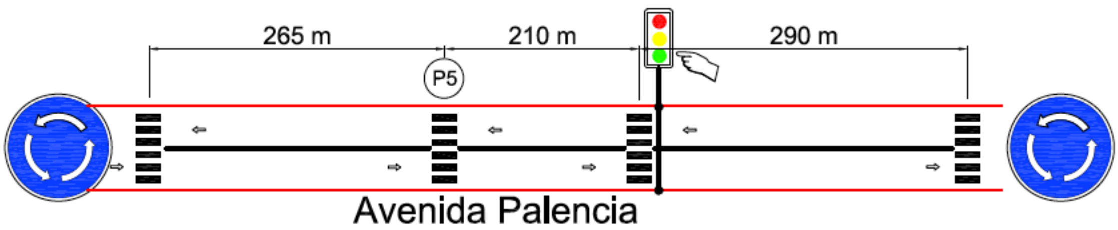

Figura 3: Puntos analizados en Avenida Palencia (Zona tipo 2).

Respecto a la calle Pozanos (Fig. 4), se han realizado modificaciones en su geometría en su primer tramo (Gonzalo-Orden et al., 2016), reduciéndose de dos a un carril para cada sentido. Respecto a la velocidad de esta vía, el tramo a estudio ya estaba reducido a 30 km/h por tratarse de una zona escolar por lo que no ha experimentado ninguna variación.

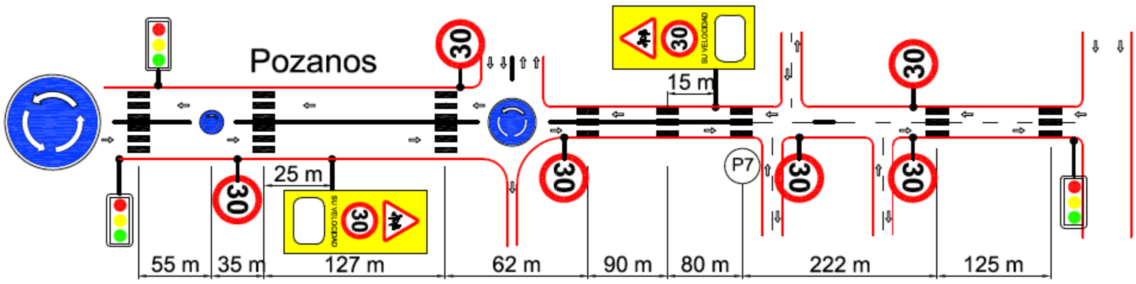

Figura 4: Puntos analizados en Calle Pozanos (Zona tipo 2).

2.3 Tipo 3

Esta zona recoge las vías que pertenecen a zonas residenciales de la zona centro en las que las vías no solo dan servicio a residentes si no que por su carácter central sirven también como vías de paso entre zonas. En esta categoría estarían los puntos pertenecientes a las calles Jose Luis Santamaría y el Carmen (Fig. 5) y el Paseo de la Isla (Fig. 6). Como puede verse en los esquemas, son vías de un solo carril para cada sentido de circulación por lo que su velocidad actualmente está limitada a 30 km/h.

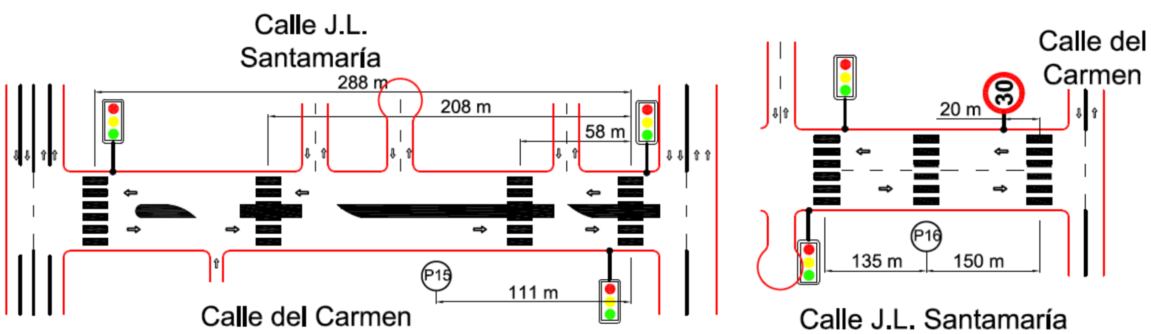

Figura 5: Puntos analizados en las Calles J. L. Santamaría y El Cármen (Zona tipo 3).

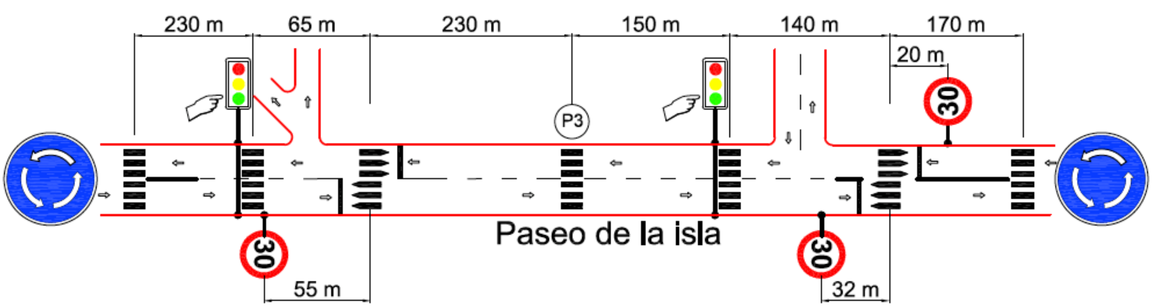

Figura 6: Puntos analizados en Paseo de la Isla (Zona tipo 3).

2.4 Tipo 4

La zona a estudio comprende dos puntos pertenecientes a zonas residenciales periféricas en las que el paso de vehículos es principalmente de residentes (Fig. 7). De igual manera a los casos anteriores, su geometría hace que la velocidad actual en esos puntos se haya reducido a 30 km/h.

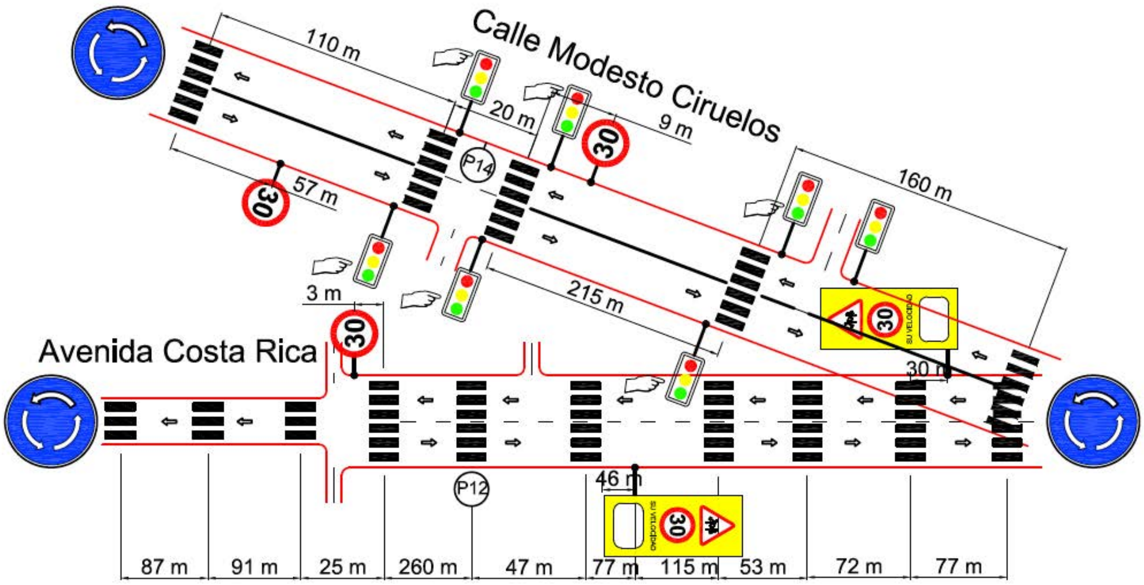

Figura 7: Puntos analizados en Zona tipo 4.

3. RESULTADOS Y DISCUSIÓN

La tabla 1 recoge los valores medidos en los puntos seleccionados en un periodo prepandémico (Gonzalo-Orden et al., 2018) y en el primer cuatrimestre del 2021 cuando todavía no se ha levantado el estado de alarma por la pandemia del COVID-19.

Año	Zona a estudio	1	2			3			4	
	Punto medido	P17	P21	P5	P7	P15	P16	P3	P12	P14
2018	Intensidad de tráfico (Veh/h)	1326	416	604	753	460	251	430	72	240
	Velocidad V_{50} (km/h)	59	44	55	42	29	40	45	44	56
	Velocidad V_{85} (Km/h)	71	50	64	50	39	50	55	55	67
	Velocidad media (Km/h)	60	45	54	41	29	39	45	40	55
	Lím. Velocidad	50	50	50	30	50	50	50	50	50
2021	Intensidad de tráfico (Veh/h)	995	285	553	491	253	236	406	78	106
	Velocidad V_{50} (km/h)	35	34	40	30	31	29	42	41	50
	Velocidad V_{85} (Km/h)	43	42	48	38	40	37	51	50	64
	Velocidad media (Km/h)	36	35	40	31	31	29	42	39	50
	Lím. Velocidad	50	30	30	30	30	30	30	30	30
2018 – 2021	% Reducción Intensidad (Veh/h)	24,96	31,49	8,44	34,79	45,00	5,98	5,58	-8,33	55,83
2018 – 2021	% Reducción velocidad (km/h)	40,00	22,22	25,93	24,39	-6,90	25,64	6,67	2,50	9,09

Tabla 1: Valores de las mediciones para los distintos periodos seleccionados.

En ésta se recogen los valores de Intensidad, V50, V85, Vm y la limitación máxima de velocidad para dichos puntos así como la variación experimentada entre 2018 y 2021.

Como puede verse tanto en la tabla 1 como en la Fig. 8, la intensidad de tráfico ha sufrido una reducción en todos los puntos salvo en el P12 en el que la intensidad prácticamente se ha mantenido.

Como puede verse en la Fig. 8, las zonas 1 a 4 se encuentran ordenadas de mayor a menor volumen medio de tráfico mientras que en la Fig. 9 muestra el % de reducción de intensidad experimentado entre 2018 y 2021.

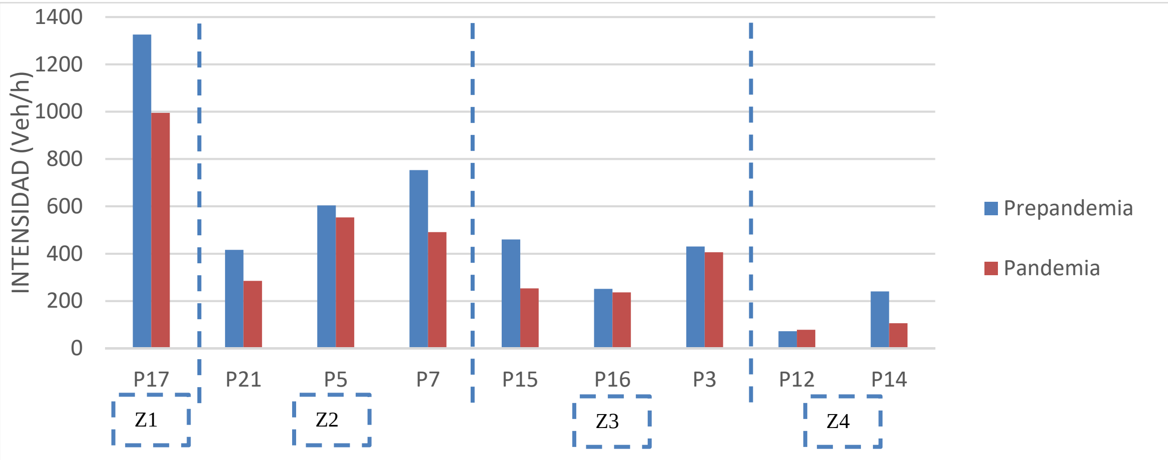

Figura 8: Intensidad horaria para los puntos medidos.

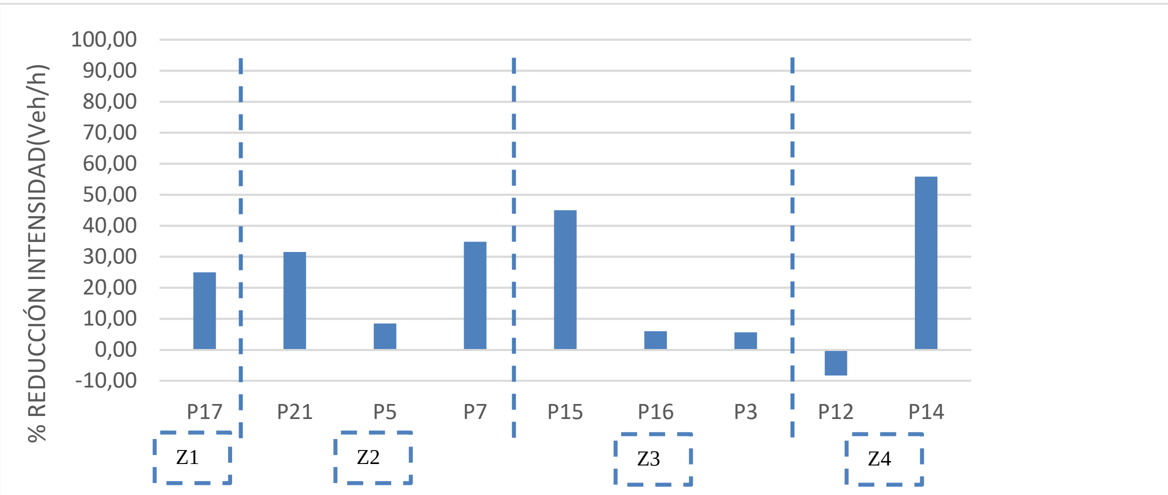

Figura 9: % de reducción de la Intensidad horaria respecto a 2018.

De manera general puede afirmarse que el porcentaje de reducción de la intensidad de tráfico experimentado en la ciudad de Burgos es del 22,64%. Discretizando por la limitación zonal predefinida, se obtiene que la zona 1 ha experimentado un porcentaje de reducción del 24,96%, la zona 2 ha experimentado un porcentaje de reducción del 18,85%, la zona 3 un porcentaje del 18,85% mientras que la zona 4 un 23,75%.

Como ya se ha comentado, la entrada en vigor de la nueva ordenanza de movilidad burgalesa (AYTO BURGOS, 2020) modificó los límites de velocidad impuestos para la mayor parte de las secciones analizadas por lo que es posible comprobar el cumplimiento de dichos límites. Tanto la limitación anterior como la actual quedan recogidas en la tabla 1. La Fig 10 recoge la variación experimentada en km/h tanto para la V_{50} como para la V_{85} mientras que la Fig. 11 recoge la variación porcentual de la velocidad media respecto a 2018.

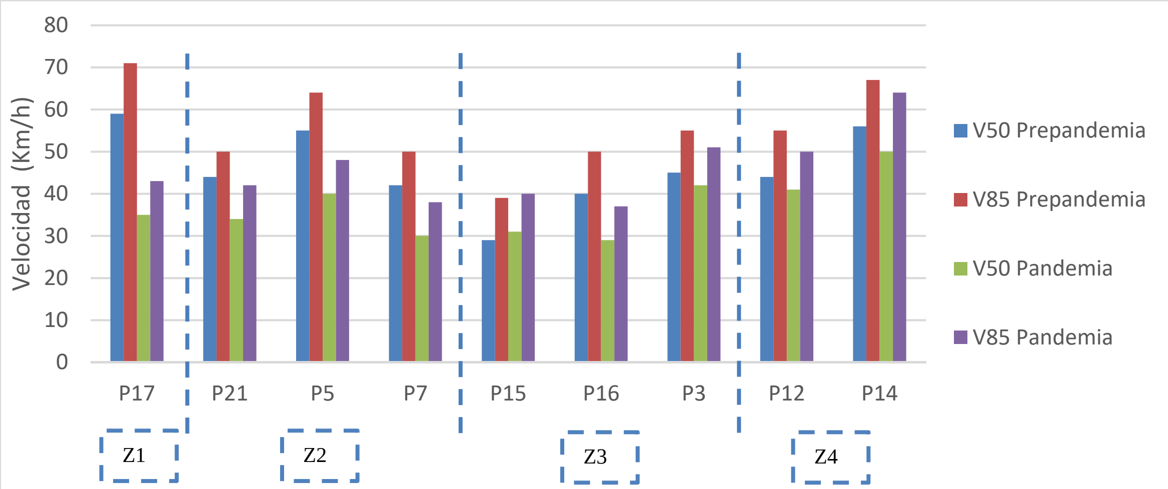

Figura 10: Valores de V50 y V85 para los años 2018 y 2021.

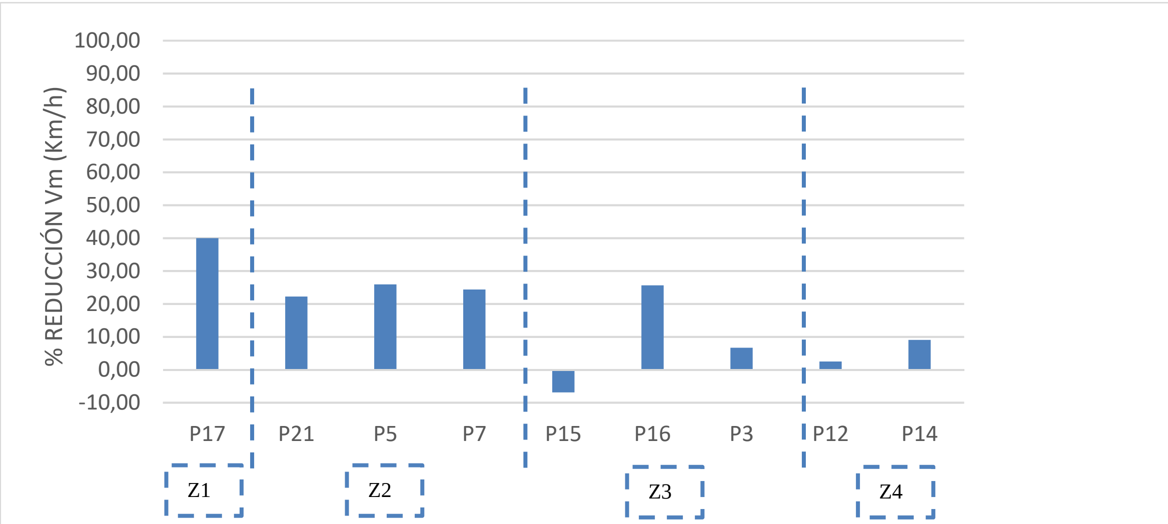

Figura 11: % de reducción de la velocidad media (Vm) para los años 2018 y 2021.

Salvo los P17 y P7, el resto de puntos han visto limitada su velocidad al nuevo valor de 30 km/h. Como puede verse en la figura 10, la V_{50} se encuentra por encima de ese valor en la mayor parte de las secciones analizadas. Según la figura 11, las vías que más han sufrido un descenso en su velocidad serían las catalogadas como vías de conexión urbana (zona 2).

Como anécdota, es necesario destacar que las mediciones en el punto P17 se realizaron con posterioridad a una campaña de radar en la que se impuso un elevado número de sanciones por exceso de velocidad.

Finalmente, puesto que las variables analizadas habían sido Intensidad, velocidad media, porcentaje de reducción de intensidad y porcentaje de reducción de la velocidad media, se trató de encontrar alguna relación entre estas variables para las cuatro zonas propuestas. Sin embargo, y en vase a los gráficos de las figuras 12 a 14 no es posible relacionar las mismas con los valores y el número de secciones analizadas.

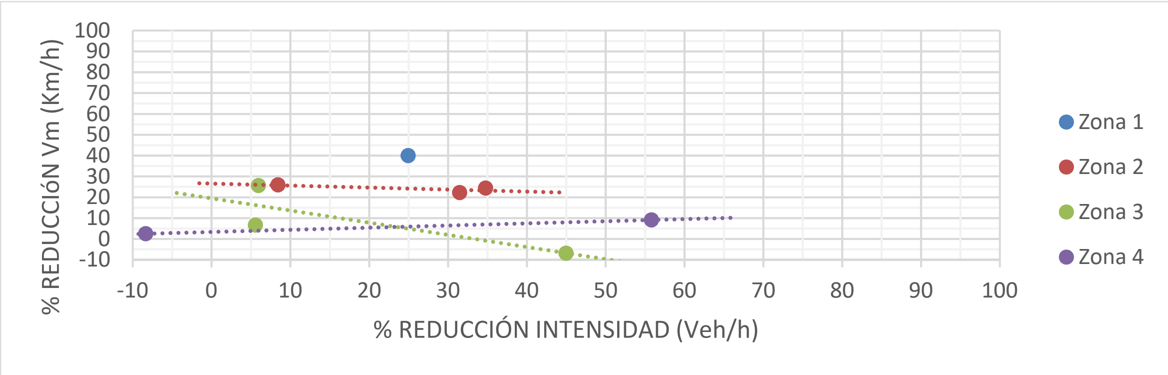

Figura 12: Relación entre el % de reducción de la intensidad y el % de reducción de la Vm para las distintas zonas analizadas.

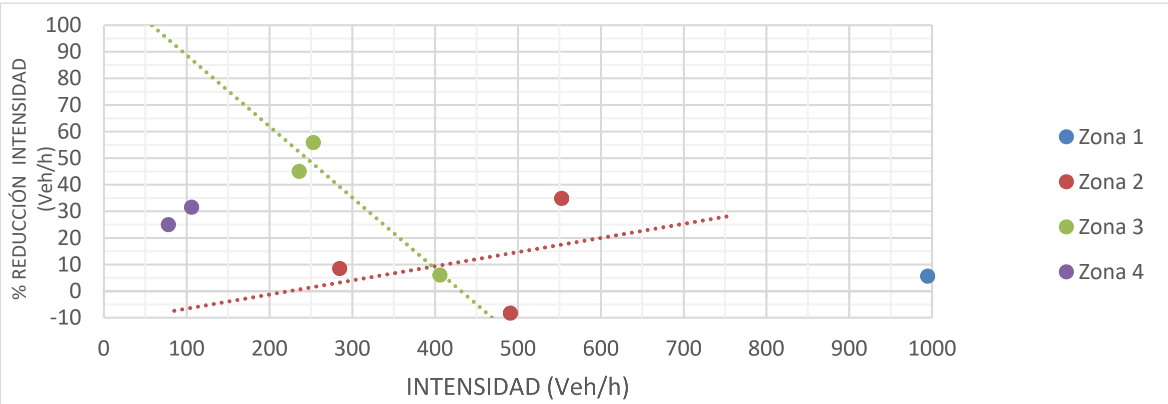

Figura 13: Relación entre la intensidad y el % de reducción de la Intensidad para las distintas zonas analizadas.

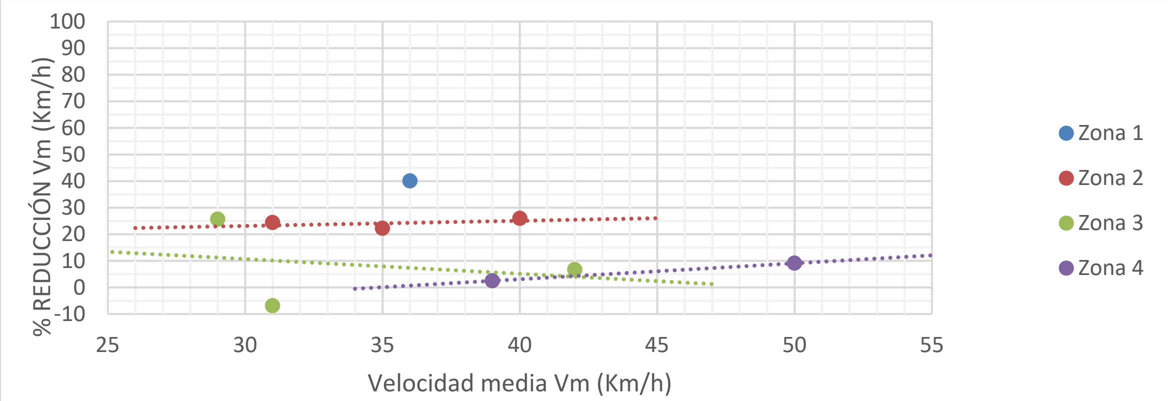

Figura 14: Relación la Vm y el % de reducción de la Vm para las distintas zonas analizadas.

4. CONCLUSIONES

Del análisis de resultados no puede concluirse que existan evidencias de relación entre la intensidad de tráfico y Velocidades medias entre periodos pre y pandémico para las vías de la ciudad de Burgos analizadas que pueden clasificarse como vías urbanas de alta capacidad (zona 1), zonas de conexión urbana (zona 2), zonas de carácter residencial y zonas de paso (zona 3) y zonas residenciales principalmente periféricas (zona 4).

Sin embargo, sí que es posible afirmar que, de manera general, el número de viajes realizados por las vías urbanas analizadas ha descendido en un 22,64% respecto a valores prepandémicos y que la nueva velocidad máxima aplicable a vías de un solo carril y sentido parece no estar respetándose, siendo las vías que más han experimentado una reducción e velocidad las que pueden ser consideradas como vías de conexión urbana.

A diferencia de lo que *a priori* se pudiera esperar, la vuelta a la nueva normalidad no ha supuesto la recuperación de los niveles de desplazamiento por carretera previos a la pandemia. Puesto que los viajes en autobús, el principal transporte público que dispone Burgos, se han visto importantemente reducidos cabe preguntarse ¿qué es lo que ha sucedido?

Está claro que la oportunidad de continuar con el teletrabajo ofertada por algunas empresas, la reducción de viajes autoimpuesta por la propia población como medida racional para evitar la propagación del virus y la floración de bicicletas y patinetes eléctricos en nuestras calles han contribuido en esa reducción de viajes.

A medida que las ciudades avanzan hacia la recuperación con la distribución de las vacunas y una vez olvidado el virus, desconocemos si este cambio en el comportamiento de los ciudadanos tendrá un efecto resiliente. Lo que sí es cierto es que antes de que desaparezca este efecto de nuestras memorias estamos ante una gran oportunidad para aprender de la experiencia y proponer soluciones de una Re-evolución verde de cambio hacia modos más sostenibles.

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MITIGACIÓN DEL IMPACTO DE LA IMPLEMENTACIÓN DEL ‘PLATOONING’ DE CAMIONES EN LAS VISIBILIDADES DISPONIBLES EN AUTOPISTAS

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RESUMEN

El ‘*platooning*’ de camiones está cada vez más próximo. Muchos expertos ven en esta tecnología la solución a gran parte de los problemas del transporte de mercancías por carretera. Sin embargo, el ‘*platooning*’ de camiones provocará una reducción de la visibilidad en los adelantamientos en curvas a derechas que deberá ser compensada de alguna manera. En ese sentido, esta ponencia se plantea como una aplicación práctica de la investigación previa sobre la influencia del espaciamiento entre camiones del ‘*Platooning*’ en la visibilidad en curvas a derechas, en la que se demostró la gran afección a la visibilidad causada y se confirmó la necesidad de plantear nuevas soluciones al problema planteado.

Para todo ello, se pretende llevar a cabo un análisis de distintas alternativas que permitan minimizar el efecto de los ‘*platoons*’ de camiones en la seguridad vial. Dichas alternativas van desde las más conservadoras, que pretenden corregir el problema, hasta otras más innovadoras que pretenden evitar el problema. Lo hacen aprovechando al máximo los recursos disponibles en la vía que podrían dejar de ser necesarios gracias al incremento de la conducción autónoma.

Las alternativas planteadas giran en torno a tres ejes: actuaciones sobre la infraestructura, actuaciones centradas en la conectividad y actuaciones centradas en la automatización. Adicionalmente, se ha cuantificado, cuando ha sido posible, el nivel de mitigación del impacto en visibilidad de los ‘*platoons*´ de camiones.

1. INTRODUCCIÓN

Tras años de desarrollo, la conectividad y automatización de los vehículos comienza a ser una realidad. La importancia del transporte de mercancías por carretera y su impacto en la economía europea (Janssen *et al.*, 2015) han llevado a que gran parte de los esfuerzos de modernización se hayan centrado en este ámbito. En ese sentido, la creación de corredores inteligentes que permitan la mejora de la industria logística ha sido uno de los ejes principales del desarrollo de los sistemas inteligentes de transporte (Oonk, 2016; Tavasszy y Janssen, 2016).

En este contexto, se conoce como ‘*platooning’* a la posibilidad de unir virtualmente varios vehículos. Aunque los orígenes se remontan a los años 80 y 90 (Sheikholeslam y Desoer, 1990), ha sido en los últimos años cuando se han planteado diferentes proyectos para desarrollarlo (Robinson *et al.*, 2010; Bergenhem *et al.*, 2012; Willemsen *et al.*, 2018). Estos proyectos incluyen enfoques muy diferentes, que varían desde la consideración de flujos de tráfico mixtos hasta otros que se centran en la unión virtual de vehículos pesados de mercancías (Bergenhem *et al.*, 2010). En este caso, este artículo se centra en el ‘*platooning*’ de camiones entendido como un conjunto de vehículos pesados de transporte de mercancías que circulan unidos virtualmente con poca separación entre ellos (Janssen *et al.*, 2015).

Se contemplan tres niveles claramente diferenciados relativos al ‘*platooning’* de camiones (Janssen *et al.*, 2015). Este hecho lleva a la necesidad de estudiar los efectos del ‘*platooning*’ en cualquiera de sus tres fases de desarrollo. El primer nivel implica que los camiones están conectados y en seguimiento automático entre ellos. Sin embargo, la presencia del conductor sigue siendo necesaria en todos los vehículos que forman el ‘*platoon’* para reaccionar ante cualquier eventualidad. En cuanto al segundo nivel, éste es análogo al anterior pero no requiere atención completa de los conductores que se encuentren en los vehículos en seguimiento. De esa forma, el tiempo de estos conductores podría conmutar como tiempo de descanso. El último nivel implica la no necesidad de conductor en los vehículos que se encuentran en seguimiento.

En cuanto a las ventajas del ‘*platooning’* de camiones, la mayoría se centran en el ámbito económico. En ese sentido, la eficiencia energética es una de sus principales ventajas. La posibilidad de minimizar la separación entre los camiones podría llevar a descensos en los consumos de combustible de hasta el 13% (Robinson *et al.*, 2010; Alam, 2014). Por otra parte, la creciente automatización podría derivar en un incremento de la productividad y, con ello, a la disminución de la necesidad de recursos humanos (Jacob y Arbeit de Chalendar, 2015; Tavasszy y Janssen, 2016).

Los ‘*platoons*’ de camiones podrían circular con separaciones de tan solo 0.3 s (Janssen *et al.*, 2015). Esta capacidad provocará que los ‘*platoons*’ de camiones circulen con separaciones muy inferiores a las de los camiones que viajan en convoy en la actualidad. Con ello, se logra una de las principales ventajas de esta tecnología: el mencionado ahorro de combustible y de emisiones. Sin embargo, el reducido espaciamiento entre los camiones es también el causante de una de sus principales debilidades: la afección a la visibilidad que podría provocar. En ese sentido, la visibilidad durante maniobras de adelantamiento a ‘*platoons’* de camiones en autovías, autopistas y carreteras multicarril podría verse muy limitada dado que la limitación de visibilidad ya no estaría impuesta por un único camión sino por un conjunto de camiones cuya longitud podría superar los 50 m (Janssen *et al.*, 2015). En la Figura 1 se muestra la situación de afectación a la visibilidad tratada.

Figura 1: Efecto de apantallamiento en las maniobras de adelantamiento a un grupo de camiones

Los modelos tradicionales para evaluar la visibilidad (Hassan *et al.*, 1995; Lovell, 1999) no proporcionan resultados satisfactorios para la evaluación de la visibilidad en este caso tan concreto, pues no son capaces de incluir las particularidades del '*platoon*' de camiones. Tampoco permiten considerar las particularidades del tráfico mixto, pues los vehículos que interactúan sobre la calzada podrían estar conectados o incluso automatizados.

Dada la necesidad de estimar el impacto de los '*platoons*' de camiones en la visibilidad de autopistas, autovías y carreteras multicarril, Pastor-Serrano y García (2020) desarrollaron un modelo que proporciona la visibilidad en cada instante del adelantamiento a un '*platoon*' de camiones, tanto para un coche con conducción humana como para un coche automatizado.

El modelo de cálculo de la visibilidad desarrollado permitió confirmar la gran afectación que provocarían los '*platoons*' de camiones en la seguridad vial. En ese sentido, se confirmó la necesidad de adaptar la infraestructura en caso de que no se desease limitar los '*platoons*' de camiones a vías con radios mínimos de 2500 m (Pastor-Serrano y García, 2020). Esto se debe a que la limitación de visibilidad provocada por el 'platoon' de camiones lleva a la necesidad de limitar la velocidad de la curva por visibilidad mucho más allá de lo requerido en la actualidad por su propia geometría.

Por todo ello surge esta ponencia que, de forma aplicada, pretende proponer diferentes soluciones dirigidas a compensar la reducción de visibilidad provocada por los ‘*platoons*’ de camiones. En ese sentido, se desarrollan a lo largo de esta ponencia propuestas centradas en tres aspectos diferentes: la infraestructura, la automatización y la conectividad.

2. ACTUACIONES CENTRADAS EN LA INFRAESTRUCTURA

Ante el problema de visibilidad que, con seguridad, los ‘*platoons*’ de camiones causarán en las carreteras, se plantean diversas soluciones. Las primeras de ellas se centran en actuar sobre la infraestructura. En ese sentido, este tipo de soluciones tienen como objetivo maximizar la separación lateral entre los ‘*platoons*’ de camiones y los vehículos que se encuentran realizando la maniobra de adelantamiento.

Las actuaciones centradas en la infraestructura deben prestar especial atención, en todo caso, a su viabilidad económica. Deben ser soluciones que exploten al máximo las posibilidades que ofrecen las infraestructuras en su condición actual. Por ello, se debe buscar el equilibrio entre la mitigación de la problemática detectada y su viabilidad. En ese sentido, es posible que las actuaciones sobre la infraestructura que no requieran de grandes inversiones se limiten a compensar el problema de forma parcial.

2.1 Separador entre carriles

En la actualidad, la circulación de ‘*platoons’* de camiones se plantea, principalmente, por autovías, autopistas y vías multicarril. Este tipo de vías, sobre todo las dos primeras, presentan con frecuencia secciones trasversales generosas que proporcionan cierto margen de actuación. El objetivo de esta propuesta es aprovechar al máximo la sección de ese tipo de vías para, como se ha mencionado, maximizar la separación lateral entre ‘*platoons’* de camiones y vehículos que se encuentran realizando una maniobra de adelantamiento.

En concreto, se propone la ejecución de un separador entre carriles con forma de huso esférico que maximice dicha distancia. Se plantea la ejecución de dicho huso de forma puntual en las curvas en las que, por sus características, se debería limitar la velocidad más allá de su geometría debido a la limitación de visibilidad causada por los ‘*platoons’* de camiones (Pastor-Serrano y García, 2020). En las Figuras 2 y 3 se puede observar simulaciones de la actuación propuesta, así como el aumento de visibilidad que proporciona respecto a la situación inicial de la infraestructura.

El diseño del huso propuesto se concreta, en vías de al menos dos carriles por sentido, como un espacio de reserva entre los dos carriles exteriores existentes en una curva a derecha (Figura 4). La configuración geométrica se corresponde con un arco circular concéntrico con el correspondiente a la línea de separación de los dos carriles y con una diferencia de radios igual a la anchura del separador. En el inicio y final de la curva, la divergencia y convergencia de las líneas de borde se logra a través de las clotoides de transición.

Dicha separación entre carriles deberá ser, en todo caso, rebasable. Al crear un espacio entre los dos carriles se logra maximizar la separación lateral entre los vehículos, aumentando con ello la visibilidad tangente al ‘platoon’ de camiones por parte del vehículo que se encuentra realizando el adelantamiento.

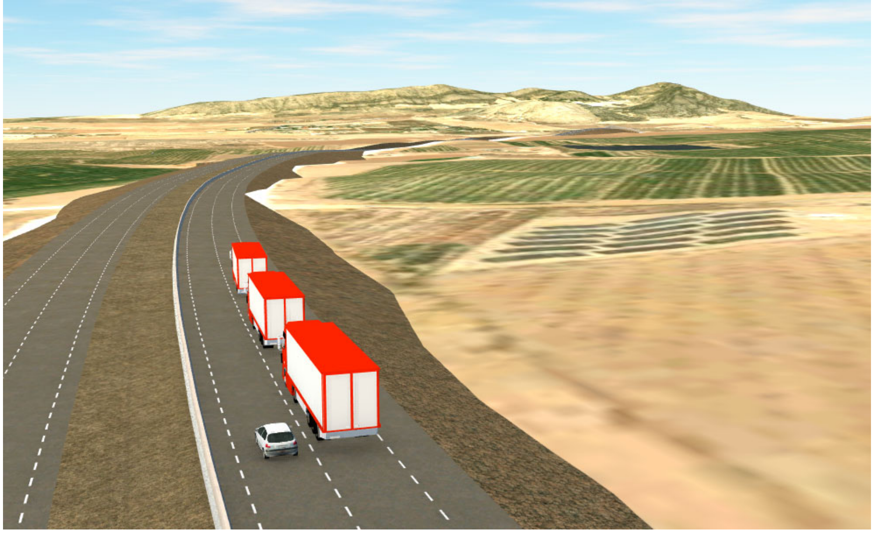

Figura 2: Simulación de un vehículo adelantando a un ‘platoon’ de camiones, antes de la actuación propuesta

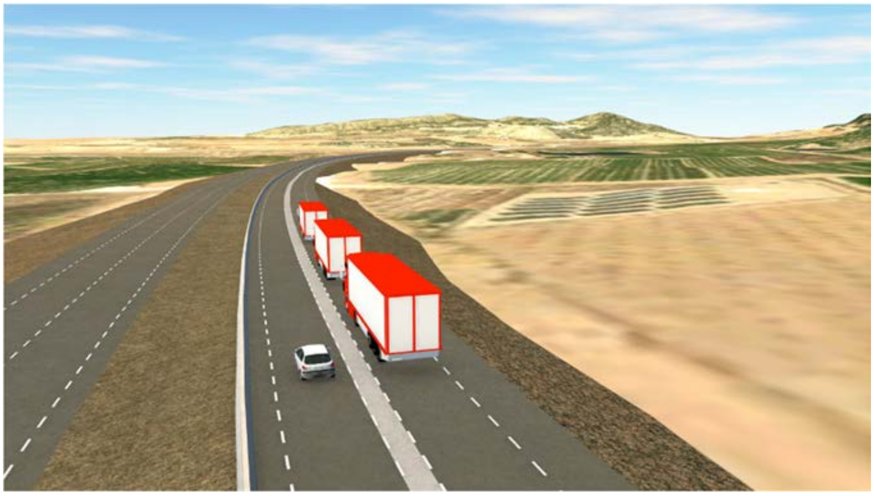

Figura 3: Simulación de un vehículo adelantando a un ‘platoon’ de camiones, tras la actuación propuesta

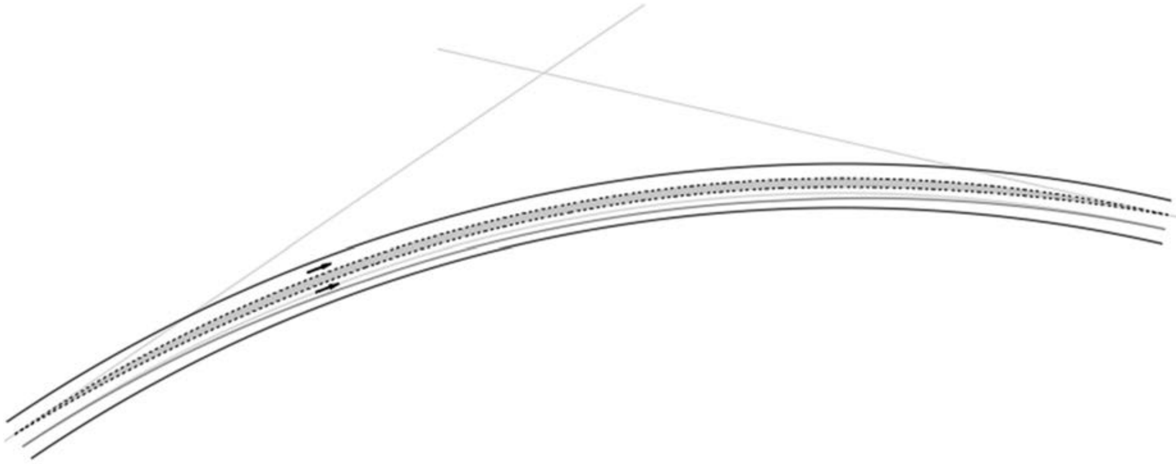

Figura 4: Esquema básico de la actuación propuesta

La señalización del huso debe ser adecuada para que, aun siendo rebasable e incluso permitiendo cambios de carril, se asegure que los conductores lo perciban como un espacio que no pertenece al propio carril. En las Figuras 3 y 4, por ejemplo, el huso propuesto ha sido representado con un color diferente al del resto de la vía.

La nomenclatura de huso se ha tomado como referencia por su similitud a un huso de una esfera. Esto se debe a la necesidad de realizar una transición conforme aumenta la curvatura de la curva, de forma que la aparición del huso intermedio se haga de forma gradual (Figura 4).

En cuanto a sus dimensiones, se ha tomado como referencia una sección transversal habitual formada por dos carriles de 3.5 m de anchura y un arcén exterior de 2.5 m de anchura. De esta forma, y teniendo en cuenta el objetivo de mitigar el problema maximizando el uso de los recursos existentes, se ha considerado una anchura máxima de huso a disponer de 2 m.

Del ancho máximo de huso propuesto, 0.5 metros provendrían del propio carril exterior. Esta decisión se ha tomado porque se considera que un carril de 3 m sigue teniendo una anchura suficiente. A la vez, el hecho de que el propio huso sea rebasable ofrece cierta flexibilidad en caso de emergencia o de necesidad de carriles de mayor anchura.

Por otra parte, se propone la reducción de la anchura del arcén a 1 m. Al tratarse de una reducción puntual y progresiva en la anchura del mismo no se considera que esta actuación penalice en ningún caso la seguridad de la vía.

En la Figura 4 se ha representado la actuación propuesta en los términos anteriormente descritos. En ese sentido, se pueden observar tanto los límites iniciales de los carriles (en gris) como las nuevas delimitaciones de los carriles (en negro) y el huso propuesto (con sombreado gris).

En cualquier caso, se podrían proponer configuraciones diferentes que permitan la creación del citado huso recurriendo a otras partes de la sección de la vía, si bien es probable que dichas alternativas requieran de modificaciones en la infraestructura. Una posibilidad podría ser la ampliación de la plataforma de la vía hacia el interior de la vía. La viabilidad de este tipo de actuaciones dependerá, en todo caso, del nivel de implementación de los '*platoons*' de camiones y la capacidad de paliar el problema con otro tipo de actuaciones.

Como se ha visto en la introducción, Pastor-Serrano y García (2020) desarrollaron un modelo de estimación de la velocidad en la maniobra de adelantamiento a un 'platoon' de camiones en curvas a derechas. Dicho modelo permitió estimar los límites de velocidad impuestos por la visibilidad de parada en dicha maniobra.

Partiendo del modelo previamente desarrollado, se ha evaluado la efectividad de la medida propuesta. Para ello, se ha estimado tanto la visibilidad como la velocidad requerida para garantizar la distancia de parada asociada a la misma. Estas estimaciones se han hecho para radios y anchuras de huso diferentes. Los resultados obtenidos se muestran en la Figura 5, que se comenta a continuación.

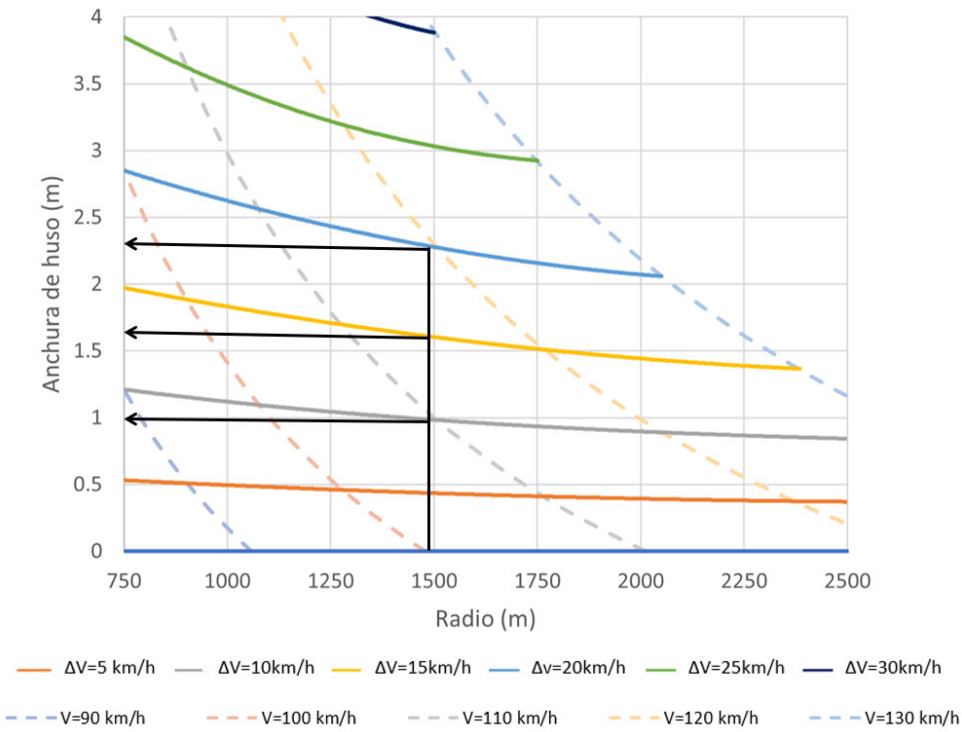

Figura 5: Anchura de huso necesaria para mitigar la limitación de visibilidad, según el radio de la curva

En primer lugar, se puede observar cómo en la Figura 5 se representa la anchura de huso necesaria para cada radio en función de dos tipos de datos. Por una parte, se representan con línea discontinua velocidades predeterminadas. En línea continua, por otra parte, se representan incrementos de velocidad cuya interpretación se detalla a continuación.

Como se ha mencionado, el estudio realizado parte del modelo desarrollado por Pastor-Serrano y García (2020). Por ello, en el caso de disponer de una anchura de huso nula (0 m), lo que se obtiene es la velocidad a la que habría que limitar la circulación para garantizar que existe la distancia de parada necesaria según el radio. Éste era, precisamente, uno de los principales resultados de la investigación inicial.

Respecto a las líneas discontinuas, estas tomas valores fijos de velocidad entre 90 y 130 km/h, con incrementos de 10 km/h. En concreto representan, dado un radio, la anchura de huso que sería necesario disponer para compensar totalmente la limitación de visibilidad provocada por un ‘platoon’ de camiones y, de esa forma, poder permitir la circulación a la velocidad correspondiente en condiciones de seguridad.

En cuanto a las líneas continúas, éstas vienen a completar la figura complementando la información anterior. En ese sentido, dichas líneas representan incrementos de velocidad. Dichos incrementos toman como referencia la velocidad a la que habría que limitar una curva (en función de su radio) debido a la limitación de visibilidad provocada por los ‘*platoons*’ de camiones. La decisión de representar los incrementos de velocidad que representaría cada huso, en comparación con la limitación causada por los ‘*platoons*’, se debe a la imposibilidad de compensar totalmente el efecto para la mayoría de radios, pues se requerirían grandes anchuras de huso.

Por ejemplo, si tomamos una curva con un radio de 1450 m, tendríamos que, si no se dispone el huso, la velocidad se debería limitar a 100 km/h. Para lograr la velocidad máxima se debería alcanzar una velocidad de 120 km/h. O lo que es lo mismo, un incremento de velocidad sobre la limitación causada por los ‘*platoons*’ de 20 km/h. Tomando cualquiera de estas dos referencias (la velocidad objetivo o el incremento de velocidad sobre la limitación provocada por el ‘*platoon*’) se obtiene un ancho necesario de huso de 2.35 m. Dado que se trata de una anchura en todo caso excesiva, se debería plantear la posibilidad de tomar anchuras de huso más reducidas, pese a que con ello solo se compensara el problema parcialmente. Continuando con el ejemplo, si se tomara un huso de 1.6 m de anchura (cercano al límite de lo que podría ser aceptable), se compensaría el efecto en 15 km/h. Si se tomara un huso de 1 m, por otra parte, la compensación sería de 10 km/h, obteniendo una limitación de velocidad a 110 km/h.

A partir de la Figura 5, se puede observar cómo solo para los radios más grandes la creación de un huso entre los dos carriles podría compensar totalmente el problema. Para radios menores a 1,750 m, le necesidad de anchuras de huso excesivas lleva a pensar que la solución propuesta puede ser efectiva para paliar el problema, pero no en su totalidad.

3. ACTUACIONES CENTRADAS EN LA CONECTIVIDAD Y LA AUTOMATIZACIÓN

Las soluciones centradas en la conectividad y la automatización son aquellas que buscan aprovechar al máximo las nuevas posibilidades tanto de los propios '*platoons'* de camiones como del resto de vehículos de la vía, e incluso de la propia vía, para mitigar el efecto de limitación de visibilidad provocado. En ese sentido, se ha decidido agrupar conjuntamente las actuaciones centradas en la conectividad y en la automatización debido a que, aunque podrían tratarse de forma separada, se considera que la conectividad debe entenderse como un paso más en el camino hacia la automatización de niveles superiores.

Aunque las soluciones propuestas se centran en la comunicación entre vehículos (V2V), la comunicación con la propia infraestructura (V2I) mediante elementos como las '*Road Side Units'* podría ser también útil para el objetivo planteado.

3.1 Adaptación y optimización del '*Region Of Interest*' (ROI)

La distancia de parada depende, como bien es sabido, del tiempo de percepción y reacción del conductor. En el caso de los vehículos autónomos, este tiempo es menor que el humano, pero está aún lejos de ser casi nulo. Minimizar el tiempo de percepción y reacción de los vehículos que adelanten a un '*platoon*' de camiones debe ser una prioridad, pues podría mitigar en gran medida el problema de visibilidad existente al minimizar la distancia de parada requerida.

Por todo ello, se plantea que se maximicen los beneficios que podría aportar la conducción autónoma minimizando el tiempo de percepción y reacción. Para ello, se propone que los fabricantes tomen conciencia de la existencia del problema evidenciado y lo compensen en la medida de lo posible. Esta compensación se realizaría mediante lo que se conoce como '*Region of Interest*' (ROI).

El ROI representa el área en el que los sensores que monta un vehículo autónomo se focalizan para reducir el tiempo de procesamiento. En general, el ROI abarca la máxima área posible teniendo en cuenta las posibilidades de los distintos sensores. Sin embargo, podría ser razonable que, en situaciones de especial riesgo, el ROI se limitara a las propias áreas de riesgo.

En este caso, lo que se propone es que un vehículo autónomo que adelante a un '*platoon*' de camiones focalice su atención en la visual tangente al propio tren de camiones. El resultado de esta focalización sería, con toda probabilidad, una disminución de los tiempos de percepción y reacción ante cualquier eventualidad en la vía. El beneficio obtenido, en función del tiempo de percepción y reacción logrado, se puede estimar a partir de los resultados ofrecidos por Pastor-Serrano y García (2020).

Por el contrario, el hecho de focalizar la atención del vehículo en un área tan específica llevaría a perder la atención de otras zonas de la vía o, al menos, hacerlo con tiempos de percepción y reacción mayores. Sin embargo, el hecho de que se trata de una situación puntual con un riesgo relevante podría justificar esta propuesta.

3.2 Soluciones basadas en la sensorización

En caso de existir cierta conectividad o incluso automatización en los vehículos, soluciones similares a la propuesta planteada de creación de un huso podrían llevarse a cabo sin necesidad de actuaciones sobre la infraestructura. Por ello, las soluciones basadas en la sensorización pretenden compensar el problema de limitación de la visibilidad mediante el uso de elementos que permitan aumentar la información disponible durante la maniobra de adelantamiento.

3.2.1 Sensorización trasera y lateral

Esta propuesta consistiría en disponer sensorización lateral y trasera en los diferentes vehículos implicados para aprovechar al máximo su automatización. En ese sentido, el objetivo sería que, en una maniobra de adelantamiento, tanto los camiones que forman parte del '*platoon*' como el vehículo que realiza la maniobra de adelantamiento sean conscientes de la maniobra que están realizando.

De esa forma, la propuesta sería que, al ser conscientes de la situación, los vehículos maximizaran la distancia lateral entre ellos. Así, todos los vehículos implicados se retirarían, en la medida de los posible, hacia los extremos de sus respectivos carriles. La distancia lateral entre ellos se maximizaría y, con ello, la visibilidad.

Al plantearse esta actuación, los fabricantes deberán tener en cuenta su compatibilidad con otras particularidades de los '*platoons*' de camiones. En ese sentido, uno de los problemas que podrían causar los '*platoons*' sería un mayor desgaste del pavimento debido al paso repetido de grandes cargas por áreas muy concretas del firme. Para solucionarlo, diferentes investigaciones han propuesto actuaciones destinadas a variar la posición transversal de los vehículos para distribuir al máximo posible el desgaste y los daños del firme (Chen *et al.*, 2016; Chen, 2020; Gungor y Al-Qadi, 2020). Dichas actuaciones deberían tener en cuenta el problema tratado en esta ponencia.

Por otra parte, esta actuación guarda gran parecido con la propuesta de creación de husos entre los dos carriles existentes, ya que comparten el objetivo de maximizar la separación lateral entre los diferentes vehículos para maximizar con ello la visibilidad. Sin embargo, en este caso no se precisa de actuación alguna en la infraestructura. Pese a ello, esta propuesta requeriría una automatización total del parque móvil, ya que en caso de existir tráfico mixto solo los vehículos autónomos se verían beneficiados.

3.2.2 Sensorización delantera

En este caso, la propuesta se centra en los ‘*platoons*’ de camiones. Dado que el ‘*platooning*’ precisa de cierto nivel de conectividad y automatización, incluso en sus niveles más básicos, parece razonable asumir la viabilidad de incorporar sensorización delantera en todos los ‘*platoons’* de camiones. Si bien dicha sensorización podría tener múltiples funciones, esta propuesta se centra en la capacidad de dicha sensorización para detectar obstáculos en el carril adyacente al del propio ‘*platoon’* de camiones.

La propuesta se centra, por lo tanto, en la posibilidad de que sea el camión delantero del ‘*platoon´* de camiones el que detecte el peligro para los vehículos que lo adelanten. Una vez detectado el peligro, sería el propio ‘*platoon*’ el que advertiría a los vehículos que le adelanten para que reduzcan la velocidad y maximicen su atención.

El principal beneficio de esta propuesta es que no requiere ni de automatización ni de conectividad entre todos los vehículos. En ese sentido, si existiese comunicación V2V el aviso sería directo. La reacción, si el vehículo fuera además autónomo, sería además inmediata. Sin embargo, la propuesta incluye la disposición de varias luces de advertencia en el lateral de los camiones que forman el ‘*platoon*’, de forma que estas se enciendan de forma intermitente al detectar un peligro (Figura 6). Por todo ello, esta solución es compatible y adecuada para casos de tráfico mixto con diferentes niveles de conectividad y automatización.

Figura 6: Propuesta de aviso en caso de peligro.

5. CONCLUSIONES

El '*platooning*' de camiones conllevará grandes ventajas, pero su implantación podría ser conflictiva si no se tienen en cuenta sus efectos sobre la seguridad vial. Por ello, es necesario prever sus efectos con la antelación suficiente, disponiendo así las actuaciones necesarias para mitigar los aspectos más negativos a la vez que se ensalzan los positivos.

Aunque es necesario seguir investigando en la materia, se puede afirmar que los '*platoons*' de camiones provocarán un efecto de apantallamiento que podría generar grandes inseguridades en las maniobras de adelantamiento en curvas a derechas. Por ello, se han propuesto a lo largo de esta ponencia soluciones que pretenden atacar el problema desde diferentes perspectivas.

Debido a la diversidad de soluciones propuestas, cada una de ellas parte de condicionantes muy diferentes. Dado su diferente enfoque y su garantizada pero limitada efectividad, es probable que una combinación de actuaciones sea necesaria para garantizar la mitigación del problema detectado en su totalidad.

En ese sentido, sería necesario ampliar esta investigación en el futuro para cuantificar la efectividad de las diferentes propuestas no solo por separado, sino también como conjunto. Además, se podrían aportar soluciones adicionales que complementen a las ya propuestas. Para todo ello, sería de especial interés la aplicación de estas actuaciones en un caso de estudio que contemple su aplicación en una vía real.

Por último, sería conveniente que el desarrollo de las actuaciones destinadas a compensar el efecto de limitación de visibilidad no colisione con el de otras actuaciones destinadas a compensar otros problemas causados por los '*platoons*' de camiones, como puede ser el del desgaste del pavimento. En ese sentido, se deberían aprovechar las sinergias existentes para generar soluciones globales que integren todas las perspectivas y afronten todas las problemáticas simultáneamente. Solo así se podrá aprovechar al máximo el potencial que estas nuevas tecnologías ofrecen en todos los ámbitos.

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WHY IS NECESSARY TO REDUCE THE SPEED IN URBAN AREAS TO 30 KM/H?

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ABSTRACT

In Spain, on November 2020, a new law imposed that the generic speed limit on single carriageway two-lane roads is reduced from 50 km/h to 30 km/h.

The changes in the general rules of traffic, proposed by the Spanish government, are a sample of the evolution, in the use of the shared space of the streets, and at the same time shows its sensitivity towards road safety. Traditionally, the objective of the regulation was to attend to the growing increase in the use of motor vehicles (mainly cars), and for this reason, it was the protagonist in most of the articles of the General Traffic Regulations. Today, in many cities, the car is no longer the protagonist and shares the space on the streets, not only with other motor vehicles as buses or motorcycles, but also with pedestrians, bicycles, electric pedal-assisted cycles (EPAC), personal mobility vehicle (PMV), …

Pedestrian mobility is becoming more and more important every day but the number of pedestrians that died inside Spanish urban areas in road accidents is almost 50% of total urban areas road fatalities. In this sense, the mobility and road safety policies developed by local administrations have to focus on the objective of the reduction of accidents and their severity involving pedestrians and other vulnerable users in urban areas.

This article collects studies and experiences in other countries that show the effects of reducing the speed of motor vehicles in urban areas in order to reduce accidents and/or their severity if they occur. It also analyzes other options that reinforce this measure and that could help reduce this problem.

1. INTRODUCTION

Several articles of the General Traffic Regulations were modified in Spain, on November 11, 2020. The changes that affect article 50, which deals with speed limits on urban roads, stand out (BOE, 2020). The generic speed limits on urban roads/streets now are established as follows:

- 20 Km/h on roads with a single-carriageway one-lane road. 30 Km/h on single-carriageway two-lane roads.
- 50 Km/h on carriageways with two or more lanes per direction.

In this paper, we will focus on the new speed limit for urban streets with a unique carriageway and two-lanes, one per direction. Before this change in the regulation, the usual maximum speed of these streets was 50 Km/h.

Speed has been identified as a key risk factor in road traffic injuries, influencing both, the risk of a road crash as well as the severity of the injuries that result from crashes. Therefore, a reduction in the speed would improve road safety (Gonzalo-Orden et al, 2016, 2018).

Over the world, road safety is one of the major problems (Llopis-Castelló and Findley, 2019). In 2013, there were 1.25 million fatalities in collisions. Fatalities among pedestrians, cyclists, and motorcyclists are painfully high and represent more than 48% of the total. If we focus on pedestrians, the average value over the world is 22%, 26% in Europe and as higher as 39% in Africa (WHO, 2015).

In the European Union, during 2019, almost 23,000 people died in crashes, which is 21 hundred less than in 2018, and 135,000 were seriously injured. The yearly cost of road crashes in the EU has been estimated to be around EUR 280 billion, equivalent to about 2% of Gross domestic product (GDP) (EC, 2020a; EC, 2020b).

The road fatalities in Spain have been decreasing in the last decades. The peak number of fatalities reached a maximum of 9,344 in 1989. This situation changed reaching the lowest annual total in 2013 with 1,680 people died in road accidents. The last official data, related to 2019, indicates that there were 1,755 fatalities, 8,613 people seriously injured and 130,745 injured. On interurban roads, 1,236 people died, 4,303 people were seriously injured and 51,407 were injured. On urban roads, 519 people died, 4,310 people were seriously injured and 79,338 were injured. (DGT, 2020).

If we look back 10 years, in 2009, 2130 people died outside urban roads and 584 inside urban areas. As the reduction outside urban areas shows a great improvement (42%), inside urban areas the improvements are smaller (11%) (DGT, 2020).

If we focus on pedestrians in urban roads, 247 pedestrians died during 2019 and 269 during 2009. For these vulnerable users, the reduction was only 8%.

	Non-Urban. Total fatalities	Non-Urban. Pedestrian fatalities	Urban. Total fatalities	Urban. Pedestrian fatalities
2019	1236	134	519	247
2009	2130	201	584	269
% reduction	42%	33%	11%	8%

Table 1: Urban/non-urban total/pedestrian traffic road deaths in Spain 2009-2019.

The reduction achieved outside urban areas has been much higher than the small decrease that has been accomplished within them.

In urban areas, apart from the 247 pedestrians who died, we find other users who, in the event of an accident with a motor vehicle with 4 or more wheels, have a high probability of suffering serious injuries or death. We can highlight that, in 2019, in Spain in urban areas, 32 cyclists, 22 moped users, and 126 motorcyclists also died in traffic accidents.

In the following sections of the article, we will see the effects of speed on urban road safety.

2. THE REDUCTION OF SPEED AND ITS EFFECT ON VISIBILITY AND IN THE STOPPING DISTANCE

One of the most important aspects to reduce the probability of an accident when the trajectory of two street users intersect is to increase the visibility distance at which they begin to see each other. For example, if the driver of a car sees a pedestrian approaching a crosswalk from further away than another driver, he/she will have more time to react and adapt his/her speed or even stop than the driver who sees the pedestrian later.

In this section, we will see how to calculate the Stopping Sight Distance (SSD) and how it varies depending on the traveling speed of the car at the moment the driver decides to stop. The SSD is necessary to provide the drivers the ability to see far enough in front of them to be able to stop before hitting a hazard that is in their path in the roadway. Also, we will need to define the Sight Distance (SD) as the distance a driver can see ahead at any specific time. To avoid an accident, the Stopping Sight Distance must always be less than the Sight Distance.

As indicated in the Spanish Standard of I.C. 3.1. related to the Design of Roads (BOE, 2016) the Stopping Sight Distances is composed of two distances:

- dpr: Distance traveled during perception and reaction time.
- db: Distance required to physically stop the vehicle.

$$SSD = (V \cdot t_{pr})/3.6 + V^2/(254 \cdot (f_l + i)) \quad (1)$$

where:

- SSD = Stopping Sight Distance (m)
- V = Initial traveling speed of the car at the moment the driver decides to stop (km/h)
- tpr = Brake perception and reaction time (s)
- fl = Longitudinal friction coefficient mobilized wheel-pavement
- i = Longitudinal grade (m/m)

The perception and reaction time assumed in the Spanish standard (2.0 s) is lower than the one assumed in the USA, where the value is 2.5 s (AASHTO, 2018). The braking action is based on the driver's ability to decelerate the vehicle while staying within the travel lane and maintaining steering control during the braking maneuver. For the values of t_{pr} of 2.0 s and 2.5 s and i=0 %, the d_{pr}, d_b, and SSD are calculated and presented in table 2.

V (km/h)	t_{pr} (s)	f_l	d_{pr} (m)	d_b (m)	SSD (m)
50	2,0 - 2,5	0,411	27,78 -34,72	23,95	51,73 - 58,67
40		0,432	22,22-27,78	14,58	36,80 - 42,36
30		0,453	16,67-20,83	7,82	24,49 -28,66

Table 2: Stopping Sight Distance, dpr, and db in a road with i=0.

The values used for the longitudinal friction coefficients (f_l) provide comfortable vehicle decelerations for the user who must stop, in a controlled manner, the vehicle before reaching an obstacle that is in his path in the roadway.

These calculated SSD distances make us see the first problem. In our cities, we find numerous examples where the design of the pedestrian crossings is not adequate. The design does not allow enough sight distance between the pedestrian and the driver of the motorized vehicle.

Figure 1: Example of crosswalk before and after improvement.

The left and center photos in Figure 1 show how the garbage containers do not allow drivers to see, with enough time (or distance), the pedestrians who want to cross.

As a partial improvement, in the right photo, the sidewalk has been widened, narrowing the lane of the street, and improving mutual visibility between the pedestrian and the driver. Other more effective solutions are removing parking spaces (Figure 2 right) or switching parking spaces for bicycle and motorcycle parking. The same problem is reproduced when we have close to the crosswalk provisional works areas (Figure 3 center), rail barriers (Figure 3 left), urban furniture, a bus stop (Figure 3 right), vegetation, etc. In other cases, we find that the difficulties in the design of the crosswalk are related to problems of sun glare or dark-lighted conditions.

In all these cases, we have limitations on the mutual visibility of the driver and the pedestrian.

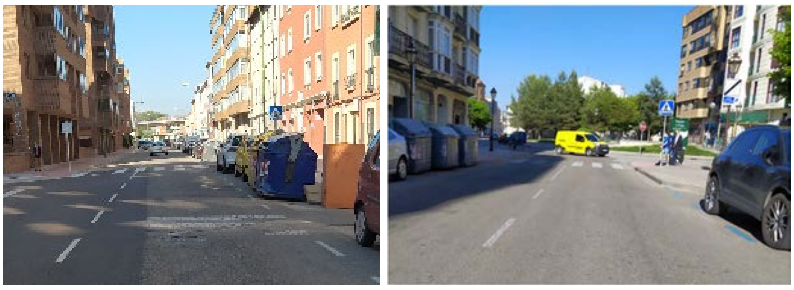

Figure 2: Examples of crosswalks with limited visibility by car parking (left) and improved by sidewalk widening (right).

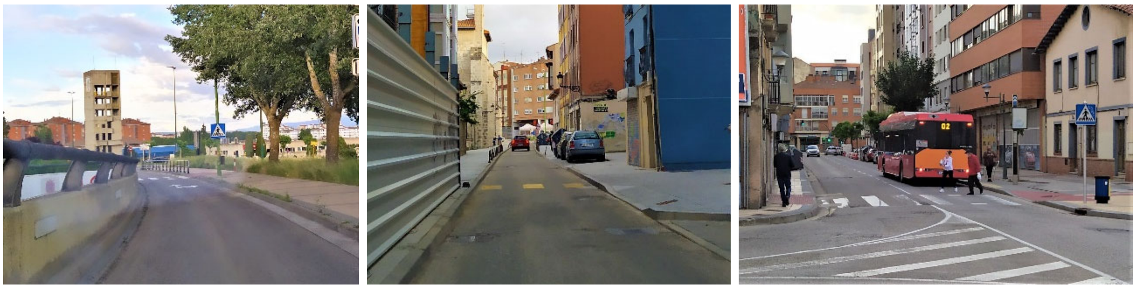

Figure 3: Other examples of crosswalks with limited visibility.

Figure 4: Blinker pedestrian sign with a real-time warning when pedestrians are in or about to enter an approaching crosswalk.

Finally, we can also find traffic signs with presence sensors that turn on a warning light when pedestrians are in or about to enter an approaching crosswalk. (Figure 4) or traffic light that activates the change to red of the traffic light for the driver.

In a few years, it will be normal to find that this information will be sent not only to the traffic lights or signs but also to the approaching vehicles.

We see that a first problem appears in many of the pedestrian crosswalks where the Sight Distance (SD) is less than the Stopping Sight Distance (SSD). In case of need, the driver can perform emergency braking, reducing d_b by more than 34% (DfT, 2007). Even so, of the 61,177 accidents where pedestrians were involved, recorded in Spain during the years 2016, 2017, 2018, and 2019, in more than 42% of the collisions, the pedestrian was crossing properly (Febres et al, 2021).

In addition to increasing the Sight Distance (SD) by changing the street design and reducing the braking distance (d_b) we can try to reduce the distance traveled during the perception and reaction time (d_{pr}). Although this objective has traditionally depended on the driver (attention, reaction time, age, fatigue ...), in the coming years it will also depend on the vehicle. Little by little, the vehicles are incorporating automatic emergency braking systems that will allow us to reduce those almost 17 m traveled at 30 km / h due to d_{pr} or the almost 28 m, traveled while we perceive and react, when we are driving at 50 km/h.

Although new vehicles with advanced emergency braking systems (AEBS) are arriving, the public space should be reorganized. The sidewalk should always be extended over the parking lane and narrowing the roadway. Furthermore, in streets where the maximum speed is 30 km/h, at the pedestrian crossings, at least the two previous parallel parking spaces (10 meters) should be replaced by an obstacle-free zone that facilitates the vision between pedestrians and drivers (or the intelligent vision systems that vehicles have incorporated). If the maximum speed is 50 km / h, it would be necessary to think about clearing a larger area and/or installing a traffic light.

Therefore, we have seen in this section that we should try to increase the SD and reduce the SSD. To increase the SD, we must consider a new design of the crossing areas, eliminating obstacles that reduce visibility or, with the incorporation of sensors in those areas, detect sooner the people approaching these crossings. In order to decrease the SSD we have seen that an instant measure is to reduce the circulation speed. Additionally, as a slower implementation action, it is necessary to accelerate the incorporation of AEBS in all the new vehicles that are sold.

3. THE REDUCTION OF SPEED FROM 50 KM/H TO 30 KM/H AND ITS EFFECT ON THE SEVERITY OF THE ACCIDENTS

Speed has been identified as a key factor in traffic fatalities crashes influencing both the probability of an accident and its severity (Aarts and van Schagen, 2006; Anderson et al, 1997; Davis, 2001; Elvik, 2004; Elvik 2009; Hussain, 2019; Kong and Yang, 2010; Kroyer et al, 2014; Kroyer, 2015; Rosen and Sander 2009; Rosen et al 2010; Telf, 2013).

Analyzing different studies, we realize the difficulty of directly relating the speed of a vehicle with the probability that a pedestrian will die if hit by that vehicle. In Spain, within the dissemination campaign of the General Directorate of Traffic (DGT) about its star measure of reducing the speed from 50 km/h to 30 km/h, it indicates that in the event of being run over at 30 km/h the probability of dying is 15% and 85% when the speed rises to 50 km/h (DGT, 2021). Older studies such as Bonanomi (1990) offer similar values as indicated in the following table.

Speed of collision (km/h)	60	40	20
Probability of death (%)	85	30	10

Table 3: Relationship between the speed of the vehicle and the probability of death of the pedestrian involved in an accident (Bonanomi, 1990).

The probability of survival and the severity of the injuries not only depend on the speed of the vehicle. Other recurrent factors, that we found in the different studies, are the age of the pedestrian, the response time of emergency assistance, or the type of the vehicle (Ballesteros et al 2004; Desapriya et al 2010; Henary et al, 2006; Hussain, 2019; Kröyer, 2015; Lefler and Gabler 2004; Rosén, 2009; Sze, and Wong, 2007). For example, for pedestrian older than 15 years, Rosén (2009), proposed the following pedestrian fatality risk function (P) (Eq. 2) where P is the probability of death of the pedestrian of age “A” in years that is hit by a motorized vehicle that circulated at a speed of “V” Km/h.

$$P(V,A) = 1/(1 - \exp(\,9.1 - 0.095 \cdot V - 0.040 \cdot A)) \qquad (2)$$

In addition to the age of the pedestrian, within the urban environment, other variables have also been analyzed, such as height, weight, sex, or Body mass index (BMI) (Telf, 2013). Basem (et al, 2006) highlighted that the irrespective of impact speed, vehicle body type, and pedestrian weight, height, and gender, senior pedestrian victims are at higher risk of morbidity and mortality than adult victims. Tefft (2013) showed that the average risk of death for a 30-year-old pedestrian struck at a given speed is similar to the risk of death for a 70-year-old pedestrian hit by the same car at a speed 19 km/h slower.

If we focus on the effects of speed reduction on pedestrian fatality risk we see that they are treated in many studies (De Pauw et al., 2014; De Pelsmacker and Janssens, 2007; Elvik, 2009; Fridman, 2020; Heydari et al. al., 2014; Hussain et al, 2019; Rosén, 2009). A reduction in speed limits can help reduce the kinetic energy of the vehicle and therefore, the damage to the pedestrian. Rosen (2009) indicated that the fatality risk at 50 km/h is more than twice higher than the risk at 40 km/h and more than five times higher than the risk at 30 km/h. Analogous values were found by Hussain et al (2019).

Hussain et al (2019), Rosén et al (2009), and Rosén (2011) highlighted that a faster and better emergency assistant and a medical care system will help to reduce the fatality risk.

Finally, it is necessary to indicate that the designs of the new vehicles take into account the damage they can do to the pedestrian in the event of an accident and to underline that Sport Utility Vehicles (SUVs) and Light Truck vehicles (LTVs) have a higher fatality risk than the passenger cars. (Ballesteros et al 2004; Desapriya et al 2010; Henary et al, 2006; Hussain, 2019; Kröyer, 2015; Lefler and Gabler 2004).

Some lessons that we extracted from these studies is that, in general, they cannot be directly extrapolated to other situations different than the cases studied. Some of the problems that we find, when applying them to other cities, are the following:

- Year of the study. Studies carried out many years ago do not consider improvements in vehicle designs or improvement in the assistance of the injured pedestrian. In these cases, these models will deliver death rates higher than the real ones.
- Distribution of the age of the population. Regions or cities in the same country with an older population will have death rates higher than the country's averages.
- Development of the emergency and medical care system. Countries with less-developed emergency and medical care will present a higher fatality risk.
- Average age of vehicles and Typology of vehicles. Cities with higher percentages of SUVs and lower percentages of passenger cars will present a higher fatality risk. Cities with more modern vehicles will have a lower number and severity of pedestrian collisions.

4. DISCUSSIONS AND PROBLEMS OF THE APPROVED REGULATION

The new article 50 of the General Traffic Regulations (BOE, 2020) that establishes the generic speed limits on urban roads/streets is flexible and allows being more restrictive or less:

- "The established generic speeds may be lowered after specific signaling, by the Municipal Authority."
- "Exceptionally, the Municipal Authority may increase the speed on roads with a single lane in each direction up to a maximum speed of 50 km / h, after specific signaling".

These two degrees of freedom make it possible for some municipalities to abuse the "exceptionally" by preserving most of their streets at 50 km/h and leaving, therefore, this standard unused or almost unapplied.

The "exceptionality" should be applied in streets with few buildings, few pedestrians, and long-distance traffic, and when the main reason is to attract long-distance traffic from other streets with a higher density of buildings and with greater pedestrian traffic.

It is necessary to indicate that, in Spain, at present, the fines for speeding up to 20 km/h, in streets limited between 20 to 50 km/h are only 50 euros if paid before 20 days from receipt. If the speeding is between 21-30 km/h the fine rises to € 150 and in case of exceeding by 31 km/h up to 40 km/h the fine would be € 200.

We see, therefore, that fines for speeding in urban streets should be reconsidered as their punishment is not comparable to the damage caused by this increase in speed in the event of a run-over. In case of maintaining this low level of penalty (low effectiveness), it should be compensated with informative campaigns so that drivers and pedestrians better understand the risks of "seeping" in urban areas and their consequences in the case of a pedestrian run over.

Finally, apart from incorporating changes in the fines for speeding, laws should be modified to improve and reduce street design problems. These laws should prevent numerous obstacles limiting visibility at pedestrian crossings and cycle lane crossings between motor car drivers and vulnerable users.

If we leave it on the hands of the specific training and sensitivity towards road safety of those responsible for our cities, it will take longer to win the battle to reduce these accidents. A State or European regulation for the design of these crossings and intersections between streets, bike lanes, and pedestrian routes would strongly help to reduce this type of accident.

5. CONCLUSIONS

The basic rule that we can deduce from this study is that in order to improve the crossing areas of the paths of pedestrians (and other vulnerable users) and motor vehicles, it is necessary to increase the visibility distance between both so that they have more time to react and make decisions that do not end in a pedestrian run over. We have seen how, at daily traffic speeds in our cities, an accident can lead to serious injuries to pedestrians and, in too many cases, their death.

Therefore, it is recommended:

- Inventory and safety audit of all the existing crossings and those areas where there is a high number of pedestrians who cross badly due to lack of enabled crossings.
- Redesign those that are needed and or install new ones that are required.
- Do not extend the reduction of the speed from 50 km/h to 30 km/h to all streets. A higher speed will help to redirect motor traffic to those areas with less pedestrian traffic and less inhabited.
- Increase fines and reduce the first range of 20 km/h of excess in the first level of infraction. The same fine for going at 31 km/h or for going 49 km/h will not help to maintain the speed limit lawbreaker at speeds closer to 30km / h.

- Education and dissemination campaigns for drivers and pedestrians.
- Promote the implementation of advanced emergency braking systems (AEBS) and other safety measures in the design of new vehicles that help reduce the number of accidents and the severity if they occur. Encourage the renewal of the fleet of vehicles not only because they are less polluting but also because they include more measures to improve safety.

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ROAD SAFETY OF ELDER PEDESTRIANS IN THE URBAN CONTEXT: AN APPROACH BASED ON INFRASTRUCTURE AND SOCIOECONOMIC VARIABLES

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ABSTRACT

The world generalized phenomenon of population ageing, caused by an increase in life expectancy, has led to a more elderly being actively part of mobility and road traffic. In developed countries, like Spain, fatalities and severe injuries among elderly pedestrians in the urban context are a matter of concern since, in the last decades, the fatal accident risk for elderly pedestrians is rising. Although there is an extensive literature on the decline of driving and pedestrian skills in the elderly, few research has been devoted to the impact of the street type and socioeconomic factors per urban district on this type of collisions.

The road safety analysis of pedestrians´ collisions is complex due to the diversity of the features, the dispersion of the data and the lack of infrastructure information associated to the accident location at official databases. The main target of this paper is the identification of the basic socioeconomic and infrastructure factors that contribute to elder pedestrian accident at urban level, taking the administrative units (districts) as territorial accident location. Madrid is the capital of one of the most rapidly ageing nations in the world, and was selected as case study because it also has a high proportion of elderly residents (19%). The Spanish General Directorate of Traffic (DGT) provided the database (2006-2018) on accident statistics and the crashes involving an elderly in Madrid were filtered to elaborate and ad-hoc data base. The study methodology was based on a negative binomial model to test the accident occurrence at district level. Results revealed the clear influence of the district population variables (density and total inhabitants) together with the activity centres associated to the elderly mobility, followed by the road length and the ageing rate per district.

1. INTRODUCTION

According to UE statistics (Eurostat, 2015), the 24% of the population in Europe will be aged over 65 years in 2030 and in 2050 this figure will reach the 28%. This fact will be translated, in terms of mobility, into more elderly being actively part of road traffic.

Road safety figures have started to provide evidence of the consequences: at the moment one road traffic fatality out of five is aged 65 or over (European Commission, 2015); but by 2050 (if the risk rates of older people and younger age groups decline at the same pace) it is expected that one road traffic fatality out of three will be an older person (European Commission, 2015).

Elder Pedestrians and cyclists, which concentrate in urban areas, are the weakest users. Statistics reflects that elderly make up 39% of all pedestrian fatalities and 40% of all pedal cyclist fatalities compared to 18 and 19% of all car driver and passenger fatalities (European Commission, 2015). If we check statistics provided by OECD countries, the real fact is that persons 65 years and over 65 years represent 13 to 20% of the population, but they make up more than 50% of pedestrian fatalities (ITF, 2012). Consequently, there is a scientific need to understand the factors that affects the elder pedestrian accidents and prevent them implementing countermeasures on our streets.

Although there is an extensive literature on the decline of driving and pedestrian skills in the elderly, few research has been devoted to the impact of the street type and socioeconomic factors per urban district on this type of collisions. Using a negative binomial model applied to Madrid case study, the main target of this paper is the identification of the basic socioeconomic and infrastructure factors that contribute to elder pedestrian accident at urban district level. The paper is divided into the following sections: Section 1 contains a brief introduction; Section 2, the state of the art on elderly pedestrians; Section 3 gives a detailed description of the case study, model structure and main results; Finally, Section 4 shows the conclusions and future research lines.

2. ROAD SAFETY OF ELDER USERS

An extensive literature (Dunbar et al, 2004; Oxley et al. 2004; Palamara and Broughton, 2013) has been devoted to study the specific physical and mental limitations of the elderly as road users. These physical and mental limitations use to be exacerbated by age-related illnesses and certain chronic medication. Having more than on illness (comorbidity) is also more usual among the elderly population and is also linked to a higher accident´s risk. Due to their physical and mental state, also this age group registers greater fatality rates (Henary et al, 2006). Until now, the higher road collision risk of the elderly has been linked to the reduction in physical and mental faculties with advancing age, which can lead to an inappropriate and unexpected behaviour in elderly pedestrians and drivers compares to the rest of road users (except children).

Elderly drivers have been paid more scientific interest than elderly pedestrians (Charlton et al, 2017; Charlton et al; 2006), although figures reflect that fatal accidents involving elderly drivers are still very few compared to elderly pedestrian fatalities (Langford et al., 2006).

We know that physical and mental limitations of elderly pedestrian are usually related to a lower walking speeds, reduced ability to make head and neck movements, less muscle agility, a poorer vision, poorer hearing, and longer reaction time. The idea of adapting street infrastructure for an ageing society is starting to grow among policymakers and local authorities and institutions like the World Health Organization is promoting the approach of creating “age-friendly” cities (WHO, 2007).

According to this idea of adapting street infrastructure to an ageing society, there is a need to study how the location features of the accident is affecting to the crash occurrence. The location of the accident can be linked to infrastructure features (street crossings, parking lots, signalling, sidewalks width, etc.) and also to socioeconomic factors of the urban district (population density, land use features, ageing rates, etc).

But in most literature studies dealing with elderly users, the analysis of infrastructure and socioeconomic variables is reduced to subjective perceptions declared by the elderly by surveys (Bernhoft and Carstensen, G. 2008, Oxley et al, 2004) and rarely backed by pedestrian collision data and the analysis of the accident location in the city.

In relation to road infrastructure as variable (sidewalks, parking lots and carriageway) some recent studies (Galanis et al, 2017; Corazza et al, 2018; Demasi et al, 2019) have analysed pedestrian road safety in relation to urban road type and traffic flows, but only a few of them have special consideration for elderly pedestrians (Corazza et al, 2018).

The works developed by Galanis et al (2017) are more focused on pedestrian behaviour (legal or illegal walking behaviour) in relation to infrastructure type and traffic flows. Pedestrian walking on the sidewalk for the entire length of the tested street segment was considered a legal behaviour and otherwise was illegally considered.

In a Greek city of 130.000 inhabitants, the legal or illegal walking behaviour in six different types of streets was recorded by video cameras and photos. Results showed that the highest rate of legal behaviour was presented in main arterials (91.8%) and the lowest one in local streets (53.7%). Low motorized traffic flow levels in combination with maintenance and mobility problems in pedestrian infrastructure push pedestrians to walk outside the sidewalk, underestimating road safety issues.

Corazza et al (2018) focused on the pavement state of the sidewalks and its influence on elderly pedestrian accidents. Distressed or too narrow sidewalks may induce pedestrians to walk outside the sidewalks and on the carriageways, providing very unsafe situations, especially for the elderly. Authors classified the pavement state of the sidewalks in a district of Rome (Italy) and studied the relationship with a higher recurrence of accidents involving pedestrians with special attention to elderly pedestrian accidents.

Finally, Demasi et al (2019) focused on all vulnerable users (pedestrians, cyclists and motorcyclists) and designed a methodology to estimate the level of road safety of each section of a street and the hazard index of the overall branch.

Apart from considering traffic flows and speed limitations, authors identified 9 categories of elements of the street infrastructure to evaluate: pavement, geometry (narrow sidewalk, narrow lane width), lighting, intersections, cross-section (missing pedestrian crossing, pedestrian crossing without ramps), private access (lack of visibility, lack of ramps), road signs (traffic lights, roadside signs), urban furniture (safety barriers, urban furniture causes lack of visibility at intersections, urban furniture occupies shoulder or lane) and stopping (illegal parking).

Although the approach of Demasi et al. (2019) is the most interesting and would be linked and applied to elderly pedestrian accidents, it needs a database fed with a very detailed road inventory. Official accident databases use to give poor infrastructure data associated to the location of the accident and sometimes local authorities cannot supply a good inventory of their streets. The quality of the accident database always conditions the research methodology of road safety studies. This database is designed by the national authorities in each country and is compiled from a collection of road traffic accident information. In comparison to other national data bases, the Spanish one is sufficiently consolidated (Casado-Sanz et al, 2019). The pedestrian accident data used in this paper was extracted from the Spanish Accident Statistics database, and includes the accidents on Madrid city streets involving single vehicle and a pedestrian, during a period of 11 years (2006-2018). Three of the weakest points of the Spanish accident database are:

- The absence of traffic exposure data (traffic flow) associated to the accident location.
- The absence of the street road layout (lane width, sidewalk width) and traffic signalling information associated to the accident location.
- The absence GPS coordinates associated to the accident location (as in the US), using instead the kilometric point on the road in interurban roads or the closest street number in urban scenarios, leading to further data processing problems.

The two first points push researchers to collect these variables from other official databases or develop a systematic procedure of ad-hoc measurement. These ad-hoc works are very laborious, but is the only way to obtain a holistic approach for road safety assessments. The third issue is especially important in urban scenarios because working with GPS coordinates eases the process of assignment of other variables (traffic flows, road layout, sidewalk geometry, etc.) to the accident location point. In this preliminary study, a great effort has been devoted to the GPD coordinates procurement process, while basic infrastructure and socioeconomic variables have been obtained directly from official databases.

3. MADRID DATA BASE AND METHODOLOGY

3.1. Madrid case study

Spain is one of the countries in the world (together with Sweden, Finland, Germany, Italy, Greece and Japan) with the largest number of elderly people. In 2019, Spanish people over the age of 65 were approximately 19.3%, and almost 6% were over the age of 80 (INE, 2019); and this amount could reach 40% in 2060 (United Nations, 2019).

Madrid city has been selected as case study in this research because it is the capital of one of the countries in the world that presents the most positive evolution of the ageing of the population. Furthermore, the city has a high overall elderly proportion of 19%. It is a large city with almost 3.5 million of inhabitants and it is divided into 21 districts. This administrative division will be used in the statistical analysis of this research, as information is available and officially provided at this detail level.

The available data for this study consists of a subset of the Spanish Accident Statistics Database during the period 2006-2018, where collisions involving 1 vehicle and 1 elderly pedestrian took place in Madrid city, as it is explained in the next section. The main issue with the database was to geolocate the events, because their location is recorded using the name of the street and not with GPS coordinates.

3.2. Database

In this section it is explained how the database for the statistical operations was constructed. It consists of two separated operation: dependent (number of crashes per district) and independent variables gathering. This last group is comprised of different nature features about each district. It was intended to use only direct data (i.e., already available) as independent variables in this research.

The first step of the data collecting process was to obtain a clean elderly road safety database containing the location and basic characteristics (e.g., date, time, and type) of the accident to perform further processes of filtration. A simplified National Spanish database of accidents for the period 2006-2018 was the starting point.

Accidents with the profile of “vehicle-pedestrian collisions” where kept, summing up a total of 20,236 accidents. Later, a subset of accidents with a configuration of “1 person and 1 vehicle involved” of 18,118 (89 % of total collisions) records were found suitable to be studied for homogeneity purposes. Finally, the database was filtered to obtain events where the involved pedestrian was 65 years or older. This process provided information about 4,663 elderly pedestrian collisions. A preliminary analysis of this database manifests the fragility of the elderly, as this group represents only 25.7% of total collisions but 50.9% and 34.2% of total fatalities and serious injuries, respectively.

One of the most important operations to perform in the proposed study was to geolocate the accidents based on the name of the street and the number or the name of two streets for street crossings. This procedure became more challenging because of the lack or misspelling of this information in some records. The geolocation of the data required the creation of a database containing every possible location of Madrid city. This was accomplished using GIS operations and different databases, mainly the Madrid Council Open Data Portal and Spain National Geographic Institute (IGN). This information was joined to the accidents database using string-searching algorithms and it was possible to geolocate 97 % of the accidents. Later, the district code was added to each observation and this dataset was grouped by district to obtain the dependent variable to study in this analysis: the number of crashes per district. Figure 1 shows the location of the accidents per city district and victim severity.

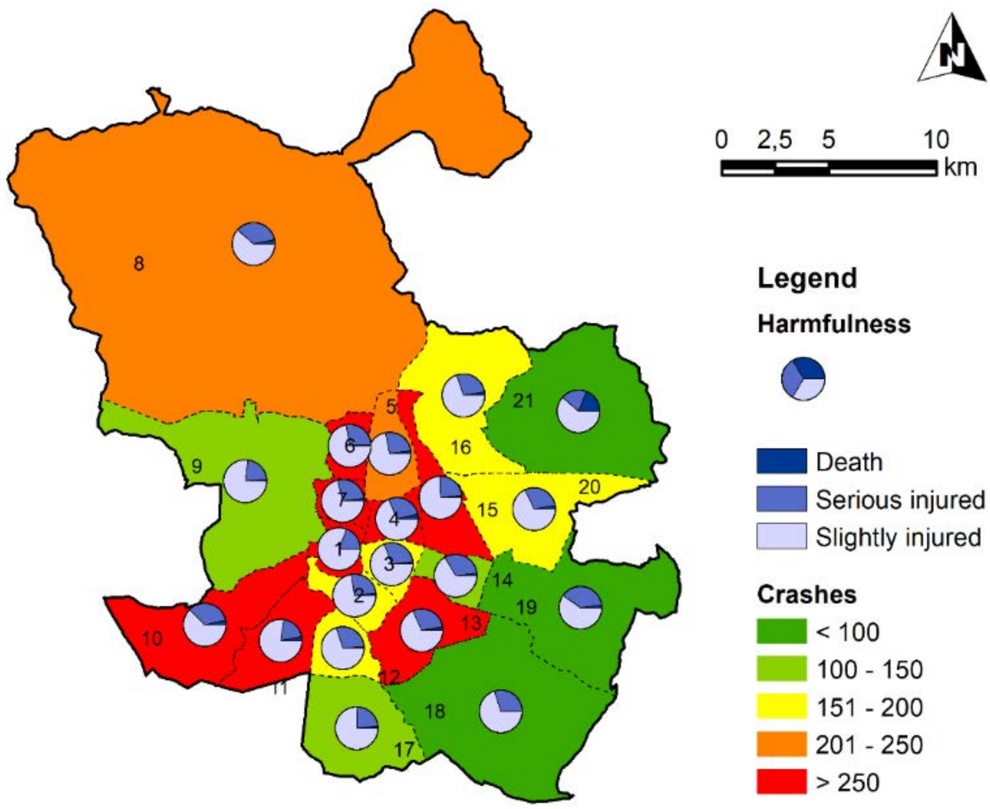

Figure 1: Number of collisions between vehicles and elderly pedestrians and harmfulness in Madrid Districts.

To measure the impact of socio-economic and infrastructure features on elderly road safety in this macroscopic analysis, different variables (see Table 1 and Figure 2) regarding Madrid districts were gathered and processed from various data sources.

Socio-economic variables are inhabitants, population density, ageing rate, average annual income per household and Activity Centres (Point of Interest, POIs). Inhabitants is an indicator of the exposure, in the absence of pedestrian flow data. Population density reflects how crowded a certain district is. Ageing rate captures the population structure.

Average annual income per household states the socioeconomic status of a district. Inhabitants information was available via the Spanish Statistics National Institute (INE) for the period 2006-2014. These data were grouped per year and census section and five-year age group, and via Madrid Council Open Data Portal for the period 2014-2018. These data were grouped per year, district, and age of inhabitants.

It was possible to postprocess both files to construct a single homogenous dataset containing the number of inhabitants living in each district and year, separating them in five-year age groups. Population density was calculated regarding the surface of each district and the information about inhabitants.

Furthermore, ageing rate was obtained as the ratio between inhabitants over the age of 65 and total inhabitants of each district. In the following analysis only last year data will be used for simplicity reasons, because ageing rate has increased slightly in Madrid city. Finally, average annual income per household was obtained for each district directly from the Madrid Council Statistical Portal for the year 2015.

Activity centres were included in this study through the location of Points of Interest (POIs) existing in each district. The number of POIs indicates the possible locations where pedestrians can access to. Hence, it can be associated with a higher pedestrian flow.

This information was obtained directly from the Madrid Council Data Base, when it was possible, and from the Madrid Council Open Data Portal in the form of point-shapefiles that were located on a map and intersected with Madrid districts' geometry. The number of locals per type -restaurants, stores, senior centres, and hospital centres- was calculated in each district. In this study, it was used the total number of these points as a unique variable named POIs.

Infrastructure data group different features about the existing road network. At this point of the research, only direct data will be used. This way, infrastructure variables that require a complex process to be obtained, such as sidewalk widths, are planned to be used in further research. Total length of roads was obtained for each district from the Madrid Council Database.

In consequence, road density considering the surface of each district was computed. Street crossing location was found ad-hoc using the geometry of the street axis and GIS techniques. In addition, signalised street crossing locations is available at Madrid Council Open Data Portal. Hence, it was calculated the proportion of signalised intersections of each district.

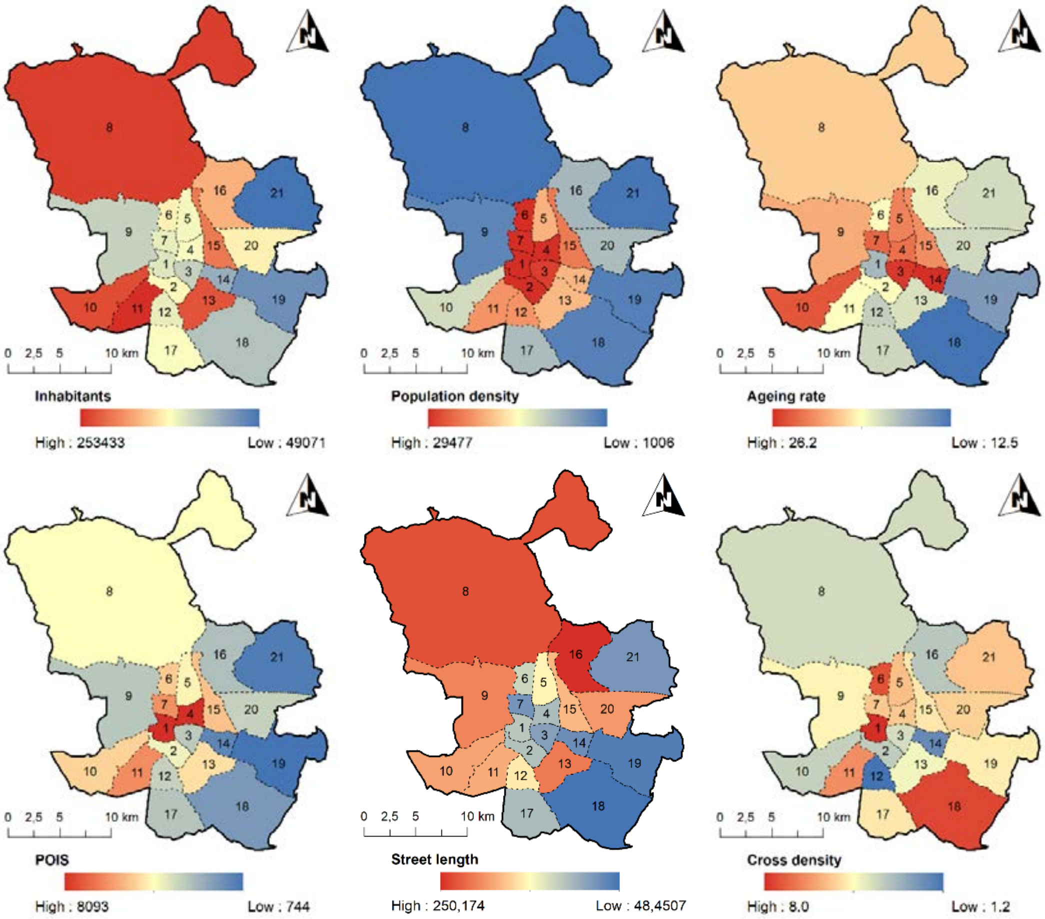

Figure 2: Spatial representation of independent variables.

Group	Variable	Unit	Mean	St. Dev.	Min	Max
Socio-economic	Inhabitants	#	155,834.40	56,436.15	49,071	253,433
	Population Density	#/km2	14,007.85	9,700.58	1,006.00	29,477.78
	Ageing rate	%	20.13	3.78	12.53	26.16
	Average annual income per household	€	39,209.01	11,146.21	24,688.07	60,947.89
	POIS	#	2,844.29	1,637.71	744	8,093
Infrastructure	Road length	km	140.21	62.58	48.45	250.17
	Road density	km/km2	11.67	7.17	0.94	22.74
	Street crossing density	#/km	4.92	1.61	1.18	8.03
	Signalised street crossing	%	18.99	9.69	5.02	43.95

Table 1: Statistical summary of the independent variables.

At this point, the information reunited in this section was ready to construct a statistical model to assess the importance of the independent variables on the number of vehicle-elderly pedestrian collisions per district in Madrid city. These operations are explained in the following sections.

3.3. The Negative Binomial Regression

This study uses a Negative Binomial (NB) Regression, which is widely spread throughout road safety crashes frequency estimation in general and in macroscopic studies (Ziakopoulos and Yannis, 2020). The output of this regression can only have null or positive numbers.

This model is derived from a Poisson-gamma distribution (Hilbe, 2011) and it can handle over dispersed data, on the contrary of the Poisson regression in which the mean and variance of the data are considered to be equal. As overdispersion was present on the crash frequency per district data, a NB was suitable to construct a statistical model. The density function of the NB is as follows (equation 1):

$$\mathrm{P}(Y = y_i) = (\Gamma(y_i + \alpha^{-1}))/(\Gamma(\alpha^{-1}) y_i!) \cdot (\alpha\mu_i)/(1 + \alpha\mu_i))^{y_i} \cdot (1)/(1 + \alpha\mu_i))^{\alpha^{-1}} \quad (1)$$

Where P(Y=yi) is the probability of Y being yi, μi is the expected number of events, α is the dispersion parameter and yi is the number of occurrences at i. The expected number of vehicle-pedestrian collisions is given by the following equation (2):

$$\mu_i = \exp(\beta_0 + \sum_{j=1}^{n} \beta_j' x_{ij}) \quad (2)$$

Where μi is the expected number of events, β0 is the estimated intercept if it is considered, βj are the estimated parameters and xij are the independent or explanatory variables at i.

3.4. Model Assessment

After collecting the proposed variables for every district, the next step is to formulate a Negative Binomial Regression that returns the best goodness of fit in the operation of calculating the total number of crashes in each district. This process involves constructing and comparing every possible combination of the 10 selected variables. Thus, an exhaustive procedure was performed to test every subset of the candidate variables and approximately 1,000 models where constructed and assessed based on their Akaike Information Criterion (AIC). The AIC (equation 3) is an estimator of the goodness of fit based on the likelihood and the number of parameters of the model. This criterion does not report an overall score on the goodness of fit, but a rating to compare a set of models that are employed on the same data. The final model is the one with the lowest AIC value.

$$AIC = 2k - 2\ln(L) \quad (3)$$

Where L is the maximum of the likelihood function and k is the number of parameters of the model.

3.5. Results

In this section it is presented the model that was found to have the lowest AIC value among all the possible ones. This final model is based on inhabitants, population density, ageing rate, road length and number of POIs. All the variables have a positive effect on the total number of collisions between vehicles and pedestrians over the age of 65. The most significative variable is the population density, followed by inhabitants, POIS, ageing rate, and road length. Every variable has a p value smaller than 5%, which means that the null hypothesis of the estimate being null is rejected.

A greater number of inhabitants in a district is found to have direct effect on the number of crashes in that district. This can be explained if it is assumed that a pedestrian that suffers a collision is an inhabitant of that very same district (i.e., pedestrian flow increases with population) or if it is presumed that it is more likely that a person walking in one district is an inhabitant of that district. This way, the variable “inhabitants” could also be understood as an indicator of pedestrians’ traffic. Also, population density is an indicator of how crowded a district is, and even a sign of how tall the buildings are. This way, population density provides an indicator of how many conflicts could happen in an equal area. Ageing rate parameter is found to be positive. It can be understood by the same argumentation about inhabitants and presuming that the elderly usually transits in their own district.

From the infrastructure perspective, as road length increases so does the number of crashes. This is explained because road length is a measure of exposure and as it improves the probability of a crash occurring increases, too.

Finally, from the land use point of view, the number of Points of Interest also has a positive effect on the number of crashes. This fact can be explained because it can be expected that there would be a higher pedestrians and vehicle traffic where there are more of these special locations. In consequence, exposure would be higher in those districts where the number of POIs is elevated. Also, it is important to note that those points act as attractive nodes to people.

Variable	Estimate	Std. Error	z value	p-value	
Intercept	3.103	1.878e-01	16.524	< 2e-16	***
Inhabitants	4.195e-06	8.722e-07	4.810	1.51e-06	***
Population density	2.768e-05	4.775e-06	5.797	6.74e-09	***
Ageing rate	2.354e-02	8.763e-03	2.686	0.00724	**
Road length	2.149e-03	8.456e-04	2.542	0.01103	*
POIs	9.958e-05	2.375e-05	4.192	2.76e-05	***
Significance Codes	0 ‘***’	0.001 ‘**’	0.01 ‘*’		
Log-likelihood	-98.859				
AIC	211.718				
BIC	219.030				

Table 2: Summary statistics of the final negative binomial model.

4. CONCLUSIONS

In this study, a negative binomial regression model was constructed to evaluate the number of collisions between one vehicle and one elderly pedestrian at a district level in Madrid city, considering socio-economic and infrastructure variables to assess their importance. It can be considered a first approach on the subject by the authors. Because of that, mainly direct data has been used to study the phenomenon. A database containing features about Madrid districts was constructed to be the independent variables in this study.

Crashes that were found to be suitable for this study were geolocated using self-designed algorithms to be placed in a GIS software in order to obtain the number of crash occurrences in each city district, that is the dependent variable in this research. Later, these two objects were joined to form the final dataset to construct the regression model. An exhaustive model search was performed to find the model with the lowest AIC, that was the indicator to assess the goodness of fit.

Variables from all groups have been found to be significant. The final regression model in composed by inhabitants, population density, ageing rate, road length and the number of Points of Interest (POIs), being population density the most significant in the model. The small sample size used in this study (21) is due to the lack of direct information about the proposed variables at a smaller spatial level, such as neighbourhoods. This issue can be solved as it is described in the next paragraph.

Further research is considered to be necessary in various respects due to some reasons:

- There is a remarkable heterogeneity inside the districts in some variables. In consequence, the study of the neighbourhoods or using a homogeneous grid is thought to be the next step to follow. Furthermore, some of the candidate variables have not been found to be significant, but in a further analysis at another scale they will be tested again. Also, sample size will be increased if another spatial unit is used. Finally, one of the most time-consuming tasks carried out was to geolocate the accidents. The data obtained in this respect is understood to be valuable and it will be used in further analysis at a smaller spatial level. Because of these main reasons, a similar study on a smaller spatial unit will be carried out, although it will be necessary to measure some already used variables in a different manner.
- New variables that require to be obtained ad-hoc will be employed in further analysis. For instance, it is the case of not available infrastructure data regarding sidewalks width.
- A change in the methodology is also a way to go. In this sense, a significant number of approaches to study the phenomenon could be used. For instance, a multinomial logistic regression to study the severity level or a study based on street segments.

These proposals imply collecting a bigger amount of data and executing more processes than the option of changing the spatial unit to be studied. Therefore, this option will be implemented after the first one.

The ultimate objective of this research is to develop a set of countermeasures to mitigate road safety issues in view of the present population ageing process. Developing criteria and strategies about how cities should be designed is an important subject to reduce elderly pedestrian road accidents. Further research will explore in more detail possible contributory factors that are not found in this paper.

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COMPARISON OF MULTIVARIATE REGRESSION MODELS AND ARTIFICIAL NEURAL NETWORKS FOR PREDICTION HIGHWAY TRAFFIC ACCIDENTS IN SPAIN: A CASE STUDY

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ABSTRACT

In recent years Spain shows the great reduction in the accident rate that has been achieved and the improvement of the behavior of road users, despite this, there is still a need to improve many areas. In 2016 for the first time since the last 13 years, the number of fatalities increased by 7% concerning to the previous year. In this paper, analysis and prediction of road traffic accidents (RTAs) of high accident locations highways in Spain, were undertaken using Artificial Neural Networks (ANNs), which can be used for policymakers, this paper contributes to the area of transportation safety and researchers. ANN is a powerful technique that has demonstrated considerable success in analyzing historical data to forecast future trends.

There are many ANN models for predicting the number of accidents on highways that were developed using 4 years of data for accident counts on the Spain freeway roads from 2014 to 2017. The best ANN model was selected for this task and the model variables involved highway sections, years, section length ,annual average daily traffic (AADT), the average horizontal curve radius, Slope gradient, traffic accidents with the number of heavy vehicles. In the ANN model development, the sigmoid activation function was employed with the Levenberg-Marquardt algorithm and the different number of neurons.

The model results indicate the estimated traffic accidents, based on appropriate data are close enough to actual traffic accidents and so are dependable to forecast traffic accidents in Spain. However, it demonstrates that ANNs provide a potentially powerful tool in analyzing and predicting traffic accidents. The performance of the model was in comparison to the multivariate regression model developed for the same purpose. The results prove that the ANN model stronger forecasted model which produced estimates fairly close to forecast future highway traffic accidents with Spanish conditions.

1. INTRODUCTION

Traffic accidents in Spain shows the great reduction in the accident rate, that has been achieved in recent years as shown in Figure 1 and the improvement of the behaviour of road users. This reduction is mainly due to the increase in the use of the helmet and the belt, the downward trend in the consumption of alcoholic beverages, better user behaviour, improvement in infrastructure and the updating of the security systems of the vehicle fleet according to (DGT,2011-2017).In spite of this, many areas such as the conservation and signalling of roads, speeding or distractions due to the use of mobile phones are still to be improved.

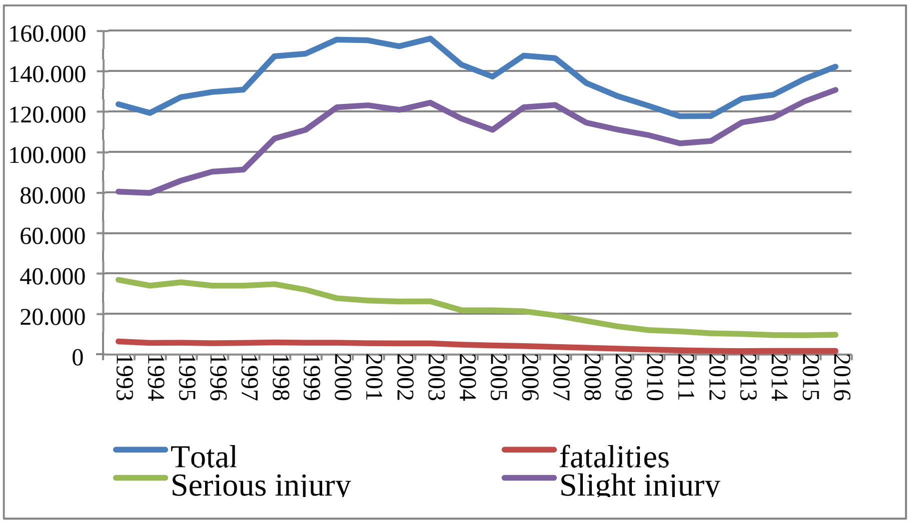

Figure 1: Number of Accidents (interurban and urban roads) in Spain. (DGT, 2017).

However, although the accident rate has been reduced in recent years, in 2016 for the first time since the last 13 years the number of deaths increased by 7% compared to the previous year (Figure 2). The cost in human lives of these traffic accidents requires the implementation of road safety policies as well as studies and methodologies that allow preventing accidents by identifying potential causes and improving infrastructure.

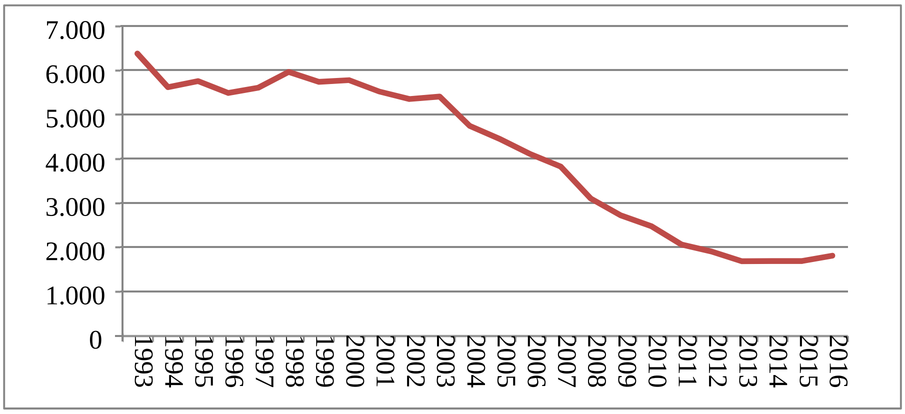

Figure 2: Number of fatalities (interurban and urban roads) in Spain. (DGT, 2017).

Even with relatively low risks, the General Direction of Traffic tries to further increase road safety. From the perspective of road owners and road safety managers, the understanding of the factors that contribute to a higher frequency of traffic accidents is of paramount importance. In addition to the three Es; engineering, enforcement and education used to manage road safety (DFT, 2011), the planning, construction and maintenance of safe roads require in general the consideration of different fields influencing the occurrence of road accidents (e.g. human behaviour, improvements in automotive manufacturing and weather).

Many research has been carried out on the prediction of traffic accidents in countries using various statistical techniques. However, the numerous variables and complex relationships between the characteristics of the various traffic elements require different analytical techniques than traditional ones. A recent approach to analyze these relationships is the artificial neural networks (ANN) that many scientists have proposed and used successfully as an alternative to conventional ones.

Regression method in predicting time series associated to complex atmospheric and environmental phenomena. This paper presents and discusses the development of a prediction model to estimate future traffic accidents in Spain using the ANN method.

2. MULTIVARIATE REGRESSION MODEL

Regression analysis approaches implement ancient accident statistics to relate accidents to the most contributing factors. Multiple linear regression model is planned to have the following form:

$$Y = B0 + B1(X1) + B2(X2) + B3(X3) + B4(X4) + B5(X5) + B6(X6) \quad (1)$$

Where:

- Y: the predicted number of accidents.
- B0: the constant coefficient of the regression line.
- B1, B2, B3, B4, B5, B6: the regression coefficients. Where,
- B1: Segment length
- B2: Slop gradient %
- B3: Horizontal curve.
- B4: Annual Average Daily Traffic (AADT)
- B5: Heavy vehicle percentage .
- B6: Speed.

The analysis was carried out using Statistical Package for Social Science (SPSS) version24 The performance of the model is expected based on the R-Squared (R^2) value of the regression which is presented in the results (Section 5).

3. ARTIFICIAL NEURAL NETWORKS AND APPLICATIONS

Artificial Neural Network is a subdomain of Artificial Intelligence (AI) system which has been used recently to solve many variety of civil engineering problems. A neural network is an information processing prototype and a data-modelling tool that represents complex relationships with similar to the human brain. ANNs are known to be universal function approaches and are capable of exploiting nonlinear relationships between variables. Neural networks are a class of flexible nonlinear regression, data reduction models, and nonlinear dynamical systems. They consist of a large number of neurons, i.e. simple linear or nonlinear computing elements, interconnected in often complex ways and organized into layers according to (Sarle, April 1994).

The fundamental element of this model is the novel structure of the information processing system. It is composed of extremely interconnected processing elements termed neurons. Every neuron has a value, weight and bias (constant) where the neuron’s net input is the value of the neuron multiply by the weight plus the bias.

Layers composed of an input layer which contains the data to be classified by the network (independent variables), one or more hidden layers which do the processing, and an output layer which contains the desired output (dependent variable). Every layer contains of neurons connected to each additional neuron in the preceding layer by a connection that represents the weight. An example of an ANN with its several layers is shown in Figure 3. (S. D. Balkina, et al., 2000).

Activation functions: These are also called transfer functions that define the mappings from inputs to hidden nodes and from hidden nodes to outputs, respectively. (Math Works, 2019) ANNs have been applied effectively in solving in many civil engineering problems related to classification, prediction, and function approximation. In the transportation area, ANN has many applications and when applied to predict speed, for example, (J. McFadden, W. T. Yang, and R. Durrans, 2000) found it to offer predictive power superior to those of regression models. This is mainly because of their ability to model non-linearity, and flexibility with large complex data sets.

Auxiliary applications include the work of (Shoukry ,2005) who used the ANNs in classification of severity levels of accidents and reported several applications of ANN in the transportation field particularly in the traffic safety area.

(Chiou,2006) employed ANN to develop an expert system for the appraisal of two-car accidents (Xiangzheng Xu ,2009) applied the ANNs technique to estimate traffic safety in China, and (Wenhui,2009) researched the evaluation of safety in traffic accident scene based on ANN.

(Alkheder et al., 2017)used data from 5973 traffic accident records that happened in Abu Dhabi (2008 -2013) to develop an ANN model to forecast the degree of injury of road traffic accidents, which model had prediction performance about 74.6 % once using the testing set.

(Borja et al., 2018)was presented an approach for founding an accident risk prediction model, which can be used as a policymaking tool in infrastructure supervision. The method allows for an appropriate handling of the existing data, study show it can be used to develop models using artificial neural networks (ANNs) and creates a systematic optimisation process to determine the optimal architecture of the ANN model. Which was executed using data for accident counts for the Swiss national roads (2009 -2012). It was found that ANNs can be used as a practicable method to predict the frequency of road accidents. As accident rates are quite exceptional events, the data were categorized through a large portion of zero observations.

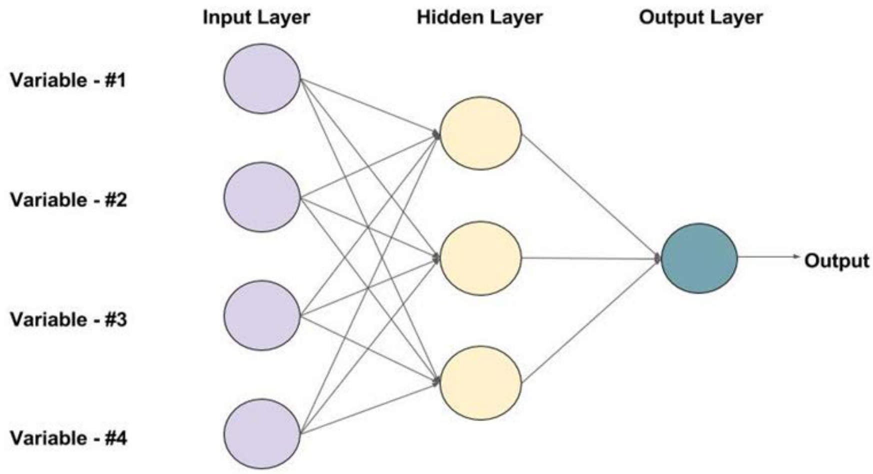

Figure 3: Typical layers in neural networks.

4. METHODOLOGY AND ANALYSIS

4.1 Case study

The collected data of the number of accidents covered a period of four years from 2014 to 2017 and relate to the road network of the many province of Spain as Segovia, Burgos, Madrid, Zaragoza, Soria, Guadalajara, Cuenca, Valencia, Toledo, Sevilla, Cordoba. The traffic accident data were collected from the General Direction of Traffic. Each accident data has several information such as the date, accident location, vehicle type, driver's gender, driver's age, accident type, the day and time, the number of fatalities, the number of injured persons, the number of involved vehicles, and the number of damaged vehicles.

In addition to these data, geometric characteristics of the highway such as 85th percentile speed, Annual Average Daily Traffic (AADT), the degree of horizontal and slope gradient in each section, were collected from ministry of public work and housing of Spain. After removing the absent and incorrect data, these data were categorized with 9 variables as shown in Table 1 (Çodur MY, 2012).

Variable	Variable Name	(Numerical /Binary) code
X1	Year (2014-2017)	Categorical Value (2012-2013-2014-2015-2016-2017)
X2	Segment length (m)	Numerical Value
X3	Slope gradient %	Numerical Value
X4	Radius of horizontal curve	Numerical Value
X5	AADT	Numerical Value
X6	Heavy vehicle %	Numerical Value
X7	85th percentile speed (kph)	Numerical Value
X8	Highway Sections	Categorical Value (A-1, A-2, A-3, A-4)
X9	Freeway Segment	Categorial Value (A-1(Segovia, Burgos, Madrid), A-2(Madrid, Zaragoza, Soria, Guadalajara), A-3(Madrid, Cuenca, Valencia) , A-4(Toledo, Sevilla, Córdoba))
Y	Number of Accidents	Numerical Value

Table 1: Input variables.

In order to analyze the traffic accidents on the highways, one needs to select highways that possess a wide variety of geometric and traffic characteristics. The aim of this data collection is to divide these highways into segments with homogenous characteristics as defined by(Deublein et al., 2015). After reviewing numerous highways around Spain, it was decided that A-1, A-2, A-3, and A-4 median-divided highways were most proper for this task (Çodur MY, 2012).

The highways with total of 655 km of freeway that connect around of Spain. These freeways are long enough to produce a satisfactory number of segments to develop the model. The information on highways includes geometric characteristics such as horizontal curve, slope gradient, and traffic characteristics such as AADT. A-1, A-2, A-3, and A-4 were divided into 3, 4, 3, and 3 highway segments, respectively and defined by any change in the geometric and highway variables. So, each highway segment is uniform with respect to all the possible geometric and traffic features (Figure 4). The freeway routes are as follows:

- (A-1) Segovia, Burgos, Madrid (101 km);
- (A-2) Madrid, Zaragoza, Soria, Guadalajara (231 km);
- (A-3) Madrid, Cuenca, Valencia (163 km); and
- (A-4) Toledo, Sevilla, Córdoba (160 km).

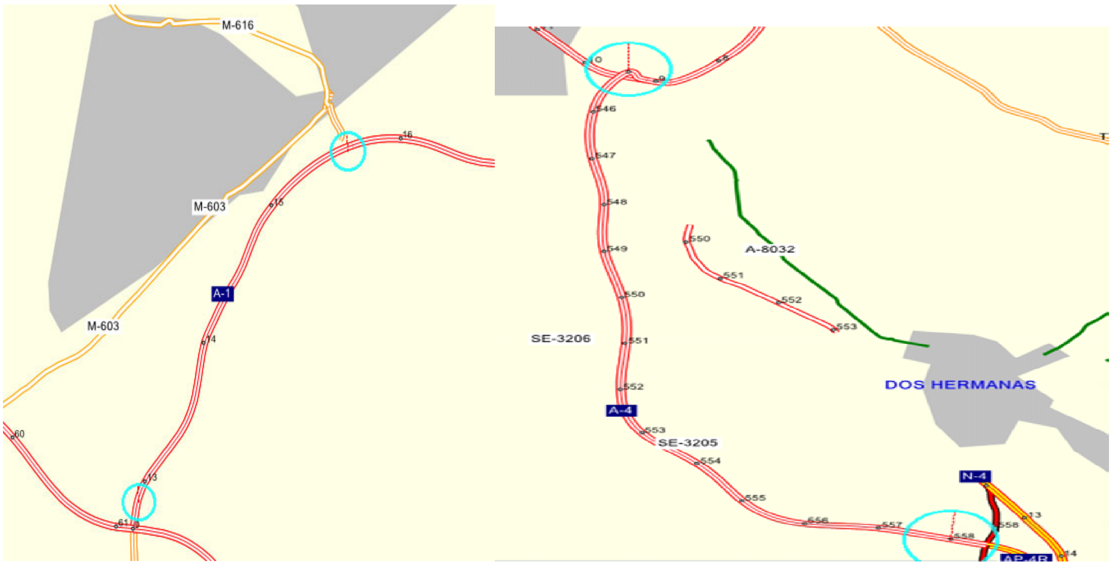

Figure 4: Spain's Freeway (Autovía).

4.2 Development of ANN models

The ANN models are multilayer feed-forward ANNs (i.e. no loops in the network) with between two and ten neurons in a single hidden layer and the equal number of neurons in the output layer as there are output variables. the number of neurons in the hidden layer (h_n) is different from 2 to 10, as advised by (Blum, 1992).

In the ANN model, independent variables are labeled as the input, and dependent variables are labeled as the output. Correlation analysis was performed to access the linear association between the variable. The results of the importance of variables relative to the number of accidents of the correlation analysis is shown in table 2. As of the parameters applied in modelling, eight significant parameters were found based on those criteria. Highlights are years, highway segments, section length (m), annual average daily traffic (AADT), the radius of the horizontal curve, slope gradient (percentage), heavy vehicle (percentage), and 85th percentile speed (km/hr).

The following nonlinear model is proposed to have the following form:

$$y = f\{[\text{years}], [\text{highway segments}], [\text{section length}], [\text{AADT}], [\text{slope gradient}], [\text{heavy vehicle traffic}], [\text{horizontal curve}], [\text{85th percentile speed}]\} \quad (2)$$

Where Y= the number of accidents

Data sets were divided into three sets: the training set (70% of the total data), the validation set (15% of the total data) and the test set (15% of the total data), these phases were performed using MATLAB. Training algorithms don't use the validation or test sets to adjust network weights. The structural design of the ANN was as shown in Figure 5, Personal Communication with(Mosa AL-Akhras, 2019).

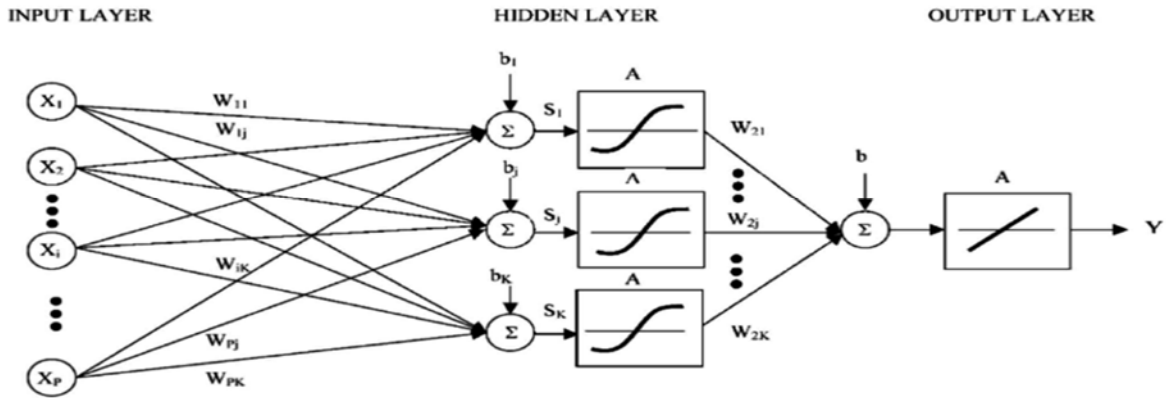

Figure 5: Structural design of the ANN.

The validation set may optionally be used to track the network's error performance, to identify the best network and to stop training if over-learning occurs.

The test set is not used in training at all, and it is designed to give an independent assessment of the network's performance when an entire network design procedure is completed. Selected activation functions were used for input hidden layer; Tan-sigmoid transfer function and for output hidden layer; Linear transfer function.

Variable name	Importance %
AADT	77 %
Segment length	53.4 %
Heavy vehicle percentage	50.3 %
Radius of horizantal curve	41 %
Slope gradiant percnetage	35.5 %
85^{th} percentile speed	22.7 %

Table 2: Importance of traffic accidents variables.

5. RESULTS

The Neural Networks allow the development of different alternatives by changing the number of hidden layers. Nine alternative models, with different number of hidden layers, were considered and Table 3 summarizes the results. Model 8 was found to be the best model with the highest coefficient of determination (R^2 =0.9992).

A comparison between the actual and the predicted values using model 8 produced the results shown in Table 4. The results were found to be very satisfactory with relatively small residuals especially in recent years where more reliable data bases are available through using more advanced data compilation techniques. The ANN model outputs are exhibited in Table 6.

Model No.	Number of hidden neurons (h_n)	Correlation Coefficient (r)
1	2	0.9668
2	3	0.9930
3	4	0.9772
4	5	0.9639
5	6	0.9900
6	7	0.9950
7	8	0.9871
8	**9**	**0.9992**
9	10	0.9927

Table 3: ANN models alternatives with different number of neurons.

R^2 is used to measure the nearness of fit. A perfect fit would result in R^2 approximately equal 1 , a very good fit near 1, and a poor fit would be near 0. In the ANN model R^2 is 0.9992 . This shows that the ANN model is an suitable method for analysing road traffic accidents.

Segment Name	Actual	Forecasted	Residual
Segovia(A-1)	9	40.783	-31.783
Burgos (A-1)	36	28.390	7.609
Madrid(A-1)	735	735	0
Madrid(A-2)	704	704	$-2.27e^{-13}$
Zaragoza(A-2)	325	325	$5.68e^{-14}$
Soria(A-2)	38	38	$-1.27e^{-13}$
Guadalajara(A-2)	183	183	$-5.68e^{-14}$
Madrid(A-3)	543	534.093	8.906
Cuenca(A-3)	42	42	$2.842e^{-14}$
Valencia(A-3)	481	481	0
Toledo(A-4)	209	209	$-8.526e^{-14}$
Sevilla(A-4)	62	53.445	8.554
Córdoba(A-4)	228	228	$-5.68e^{-14}$

Table 4: Actual and forecasted number of accident by ANN during four years (2014-2017) for model No. 8.

A summary of the results obtained from the regression model is shown in table 5. it reported the strength of the relationship between the dependant and independent variables.

R	R^2	Adjusted R Square	Std. Error of the estimate
0.976[a]	0.952	0.903	80.851

a. Predictors: (Constant), Speed, Segment_length, Slop, Heavy_veh, AADT, H.Curve

Table 5: Model Summary.

The multiple–correlation coefficient(R) reflects the linear correlation between the observed value and the expected value, it is large value reflects a strong relationship of how the independent variables can affect the predicted value of accidents.

The high value of R^2 indicates that 0.95 of the variation in accidents is explained by the independent variables in cooperated in the model. Table 6 shows the results obtained from the regression model.

The final regression model developed using the available data as the following form :

$$y = (\mathrm{B1} * 0.004) + (\mathrm{B2} * 7081.988) + (\mathrm{B3} * -11.383) + (\mathrm{B4} * 0.008) + (\mathrm{B5} * 3.07) + (114 * \mathrm{B6}) - 677.128 \quad (3)$$

Segment Name	Actual	Forecasted	Residual
Segovia(A-1)	9	-49.2	58.2
Burgos (A-1)	36	29.1	6.9
Madrid(A-1)	735	573.1	161.9
Madrid(A-2)	704	677.9	26.1
Zaragoza(A-2)	325	339.8	-14.8
Soria(A-2)	38	-58.4	96.4
Guadalajara(A-2)	183	121.6	61.4
Madrid(A-3)	543	605.5	-62.5
Cuenca(A-3)	42	141.8	-99.8
Valencia(A-3)	481	394.2	86.8
Toledo(A-4)	209	191.1	17.9
Sevilla(A-4)	62	28.7	33.3
Córdoba(A-4)	228	119.9	108.1

Table 6: Actual and predicted number of accidents using Regression.

A comparison between multiple linear regression model and the model produced by the ANN is presented in tables above ,it can be seen that the ANN model has better predictive power than regression model.

6. CONCLUSION

In this study, the factors that cause accidents are investigated, for providing road safety, and accident prediction models that include relations between these factors have been established. For the geometrical features of highways sections and traffic accident reports the years from 2014 to 2017 were used to form the database. The obtained data from the database in this study have been investigated with ANN as a tool of forecasting techniques. Since ANN method is a more flexible methodology also, capable of evaluating all of the traffic accident characteristics, it is selected for modelling the traffic accidents data.

The model results show that the traffic volume (AADT) with the high percentage (77%) is the most significant factor affecting the number of accidents on the highways. Heavy vehicle percentage and segment length have almost the same effect as the second important parameter. The degree of horizontal curvature is the third one and Slope gradient %, percentile speed have small influence on the output factor.

These results have suggestions for policy makers, transportation system designers, and researchers. Transportation safety designers cannot easily identify factors, make recommendations for incremental changes in the factor, and hope to achieve major differences in accident levels. The problems have to be evaluated from a multidimensional perception: a wide variety of geometric and traffic characteristics. Researchers similarly may adopt techniques such as neural networks for analysis of such variables. This paper goals to proposal and apply the potential of neural network analysis concluded an pattern of the accident prediction model in the transportation engineering.

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URBAN ROAD ACCIDENTS AND RIDEHAILING SERVICES: A STUDY OF DEPENDENCE IN MADRID

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ABSTRACT

Few studies have examined whether there is an association between these services and traffic accidents, and virtually all of the existing studies focus in cities of United States. In this study, we analyse the impact of ridehailing services on traffic accidents with at least one young person dead or seriously injured (16-39 years old) in the municipality of Madrid from 2014 to 2018. To do this, a regresion analysis has been carried out using a Random-Effects Negative Binominal Regression (RENB). The results of the model show that Uber and Cabify services are related to a reduction in urban accidents.

1. INTRODUCTION

Traffic accidents are one of the world´s leading causes of death among children and young people between the ages of five and twenty-nine. Around 1.35 million people per year die as a result of a traffic accident. Furthermore, between 20 and 50 million people involved in traffic accidents sustain injuries which, in many cases, result in a disability (World Health Organization, 2018).

In Spain, 1.755 people died in traffic accidents, according to the final balance of the General-Directorate for Traffic (2020). This figure includes people who died on interurban and urban roads during the 30 days following the accident. On urban roads, there were 519 deaths, 6% more than in 2018. Cities accounted for 30% of all deaths, the highest percentage since records have been kept.

The emergence of “ridehailing” platforms, such as Uber, which operates in more than 630 cities in 80 countries around the world (Uber, 2020), or Cabify, which is present in 11 countries and more than 90 cities in the world (Cabify, 2020), can improve the supply in demand segments that previously had difficulties to access taxis, thereby reducing road traffic-related deaths and injuries.

Despite the fact that two of Uber's top five markets are located outside of the United States, and that the majority of ridehailing trips worldwide occur beyond US borders, most studies of the relationship between the advent of Uber and road accidents have focused on the United States. Research from the United States has produced mixed findings, with some research observing a decline in at least some types of traffic fatalities following the rollout of Uber, but with other studies finding evidence for either no effect of Uber or even an increase in fatalities (Kirk et al., 2019; Barrios et al., 2019; Greemwood and Wattal, 2017; Martin-Buck, 2017; Peck, 2017; Dills and Mulholland, 2018; Morrison et al., 2018; Brazil and Kirk, 2016).

Most of these studies have analysed the impact of these services on alcohol-related road accidents. For example, A report by MADD (Mothers Against Drunk Driving) shows that this type of services offers positive results in terms of road safety: young people prefer to use this service as a designated driver instead of trying to drive themselves home after they had too much to drink.

The study results are also supported by other data: after UberX launched in cities across California, monthly alcohol-related crashes decreased by 6.5 percent among drivers under thirty (Flor et al., 2020).

Although alcohol consumption is one of the main causes of death in road accidents, this study focuses on Madrid, and ask whether the deployment of ridehailing services, as Uber or Cabify, has been associated with a significant change in the number of traffic accident fatalities and seriously injuries related young people, whether or not they have consumed alcohol.

If ridehailing yields declines in traffic fatalities and seriously injuries in Madrid and beyond, it may be advantageous for cities to partner with ridehailing companies to promote its use. Conversely, if ridehailing actually increases the risk of road accidents and fatalities, it may be advisable for cities to be cautious in their licensing and regulations with respect to ridehailing (Kirk et al., 2020).

2. METHODS

To analyse the impact of ridehailing platforms on traffic accidents in Madrid, the authors had to face two main challenges.

On the one hand, in a big city like Madrid, with more than 3 million inhabitants, there are large geographical contrasts. For this reason it was necessary to analyse performance by districts.

On the other hand, to carry out an indeph study of the traffic accidens, with young victim, ocurred in the period from 2014 to 2018.

It is also necessary to know the impact of Uber and Cabify as well as the evolution of other socio-economic factors on accident rates. To this end, it was decided to carry out a spatio-temporal analysis to establish a comparative analysis between the accident rate in the previous years to the implementation of these services and the years thereafter.

2.1 Sample

We used an observational panel study design to examine within-district changes in traffic accident fatalities and seriously injuries related young people before and after implementation of Uber and Cabify services for the period from 2014 to 2018. The analytic sample contained yearly observations of each of the 21 district of Madrid (Fig.1).

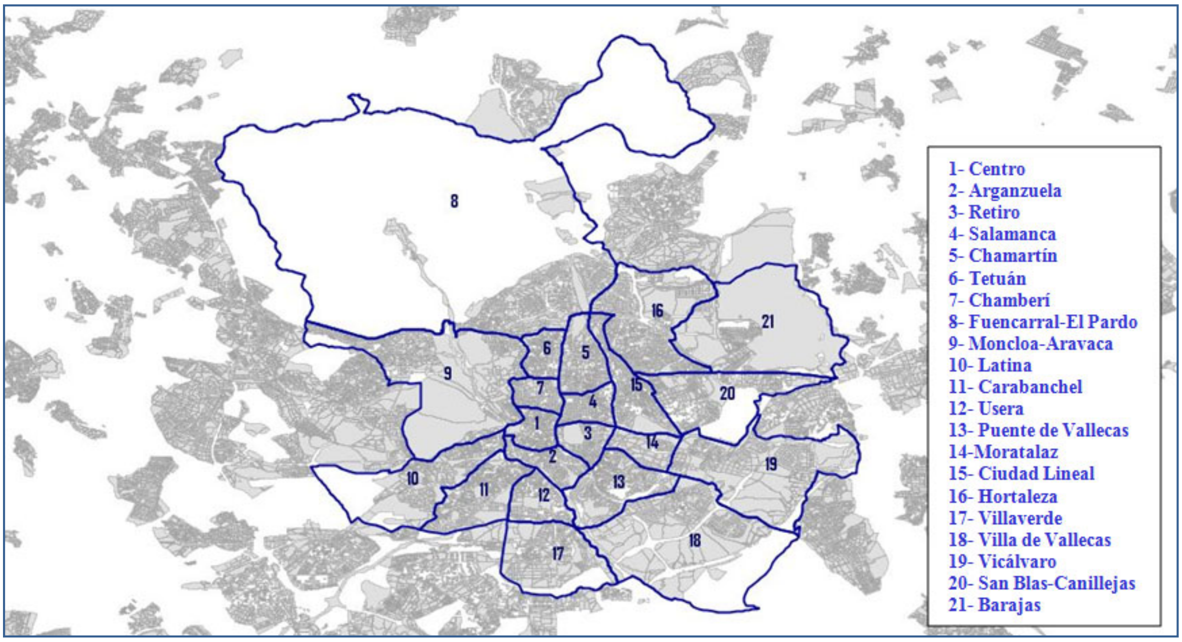

Figure 1: Map of the 21 districts of Madrid. Source: own research.

2.2 Dependent variable

According to the study carried out by Young and Farber (2019) in the city of Toronto, with regard to age, ridehailing users tend to be younger than average, and to be most often aged between 20 and 39 years old. Despite there being slightly more 30-39 than 20-29 years old ridehailing users, raidhailing trips made by 20-29 years old represent 2% of all trips conducted by individuals in this age group, which is more than double the share of raidhailing trip overall, making this age group the most likely to use radehailing service.

For this reason, in this study we wanted to analyse what has happened to accidents with victims in these age groups since the arrival of Uber and Cabify in Madrid. As all kinds of traffic accident variables have been considered, the dependent variables are divided into two separate group. In the first group, the age range for young victims cover from 15 years, in the case of involved moped accidents, up to 29 years.

The second group includes young victims from 30 to 39 years old. The two dependents variables measured for each of the 21 districts of Madrid are:

- total accidents with at least one fatality or serious injury between 15 and 29 years of age
- total accidents with at least one fatality or serious injury between 30 and 39 years of age

During the period from 2014 to 2018, a total of 2.182 accidents, with at least one young people death or seriously injured, were recorded (Fig.2). These data have been obtained from the City Council of Madrid which regularly publishes road accident data of the city and was produced by the Municipal Police. Each file includes a record for each person involved in the accident (drivers, passengers, pedestrians, witnesses, etc.), the type of accident (double collision, multiple collision, pedestrian impact, etc.), the time of the accident, the district, the street, the meteorological factors and the harm caused.

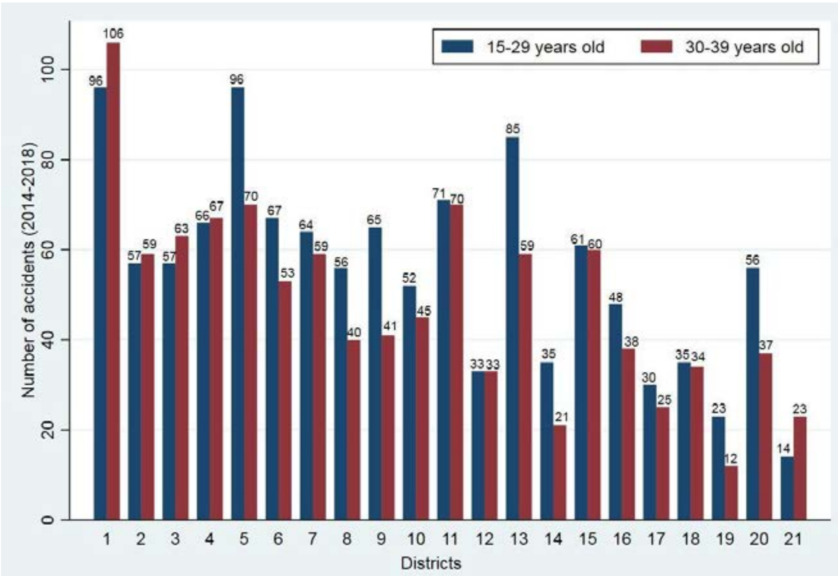

Figure 2: Crash count distribution in each district of Madrid. Source: own research.

2.3 Independent variable

The measure of Uber and Cabify deployment is a binary indicator of whether, in a given year, Uber or Cabify had established services in Madrid.

Cabify arrives in Madrid in 2011. Although it may seem logical to consider years prior to 2014 for this study, 2016 has been considered as the first year in which these services have been operating in the city of Madrid for two main reason:

- Uber arrives in Madrid in 2016
- In the case of Spain, the companies running the ride-hailing platforms Uber and Cabify recorded a considerable increase in revenues from 2015 onwards (Fig. 3).

The revenues of these companies in previous years reflect that the weight of these platforms might not be significant, as they were not yet well known among users.

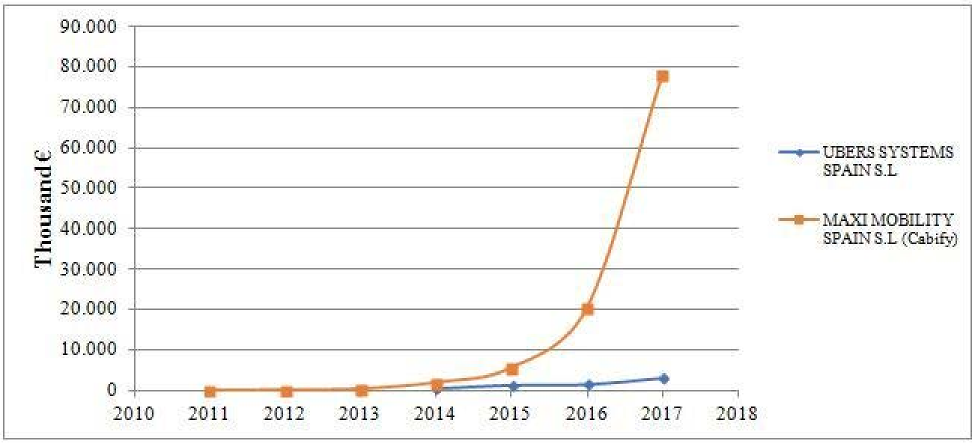

Figure 3: Evolution of Uber and Cabify income in Spain. Source: own research.

It has also been considered relevant to take into account other factors associated with crash risk. In previous studies, investigators found evidence that population influenced the rate of driver fatalities (Kirk et al., 2020). Dumbaugh and Rae (2009) studied how urban form—specifically land use and street network configurations— may influence the incidence of traffic-related crashes injuries and deaths in the City of San Antonio (Texas, USA).

The results showed that specific types of commercial land uses, such as big box stores, are related to a higher risk of accidents. Therefore, for this analysis we have taken into account the number of leisure establishments per district as points of attraction for drivers. We have also taken into account the density metro/cercanias station per district (equation 1), as a if young people do not have their own vehicle or a metro/cercanias station nearby, they may be captive to these services, generally cheaper than taxis. These data have been obtained from the City Council of Madrid publishes in its open data bank.

$$Density\ Urban\ Transport = Population/Number\ of\ metro\ stations \quad (1)$$

Table 1 shows a summary of the variables considered in this analysis.

Variables	Definition
Total accidents (15-29 years old)	Number of total accidents in each district of Madrid with at least one fatality or serious injury between 15 and 29 years of age
Total accidents (30-39 years old)	Number of total accidents in each district of Madrid with at least one fatality or serious injury between 30 and 39 years of age
Population	Number of people registered in each district
Leisure Establishments	Number of premises dedicated to the catering, leisure and entertainment activities
Density Metro/Cercanias Stations	Indicator calculated from the population of each district and the number of metro/cercanias stations.
Ridehailing	Year dummy variables 1: Uber or Cabify presence 0: neither Uber nor Cabify

Table 1. Explanatory variables. Source: own research.

2.4 Modelling urban traffic accidents

Models such as the Poisson regression, the Negative Binomial (NB), the Zero-inflated Negative Binomial (ZINB) or Multivariate analysis are frequently applied for statical analysis at the section level, but limitations in the available methodology should be tested (Lord and Mannering´s, 2010).

Considering the Madrid database of the study, over-dispersion affects the registered data corresponding to road accidents. This is one notable characteristic of crash-frequency data: the variance exceeds the mean of the crash counts, and indicates that the most common count-data modelling approach (the Poisson regression model) cannot be used.

Consequently, the most common models applied with over-dispersion and cross-sectional data are the Negative Binomial model and the Zero-Inflated Negative Binomial or ZINB model. The latter is applied when the database has a large number of zero-crash observations, thus the most appropriate model for this case is Negative Binomial, which can account for overdispersion (Casares et al., 2019).

Moreover, temporal analysis has to be included in the modelling. In other words, information has been gathered from several individuals (districts) in a given moment during various periods of time (series of years) and the best of way of processing this data is by using a cross-sectional panel data structure.

Therefore, the multivariate analysis cannot be used. As a result, the most common models applied with cross-sectional data and in the case of over-dispersion are the Negative Binomial model and the Zero-inflated Negative Binomial or ZINB model. The latter is applied when the database has a large amount of zero shock observations, so the most appropriate model for this case is the Negative Binomial model, which can explain the excessive dispersion.

However, in this case, and as we have previously seen, the accident data have been collected from 21 districts over a period of five years, which means that the data could have specific location effects and it is likely that they are serially correlated.
If there are spatial effects in the data that cannot be considered as such, the estimated standard deviations of the regression coefficients will be underestimated, as each observation actually contributes less information than the real one (Chin and Quddus, 2003). For this reason, it was decided to consider the Random-Effects Negative Binomial Model (RENB).

3. RESULTS

As previously mentioned, the study was conducted using data corresponding to the period between 2014 and 2018. Table 2 provides descriptive statistics of the variables.

	Obs	Maximum	Minimum	Standard Deviation	Mean
Dependent variables					
Total accidents (15-29 years old)	105	27	2	5,67	11,11
Total accidents (30-39 years old)	105	24	0	5,26	9,67
Independent variables					
Population (per 1.000)	105	253,433	45,95	54,11	152,67
Leisure Establishments (per 1.000)	105	3,22	0,058	0,61	0,86
Density Urban Transport	105	29.800,8	6.028,14	7.177,76	14.256,78
Ridehailing	105	1	0	0,49	0,6

Table 2: Descriptive statistics. Source: own research.

Both models are statistically significant as shown in Table 3. The ridehailing services variable is statistically significant with a negative coefficient in model 2, showing that the entry of ridehailing services has reduced young casualty crashes aged 30-39 years old.

	Dependent variables	
	Model 1	**Model 2**
Independent variables	**Total accidents (15-29 years old)**	**Total accidents (30-39 years old)**
Population	0.00379** (3.20)	0.00338** (2.89)
Density Urban Transport	-0.0000158 (-1.71)	-0.0000194* (-2.13)
Leisure Establishments	0.275** (2.80)	0.358*** (3.78)
Ridehailing	-0.0789 (-1.07)	-0.215** (-2.94)
Ln_r	4.407*** (7.50)	5.020*** (6.66)
Ln_s	3.649*** (5.77)	3.676*** (5.11)
Log-likelihood with constant only	-325.5092	-317.26
Log-likelihood at convergence	-297.60511	-281.98443
Ratio of log-likelihood index (ρ^2) and adjusted log-likelihood index (ρ^{-2})	0.091, 0.074	0.111, 0.10
Prob > chisq	0.0000***	0.0000***
LR test vs. pooled: chibar2(01), Prob>=chibar2	7.05, 0.004	4.69, 0.015
Hausman Test: chi2(8), Prob > chi2	4.87, 0.3012>0.05	6.67, 0.1547>0.05
***Significant at 0.001 level **Significant at 0.01 level *Significant at 0.05 level		

Table 3: Results of the estimated model (z-statistics in parentheses). Source: own research.

As for leisure establishments, this variable is significant with a positive coefficient in both models, which means that there is a strong relationship between agglomerations of leisure venues (restaurants, pubs, theatres, cinemas...) and a higher concentration of accidents with young people seriously injured or killed in the municipality of Madrid. With respect to the influence of the population on traffic accidents, this variable is also statistically significant with a positive coefficient in the two models, which shows that a higher level of population generates more traffic and, as a result, gives rise to an increase in traffic accidents, in the same way as in the study carried out by Casares *et al.* (2019). With respect to Density Urban Transport this variable is significant with a negative coefficient in Model 2, indicating that a higher number of metro stops decreases accidents with young people 30 to 39 years old.

4. CONCLUSIONS

The findings presented in this study reveal that the arrival of ride-hailing services in the Madrid municipality is related to the decrease in accidents with seriously injuries or deaths with young people aged between 30 and 39 years. The analysis also shows that metro stations decreases road traffic fatalities and serious injuries in this group of young people. Furthermore, population, as well as the presence of leisure establishment, increase traffic accidents with young people.

Finally, this study has only considered the traffic accidents with at least one person dead or seriously injured with young people aged betweeen 15 and 39 years. But it is very interesting to analyze what happens with other types of accidents. That is why, at present, this line of investigation continues and it is being analyzed how others variables and the presence of Uber and Cabify affect the 21 districts of Madrid, considering other kinds of road accident variables.

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ESTUDIO DE LA SEVERIDAD DE ACCIDENTES DE TRÁFICO DE AUTOCARES Y AUTOBUSES EN ARGENTINA Y ESPAÑA CON ÁRBOLES DE CLASIFICACIÓN

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RESUMEN

El transporte colectivo de personas en autobús y autocar es muy importante en la mayoría de los países de Iberoamérica, y los accidentes de tráfico con implicación de estos vehículos involucran pérdidas elevadas si se consideran las pérdidas humanas, materiales y de productividad de las empresas del transporte. En cualquier país del mundo en el que éstos eventos ocurren, tienen un alto impacto mediático y avivan la preocupación por la mejora de la seguridad y la protección de los ocupantes. En la región de América del Sur, la mejora de la seguridad vial necesita alcanzar un mayor nivel de desarrollo de los sistemas de información que permitan llevar a cabo una investigación detallada y en profundidad.

Para suplir la escasez de información detallada de los accidentes con implicación de autobuses y autocares del transporte colectivo de personas (AT-TCP), cinco equipos de investigadores de las universidades: UPM de España, UPS de Ecuador y UTN, UNSa y UNTDF de Argentina, participaron en un proyecto cooperativo de investigación de accidentes en transporte colectivo de pasajeros (COOPERAXVII-12) ocurridos en los tres países y desarrollaron una metodología de análisis de datos tomados de publicaciones en medios de comunicación y datos oficiales disponibles, enfocado en el desarrollo de estudios de patrones y aplicación de modelos estadísticos.

En este trabajo se evaluó la severidad de una sub-muestra de 94 accidentes AT-TCP ocurridos en Argentina y España entre los años 2017 y 2018. Los datos fueron analizados con modelos de minería de datos: árboles de clasificación y bosques aleatorios. Los modelos permiten identificar los factores de influencia en la severidad del accidente y algunos patrones según el contexto y concurrencia de diferentes factores. De los resultados, se destaca que los accidentes de mayor severidad han ocurrido en vías interurbanas y son de tipo colisión entre vehículos, vuelco sobre la calzada y salidas de la vía con desbarranco.

1. INTRODUCCIÓN

El transporte colectivo de personas por vía terrestre, tiene una función vital en todos los países y en especial en aquellos en los que los costos del transporte por medios más veloces son elevados para grandes sectores de la población. En los países en los que existe un sistema de transporte de personas de mayor desarrollo, los medios de alta velocidad ferroviario, ofrecen a los ciudadanos una oferta mayor en un sistema competitivo de precios del transporte. Pero en países sin un sistema de transporte con alternativas, el realizado con autobuses y autocares (AyA) cumple un papel vertebrador del territorio y de la economía. Los impactos negativos del transporte como los accidentes de tráfico en todo el mundo superan el número de 1.200.000 víctimas mortales, con las consecuencias graves desde el punto de vista humano y económico dentro de la colectividad. Distintos organismos (World Health Organization (WHO) – UN) coinciden en señalar a los accidentes de tráfico como una de las principales causas en la pérdida de vidas humanas y especialmente en los colectivos de edades más tempranas. Villar Fernández, (2012) señala que los accidentes de tráfico son la segunda causa de muerte, y la primera dentro de la población juvenil comprendida entre 15 a 29 años, siendo uno de los principales problemas de Salud Pública en España.

En referencia a pérdidas humanas en España, durante el año 2017, los diferentes miembros policiales notificaron 102.233 accidentes con víctimas. Estos accidentes ocasionaron 1.830 fallecidos (en el momento del accidente o hasta 30 días después del mismo); además, 9.546 personas fueron ingresadas en un centro hospitalario y 129.616 resultaron heridas no hospitalizadas. Del total de víctimas en accidentes de tráfico con implicación de autobuses, se produjeron 3 muertos, 47 personas fueron ingresadas en un centro hospitalario y 1.171 resultaron heridas no hospitalizadas. La mayoría de ellos (87%) se produjeron en vías urbanas , los restantes (el 13%) en interurbanas, siendo la lesividad de los accidentes, en general, mayor en vías interurbanas. (DGT, 2017).

La Asociación Civil Luchemos por la vida de Argentina en el año 2017, reporta que 5.420 personas fallecieron (en el lapso de los 30 días posteriores al accidente), 6.626 resultaron heridos graves hospitalizados y 51.945 con heridas leves en los accidentes de tráfico ocurridos.

Otra fuente de Argentina (Anuario estadístico de siniestralidad vial) reporta para el mismo año: 5.472 víctimas fatales; 113.805 heridos, de los cuales 8.174 son graves que requerían hospitalización, en un total de 81.592 siniestros ocurridos. Las principales causas de muerte por accidentes de tránsito fueron: la velocidad y el consumo de bebidas alcohólicas. Para los peatones y los conductores, el problema principal es la distracción. De los números expuestos para Argentina, se deduce que existe dispersión entre ellos según las fuentes y no se disponen de datos desagregados para el estudio científico de los accidentes con AyA.

Contrariamente, en España, existe un sistema de información accesible a los investigadores y que posibilita la realización de estudios de investigación de colectivos de interés (vulnerables, transporte de viajeros, trabajadores in itinere, etc.).

El cuestionario aplicado en el proyecto de investigación COOPERA TCP se ha creado teniendo como base el existente en España, que la DGT aplica para la recogida de datos in situ. El cuestionario COOPERA TCP incluye además campos para las variables de infraestructura obtenidas con Google Maps, con las coordenadas del lugar del accidente en el marco del proyecto de investigación de accidentes con implicación de autobuses y autocares, en el que participaron varias universidades de 3 países participantes (Argentina, Ecuador y España).

Este trabajo analiza una muestra de accidentes de tráfico en Argentina y España, donde se han visto implicados autobuses y autocares, con el objetivo principal de identificar las variables que influyen en la severidad de los accidentes.

Para la identificación de los factores de influencia se utilizan modelos estadísticos cuyo análisis que permitirá realizar un diagnóstico más riguroso y completo dentro de los límites que proporcionan los datos disponibles. Con este estudio se pretende profundizar en el conocimiento de la situación accidentológica de AyA en los países participantes, con limitaciones en el acceso a los datos necesarios para tal fin.

El desarrollo de estudios como éste permitirá analizar los fenómenos causales y extraer los patrones y combinaciones de variables de influencia, y así adoptar las mejores decisiones para la mejora de la seguridad del transporte colectivo de personas.

2. MATERIALES Y MÉTODOS

2.1 Metodología de recolección de la información

El estudio toma como base el proyecto COOPERA-TCP que estandarizó una herramienta de recolección de datos de accidentes de tráfico de autocares y autobuses (Arenas et al., 2018), y de otros vehículos TCP como microbús, combi, autocar de un piso, microbús y autocar de dos pisos en los países participantes. La recolección de datos se realizó entre 2017 – 2018, para la cual se utilizó la metodología de búsqueda, localización y análisis de medios de comunicación masivos. Esta información se contrastó con las bases de datos disponibles en el país y la información se recogió en el instrumento destinado para la recopilación de datos en formato digital.

El formulario utilizado para la ejecución del proyecto reúne los datos de accidentes, de la vía en donde ha ocurrido el accidente y del estado en el que han quedado los vehículos de transporte implicados en el accidente de tráfico, por lo cual contiene campos con las variables de interés para abordar estudios científicos en países de Latinoamérica.

En la figura 1 se presentan los factores del formulario del proyecto COOPERA-TCP, basados en la estructura del modelo MIICA.

Número de factor	Factores de influencia y otros	Tipo de factor de acuerdo a MICAA
1	Datos generales	Datos del momento y espacio. Geo-referenciación.
2	Tipo de vía	Infraestructura
3	Tipo de servicio del autobús o autocar / TCP	Vehículos
4	Lugar	Dato de tiempo y espacio
5	Tipo de accidente	
6	Condiciones en el momento del accidente	Condiciones ambientales y del tráfico
7	Vehículos	Vehículos
8	Datos de los ocupantes (conductor, pasajeros, otros) y víctimas	Actores del tráfico
9	Datos del conductor del autobús o autocar / TCP	Actores del tráfico
10	Evacuación de las personas lesionadas	Otros datos - aportes de datos para la investigación del siniestro
11	Presuntas infracciones del conductor	Actores del tráfico
12	Posible responsabilidad del accidente	Actores del tráfico
13	Factores que pudieron afectar la atención y presuntos errores del conductor	Actores del tráfico
14	Descripción del accidente	Otros datos - aportes de datos para la investigación del siniestro
15	Daño estructural en el autobús o autocar / TCP	Otros datos - aportes de datos para la investigación del siniestro
16	Esquema de daños en los vehículos	Otros datos - aportes de datos para la investigación del siniestro

Figura 1: Factores y datos recogidos en el formulario de accidentes del Transporte colectivo de personas – Proyecto COOPERAXVII-12 (TCP). (Arenas et al., 2018).

La base disponible para este trabajo está conformada por una muestra de 94 accidentes ocurridos en España y Argentina y contiene más de 80 variables. El análisis realizado permite resaltar la potencialidad de la metodología de COOPERA-TCP y de las herramientas propuestas para los objetivos planteados.

Se ha realizado una selección de variables con varios criterios (como evitar repetición de la información, valores nulos o vacíos, etc.) y con modelos Random Forest (RF) considerando su error de clasificación. Se seleccionan las 13 variables superiores en la clasificación con las que se elabora un modelo final. Las 13 variables explicativas se han agrupado en 4 grupos: factor infraestructura, vehículo, entorno y factor humano. Con las variables seleccionadas, se desarrollará un modelo de análisis de la severidad del accidente.

2.2 Metodología estadística para el análisis

2.2.1 Modelos de bosques aleatorios (Random Forest (RF))

Es una versión sofisticada del procedimiento bagging, señalada por (Breiman, 2001), que replica subconjuntos de registros y elige al azar un subconjunto de las variables de entrada (Hastie, Tibshirani, & Friedman, 2008). La herramienta indicada se enfoca en la técnica de aprendizaje automático estándar denominada "árbol de decisiones. Esta metodología también se usa para análisis de sensibilidad (Grömping, 2009).

La técnica de conjuntos de árboles tienen enfoque clásico o frecuencista, y el algoritmo utilizado es el RF (Random Forest de R Core, 2016). Este algoritmo optimiza la precisión en la clasificación mediante la incorporación de aleatoriedad en la construcción de cada clasificador individual. Para la selección y optimización se utilizan dos índices: criterio de Gini y de clasificación.

El mecanismo de construcción de RF establece un baremo que prioriza cada variable en la predicción final. Para ello se calcula el error de la muestra. Para cada variable de la muestra, se intercambia un par de elementos y se calcula el error de la muestra permutada. El resultado debería ser peor que para la muestra original. Este procedimiento se realiza para todos los valores de cada variable y se calcula el promedio. El proceso es realizado para todas las variables. Las variables de menor importancia deberían alterar menos la diferencia entre el error y el error permutado que las variables importantes.

2.2.2 Modelos de árboles de clasificación (CART y Rpart)

Los modelos de Árboles de clasificación son una técnica de aprendizaje controlado para modelar relaciones entrada – salida, no paramétrica, de segmentación binaria, esto es, las particiones se hacen de forma permanente hasta alcanzar un criterio de parada, es decir que el árbol se construye dividiendo los datos repetidamente, en cada nueva división los datos son divididos otra vez en dos grupos mutuamente excluyentes.

El enfoque algorítmico más habitual para el CART creado por (Breiman, Friedman, Stone, & Olshen, 1984) produce de manera inicial un árbol muy grande, para consecutivamente podarlo; es decir, recortar ramas que no incrementen su capacidad predictiva. El grado de poda se define en función de un compromiso entre bondad de ajuste y confusión del árbol, o incluyendo también criterios de precisión de una validación cruzada.

La figura 2 muestra un nodo raíz o madre, que se divide después en nodos hijos, y finalmente el procedimiento de partición se aplica a cada nodo hijo por separado. Estas divisiones se seleccionan, de modo que la impureza de los grupos hijos sea menor que la del grupo madre. Este procedimiento tiene por objetivo, discriminar la respuesta en grupos homogéneos, de tal manera que se pueda mantener el árbol relativamente pequeño. (Pillajo et al., 2018).

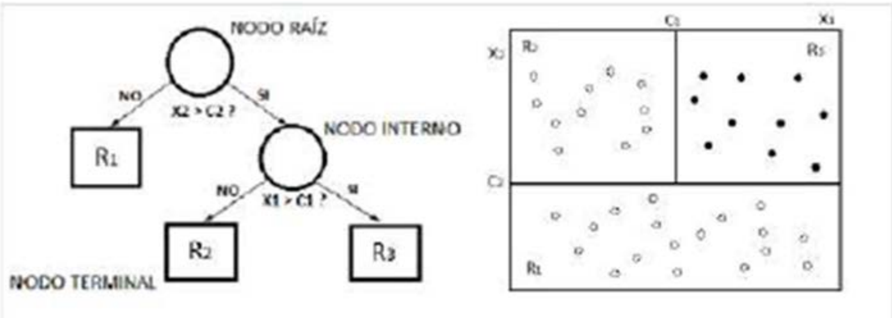

Figura 2: Descripción de objetos de un árbol de clasificación (Zhang / Singer, 2010).

Mediante la función Rpart del programa R, se analiza el modelo de clasificación con las 13 variables seleccionadas previamente con RF y se ejecuta la poda del árbol en función del % de error relativo y del índice de complejidad de división CP óptimo para generar el árbol de clasificación final.

3. RESULTADOS Y DISCUSIÓN

A continuación, se muestra el análisis descriptivo de los datos concernientes a la muestra de 94 accidentes de tráfico de autocares y autobuses ocurridos en las carreteras de Argentina y España implicados entre los años 2017– 2018.

En la Tabla 1 se indica los accidentes según tipo de vehículo de la muestra.

Argentina				Total	España				Total
Autocar/Micro		Colectivo/Autobús			Autocar/Micro		Colectivo/Autobús		
N.º	%	N.º	%		N.º	%	N.º	%	
30*(0.6)*	31.91	20*(0.4)*	21.28	50*(1)*	37*(0.84)*	39.36	7*(0.16)*	7.45	44*(1)*

Tabla 1: Descripción accidentes de TCP en Argentina y España.

El número de accidentes de tráfico con implicación de Autocar/Micro es mayor en España, con un total de 39.36% en comparación con el 31.91% de Argentina. Por otra parte, en lo que concierne a accidentes de tráfico con Colectivo/Autobús, se observa una mayor incidencia en Argentina con el 21.28% en relación a la de España (el 7.45%). Los porcentajes se han tomado en base a los 94 accidentes en los dos países.

Con respecto a Argentina se produjeron más accidentes de tráfico en los que estáninvolucrados Autocar/Micro, el 60% en comparación con la implicación de Colectivo/Autobús que alcanza el 40%. Lo mismo sucede en España con una mayor implicación de Autocar/Micro en accidentes (el 84%).

Se puede identificar que en cualquier relación ya sea en función de los 94 accidentes o por país, en España existe un mayor número de accidentes con tipo de vehículos TCP Autocar/Micro.

Se han generado dos graficas de árbol de clasificación (Fig. 3 y 4) para Argentina y España respectivamente por medio de modelos CART de severidad de los accidentes de tráfico de TCP para las que se ha utilizado el Software R Studio. Dentro de la misma la librería llamada “rpart” que se encarga de realizar los cortes para las ramificaciones, que se han utilizado para el cálculo de Cp (Complexity parameter) y el Error Relativo. La elección de las variables más importante se realizó con RandomForest (RF) de R Studio para la variable respuesta “severidad”. Con respecto a Argentina indica que la variable más importante es el Tipo de arcén, en segundo lugar el tipo de accidente, tercer lugar el tipo de vía, mientras que para España la variable más importante es el Tipo de vía, seguido de Tipo de accidente y en tercer lugar Responsable; con lo cual se aprecia que dentro de los tres primeros lugares están presentes en los dos países las variables Tipo de accidente y Tipo de vía, lo cual indica que estos dos son la factores que más inciden en la severidad de accidentes de tráfico con autocares y autobuses.

Figura 3: Árbol de severidad de Argentina.

En síntesis, en Argentina cuando el tipo de arcén es natural, o cuando está en mal estado, pavimentado u otros, el tipo de accidente es un alcance, y el accidente se ha producido en una intersección resultaría una alta lesividad.

Figura 4: Árbol de severidad de España

En España, cuando el tipo de vía es autopista o carretera de doble sentido y el tipo de accidente es por alcance al autobús, salida de la vía con desbarranco, salida de la vía u vuelco la severidad es alta. De la misma manera , si el tipo de accidentes es por alcance del autobús, choque o vuelco sobre la calzada, y el estado de la vía es mojado y ambos vehículos implicados son responsables, el accidente tiene una alta severidad.

4. CONCLUSIONES

Al existir un incremento de la velocidad en carretera para el tipo de vehículo ‘autocar’, la colisión tiende a ser más grave, por lo que se manifiesta una mortalidad mayor, y no hay diferencias significativas en Argentina con respecto a España.

El factor infraestructura (referente a tipo de vía) es el que resulta con mayor connotación; así como también el factor humano (responsabilidad) en algunos tipos de accidentes.

Los vuelcos de autocares son los accidentes más severos tanto en Argentina como en España, en comparación con autobuses (que se mueven más en ámbitos urbanos o suburbanos).

El método descriptivo estadístico utilizado con BBDD-AyA, es adecuado para identificar y comprender los factores y características que influyen en los accidentes de tráfico con implicación de autocares y autobuses tanto en España como en Argentina. La metodología aplicada en este estudio ha permitido realizar e interpretar clasificaciones claras de variables y combinaciones que determinan la severidad de los accidentes con implicación de AyA.

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THE ROLE OF DRIVERS' SCHEMES ON TRAFFIC SIGNS COMPREHENSION.

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ABSTRACT

Current road signs confront a fundamental issue: are signs displayed in different devices (posted, on-board, painted or electronic) making the most of the same design rationale? Convergent design principles help drivers enjoy an easier coding, learning and retrieval of the schemes enhancing comprehension. This paper focuses on posted road signs (painted vs electronic) that locate events and how well they complement each other. Fixed signage must be the starting point (*the scheme formed*) to investigate how electronic devices (*the new information*) can functionally locate variable events or situations.

The paper presents preliminary data regarding a sample of 39 participants. The experimental task consisted of 27 blocks of traffic signs. Electronic-adapted traffic signs were shown to all participants; however, only one group was exposed also to fixed (painted) signs. A 3x2 mixed design was used (experimental condition as inter-group factor and event location as intra-group factor), and in addition, the design also included a working memory measure as a covariate. Comprehension rates were high in all formulas of event location. As previous studies, time response showed higher means when the variable event is located 'between' two referents. Moreover, 'working memory (WM) span' showed a marginal significance with time response. This result leads to an interesting question about the consideration of influence of individual differences in WM capacity when designing complex traffic messages. Overall, results highlight the importance of understanding how complex traffic messages are encoded, processed and de-encoded, and the limits human WM may pose.

1. INTRODUCTION

In our interconnected and globalized world it is essential that the main communication routes exhibit effective and functional signage for all drivers (Shinar & Vogelzang, 2013). In consequence an adequate integration of the different road message display devices must be ensured: fixed or electronic panels, on-board systems, etc. At this point considering the characteristics and limitations inherent to the cognitive systems of drivers is essential.

This work addresses the case of electronic signage, specifically, complex traffic signs that inform about the location of circumstantial or variable events (congestion, snow, construction sites).

In this type of signal, the content displayed is specific to each situation. This implies that it is not possible to simply 'recover' or 'remember' the meaning from the previous knowledge, but rather that its understanding requires reasoning processes that must be carried out in real time while driving.

1.1. Traffic signs state of art

Despite the importance of traffic signs messages, its comprehension is not always guaranteed (Ben-Bassat et al. 2019; Arbaiza & Lucas-Alba, 2012). Nowadays, a driver can see and understand similar painted signs in different places (68 countries have ratified the 1968 Convention; UNECE, 1968). However, when it comes to electronic devices, design guidelines are not fully developed. Several aspects regarding traffic configurations are established by national regulations, facing less consistency than painted signage (Ben-Bassat et al., 2019).

In Spain, electronic signals in the national territory are mainly exhibited in Variable Message Signs (VMS) with a hybrid matrix (Fig. 1b). VMSs inform about possible re-routings or variable events on the road (works, congestion, fog, snow; Arbaiza & Lucas, 2012), among others. Focusing on painted signs, the Confirmation Signs in particular (CS, Fig. 1a; S600 / S-699; BOE, 2014) have special relevance because they are frequently displayed on the roads, and are the main way drivers learn to locate places in the road network. The CSs constitute the reference matrix through which drivers understand and anticipate situations and events along the network.

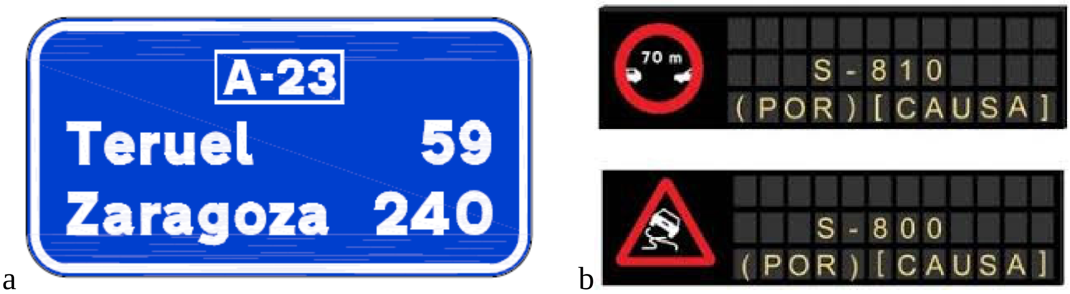

Figure 1: (a) Confirmation Sign (CS); (b) Variable Message Sign (VMS).

This is a key point since the drivers gains in safety and mobility depend on their adequate anticipation of road situations, including their comprehension of complex traffic signs. This research explores if fixed signs facilitate the understanding of new VMS, which electronic format designs are best suited for integration with existing signage, and the cognitive benefits that a better integration of signalling systems could bring to drivers.

1.2. The role of human cognition: schemes and working memory

According to Carroll (2008), a person is able to understand a situation when she is able to activate a memory scheme to assimilate the coming information. Similarly, we propose CS as the starting point (the formed scheme) to investigate the functionality and comprehension of VMS (new information).

One of the VMS functions is to inform about variable events. VMSs display something new when they are presented to the driver. Although some elements can be recovered from the Long-Term Memory (LTM; pictograms, numbers; Arbaiza & Lucas-Alba, 2012), drivers must integrate all the elements (new, known) in real time, and also determine the rules that govern their composition to decode VMSs. Figure 2B shows an example of a circumstantial event (congestion) located at a distance (31 km), before two reference points (Serrada and Alcores).

a b

Fig. 2. (a) Confirmation Sign (CS); (b) Adapted Sign from VMS (AS).

Extracting or decoding the meaning of the traffic message implies that the driver must keep the new (circumstantial) elements of the sign active, as well as those recovered from the LTM in WM (Baddeley and Hitch, 1974). This task must be carried out in real time while driving. However, WM has a limited processing capacity (typically, ±7 units, along roughly 30-60s), so the cognitive load should not exceed these constraints (Baddeley, 2000). At some point, individual differences in people's WM capacity may be important too (Just & Carpenter, 1992), so different tasks have been developed to measure WM capacity (e.g., the Reading Span Test; Daneman & Carpenter, 1980).

1.3. The location of variable events

Previous studies have shown a consistent pattern of results in VMS location formulations concerning a fixed reference point (eg, a city). Drivers understood well (comprehension rates of around 70%) that a variable event (congestion, road works) is located 'before' or 'between' cities, compared to events located 'after' a city (30-40% comprehension rates). (Lucas-Alba et al., 2016). In those cases, the formats tested did not include the numeric distance to events or locations, making the information less determined (Tversky, 2005). Incorporating numeric distance, and approaching the ASs structure to CSs one, could diminish ambiguity promoting higher comprehension rates.

1.4. Objectives and hypotheses

This study intends to determine if the previous exposure of CS affects the subsequent comprehension of the signs adapted to the electronic format of VMS (AS; Fig. 2b) in terms of comprehension rate and response time and if individual differences in WM relate to drivers' performance.

We hypothesize:

- The adapted sign (AS) provides a strong structure obtaining high comprehension rates (higher than previous studies). A ceiling effect on comprehension (no differences between experimental / control) could be observed.
- The previous presentation of a CS facilitates comprehension in terms of response time. Therefore, the experimental condition (presence of CS) will obtain a lower mean response time compared to the control condition (absence of CS).
- Individual differences in WM might be related to performance in the experimental task.

We expect that higher scores in the working memory measure will be related to a shorter response time. Additionally, there will be no significant correlation in the case of comprehension rate, since the cognitive load involved does not exceed the limits of WM.

2. METHOD

2.1. Participants

The sample was made by 39 (30 women), between 18 and 35 years (*M* = 22.36; *DT* = 4.69), mostly university students (87.2%). Participants were required to be in possession of a driving license (82.1%) or having passed the theoretical part of the driving license. Full drivers were asked how frequent their driving on the highway was; 25.6% indicated 'sometimes' and 38.5% 'often' (the rest indicated 'never' or 'not applicable'); their driving experience was relatively short: 84.7% drove for less than 5 years, 15.4% between 5 and 15 years, and 2.6% more than 15 years. Participants were randomly assigned to conditions, 20 to the experimental group -presence of CS- and 19 to control group -absence of CS.

2.2. Stimuli and materials

To prepare the stimuli (CS and AS traffic signs; Figure 2) place names were extracted from the database of the National Institute of Statistics (INE, 2015). This selection was filtered through the ESPAL database (Duchon, Perea, Sebastián-Gallés, Martí & Carreiras, 2013), in order to control for possible strange variables (word length and familiarity).

Thus, 192 place names (outside the region where the study was conducted) remained with a frequency of less than 1 per million words and a length of 3 syllables. One type of sign used as stimuli was based on the CSs mentioned above (Fig. 2a).

The characteristics of the format (typeface, size, box, arrangement of elements) of these signs were consistent with what was published in official documents (BOE, 2014). The elaboration of the second type (AS; Fig. 2b) was based on the structure of the CS, adapting it to the electronic format of the VMS. The study was carried out in the facilities of the Faculty of Social and Human Sciences of the Teruel Campus and in the Faculty of Education of the San Francisco Campus, both centres belonging to the University of Zaragoza. In both cases, the table and chair were arranged in the same way, in rooms with adequate temperature and light conditions for the study. All stimuli were presented through MediaLab software (v. 2014).

2.3. Procedure

Upon arrival, all participants received and signed the Information Consent. The total duration of the study was around 30 minutes.

2.3.1. Experimental task

First, they were asked a series of sociodemographic questions (sex, age, educational level, possession of a driving license, frequency of driving on the highway, approximate number of km per year). Subsequently, they were shown the instructions for the task, performed three test examples, and then performed the experimental task. The experimental phase consisted of 27 blocks with two traffic signs (CS and AS) in the experimental condition, and with only one sign (AS) in the control condition. All stimuli were placed in the centre of the screen. The panels were displayed for 4 seconds, an estimated time that traffic signs can be displayed in real conditions at a standard speed of 120 km/hour. After showing the stimuli, participants were required to answer the question: 'According to the sign displayed, where is the event located?', and two response options were offered. The order and display of responses was controlled through balancing.

2.3.2. Reading span test: measurement of verbal working memory

Once the experimental task was completed, the second part of the study began. The procedure to measure WM capacity was extracted from the study by Elosúa, Gutiérrez, Madruga, Luque & Gárate (1996; Prueba de Amplitud Lectora- PAL). This is a Spanish version adapted from the Reading Span Test elaborated by Daneman & Carpenter (1980).

The person responsible for the administration of the study was located to the side, with access to the mouse that passed the screens, without interfering with the direct vision between the participant and the screen. The responses were recorded in a standardized rubric and the data were subsequently coded according to the descriptive criteria proposed by Elosúa et al. (1996). According to these authors, this test requires the two components of

WM to be activated: processing and storage. This test shows a relationship with reading comprehension, both components being necessary; therefore, it would be expected that if the information processing in complex traffic signs is based on a process similar to the reading of verbal language it could be reflected in the results.

2.4. Statistical design and analysis

A 3x2 design was used: an intra-subject factor (location of the event: before / between / after), an inter-group factor (presence / absence of AS) and a continuous variable such as covariate (score obtained in WM measure; Elosúa et al., 1996). The dependent variables are: the comprehension rate (measured in successes and errors) and the response time (time it takes the subject to answer since the question is displayed).

3. RESULTS

3.1. Descriptive

Table 1 presents the means and standard deviations of the comprehension rate (correct answers) and the response time, divided by the factors: condition and location of the event.

		Comprehension rates		Response times (ms)	
Factors	Levels	*M*	*SD*	*M*	*SD*
Experimental condition	Presence AS	.92	.018	2022	136.133
	Absence AS	.92	.019	2120	139.669
Event location	Before	.96	.010	1660	86.214
	Between	.90	.022	2797	133.067
	After	.90	.020	1755	98.641

Table 1. Descriptive measures of comprehension rate and times response.

3.2. Inferential: performance in the experimental task

The results of the statistical analyses carried out in relation to the comprehension rate and response time are presented below. In both cases, a mixed analysis of co-variance (ANCOVA) was carried out with a 3 x 2 design (event location: before / between / after-intra-subject; presence / absence of CS - inter-group) and a continuous variable included in the design as a covariate (score obtained in the WM measure).

3.2.1. Comprehension rate (correct answers)

The analysis does not show statistically significant differences in the effect of any of the main factors or their interaction. Although the main factor ‘event location’ is not significant, when carrying out simple comparisons it is observed that, in a significant way, locating the event variables 'before' a location (M = .96), obtains greater number of correct answers than when it is based on two locations ('between'; M = 0.90) or 'after' a location (M = .90).

3.2.2. Response time

In relation to reaction time, the main factor ‘event location’ shows statistically significant differences, $F_{(2,72)} = 59.13$; $p <.01$, $\eta_p^2 = 0.62$. The relationship observed between the levels of this factor is quadratic, $F_{(1,36)} = 90.42$; $p <.01$, $\eta_p^2 = 0.72$. Simple comparisons show that the differences are found between the level ‘between’ two localities (*M* = 2797 ms), compared to the other two levels: ‘before’ (*M* = 1660 ms) and ‘after’ (*M* = 1755 ms) a locality.

Furthermore, the main effect of the covariate 'WM score' is marginally significant, $F_{(1,36)} = 2.86$; $p = .099$, so it would be positive to take this influence into account in future studies to see if the trend suggested by these results is confirmed with a larger sample size.

However, the interaction between the covariate ‘WM score' and the intra factor 'event location' is statistically significant, $F_{(2.72)} = 5.67$; $p <.01$, $\eta_p^2 = 0.14$. In order to deepen the relationship between these two variables, this relationship was studied through regression analysis. In this line, it is observed that the variable referring to the scores obtained in the ‘WM score’ correlates significantly with the relative response time only at the level 'between' two locations, of the intra-subject factor 'event location', $r_{xy} = -.379$, $p = .017$. The linear regression hypothesis test, through the ANOVA technique, indicates that the relationship is significant, $F_{(1,37)} = 6.20$, $p = .017$. Knowing that r_{xy} is the same as beta coefficient, the interpretation of these data indicates that the reaction time increases by a factor of 0.379 for each unit decrease in ‘WM score’. The coefficient of determination, $R^2 = .120$ specifies the gain that we can obtain when predicting a variable using this ‘WM score’ variable.

4. DISCUSSION

The comprehension rates achieved in this study exceed 90% of correct answers, which is a first evidence that this format (AS) could be effective in transmitting the location of variable events according to the usual standards (ISO, 2007). The key is knowing why. As we expected, compared to previous studies, higher rates are shown in terms of comprehension rates (Lucas-Alba et al., 2016). One possible explanation is based on the incorporation of numbers (information on the distance between the driver and the reference) improves the comprehension rate with respect to other VMS formats tested so far, which did not have this information. It seems that the structure and elements incorporated provide enough information to correctly extract the meaning of the traffic sign. According to Tversky (2005), determined information (versus indeterminate) contributes to the ability to build a mental model and facilitates the understanding of the message, reflected in the increase in the rate of understanding.

On the other hand, these results are consistent with previous outcomes: locating an event 'before' the reference point is more efficient, compared to 'between' and 'after' in terms of comprehension. The fact that the format of the AS is so structuring could be promoting that the differences between locating an event 'before' and 'after' are diluted in comparison with other studies (ceiling effect).

On the other hand, it has been shown that subjects take longer to respond to the location 'between' two references. This could reflect a greater cognitive load, since the information of one more element must be processed (my situation as a driver, the first reference point, the variable event, the second reference point).

However, it must be taken into account that all the ASs show the same number of elements on the poster and they had the same exposure time. Our explanation is related to reference frames and how these frames can influence our mental representation of spatial information.

Anyway, based on the WM model proposed by Baddeley and Hitch (1974; Baddeley, 2000), we hypothesize that an increase in the number of information elements that the driver must keep active on the WM could be causing a greater consumption of time to evaluate the options and extract the correct meaning; being also not very effective (less success rate than 'before').

This is especially relevant considering the relation showed with the WM measure (PAL, Elosúa et al., 1996). Although further analyses and larger samples are needed, this relation has been especially significant on the 'between' level of the event location. Our explanation arises from WM model. According with these premises, it seems that potential individual differences on WM capacity could be more relevant as the cognitive load they must manage increases.

Moreover, application to the real context would imply a simultaneous driving activity, so the consequences could be more considerable. These data could show initial evidence of the importance of human cognition in comprehension of traffic signs and, obviously, in their design.

One of the most relevant limitations of this study is the size of the sample. As they consist of only preliminary data, they must be completed with a new data collection, thus achieving greater statistical power. Likewise, including participants from other age ranges and driving experience would also mean an improvement in the robustness and generalization of the data.

In conclusion, communications and technology advance all together to improve road safety and mobility services. Specifically, aspects of human cognition also play an important role in understanding traffic signs. Integrating the different signage systems can be a way to take advantage of previous schema of the conductors to facilitate the comprehension of new electronic formats.

In addition, it is essential to understand how the information of these complex signs is encoded, processed and de-encoded; as well as the limits that our information processing systems such as WM may pose. Ultimately, designs consistent with the road environment and drivers' cognition can contribute to prevention and safety in the field of traffic mobility.

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HOW TO INCORPORATE AUTOMATED VEHICLES ON ROAD SAFETY AUDITS

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ABSTRACT

Road Safety Audit (RSA) has proved to be one of the best road safety management procedures for design, construction, and maintenance of existing and new road infrastructure. At the beginning, the safety review only focused on motor vehicles and the human driver. Later, as well as nowadays, procedures are also applied to the needs for all vulnerable road users, taking into account that each of the groups (pedestrians, cyclists, motorcyclists) has its own specific requirements.

The new and better capabilities of automated vehicles should be in accordance to road technical features, such as geometry, sight distance, signs, and markings. However, the corresponding standards were developed for human driving, and therefore they must be adapted to the new systems without losing compatibility with lower automation levels. While considerable research effort has been carried out for the digital infrastructure, only some studies have been carried out for the physical one with interesting findings that deserve to be incorporated into RSA procedures, such as: new available and required stopping sight distance; new automated speed as the maximum speed that allows the automated system to maintain the longitudinal and lateral control; readable road markings and road signs to facilitate recognition by both human drivers and connected and automated vehicles; etc. The main objective is to achieve the optimal performance of Advanced Driver Assistance Systems (ADAS).

The main result of this study is a first proposal for a new chapter to be included in the checklists to carry out road safety audits for the different stages and road safety inspections.

1. INTRODUCTION

Road Safety Audit (RSA) has proved to be one of the best road safety assessment procedures for design, construction, and maintenance of existing and new road infrastructure. At the beginning, the safety review only focused on motor vehicles and the human driver.

Later, as well as nowadays, procedures are also applied to the needs for all Vulnerable Road Users (VRUs), considering that each of the groups (pedestrians, cyclists, and motorcyclists) has its own specific requirements.

The Directive 2008/96/EC of the European Parliament and of the Council on road infrastructure safety management (European Parliament, 2008) established the implementation of procedures related to Road Safety Audit (RSA) and Road Safety Inspection (RSI), being mandatory in the trans-European road network at the design stage, under construction or in operation.

A RSA should be carried out for all infrastructure projects, forming an integral part of the design process of the infrastructure project at the stages of: preliminary design; detailed design; pre-opening; and, early operation; following certain criteria for every stage. A certified auditor is appointed to carry out an audit of the design characteristics of an infrastructure project.

A RSI is a formal systematic and periodic road safety assessment of an existing road or road scheme, performed by an independent, qualified inspector or team of inspectors, who report on the existing road accident potential for all kinds of road users (VRUs included), identify traffic hazards related to the road environment characteristics (elements and locations to be improved), and propose measures to mitigate the detected hazards, mainly focused or described as maintenance work.

Both RSA and RSI are considered preventive tools because their application to an itinerary or road section does not require researching on their crash record. There are many checklists available for RSA/RSI. These checklists include several families of elements, such as: Road function; Alignment; Junction; Traffic signing, marking, and lighting; Roadside features; Bridge; Tunnel; Pavement; RS; Public and private service; Traffic operation; Cross-town road; Work zone. However, checklists cannot substitute the experience and expertise of road safety auditors, so the checklists should be used just a reminder of which aspects should be reviewed. There are other limitations, such as that most questions are related to a whole road segment, without any specific spatial and/or temporal focus. Another weakness might be due to the accuracy of answers (Yes/No may be for both Safe/Risk indistinctly).

New Amending EU Directive 2008/96/EC on Road Infrastructure Safety Management (European Parliament, 2019a) extends the scope to motorways and other primary roads beyond the trans-European transport network (TEN-T), including a new network-wide road safety assessment and a more targeted road safety inspection. Moreover, there will be new procedures aiming at ensuring the operational use of road markings and signs, common specifications should be established in order to foster the effective readability and detectability of road signs and marking for human drivers and automated driver assistance systems.

However, the new Directive does not include the automated vehicles as a new point of reference for carrying out the procedures for RSA and RSI.

The Society of Automotive Engineers identifies six levels of automated driving:

- 0 – no automation
- 1 – driver assistance
- 2 – partial automation
- 3 – conditional automation
- 4 – high automation
- 5 – full automation (SAE, 2016).

Every level is defined as the minimum capabilities that the system must fulfill, so a vehicle might present different driving automation levels depending on the environment.

There are vehicles in the current market that reach level 2, and even level 3 under very controlled conditions such as a high-end geometric alignments and road markings. A level 2 driving automation system can negotiate speed and lateral position under controlled circumstances. If the system is unable to process certain information (e.g. sharp horizontal curve or crest vertical curve), it transfers control to the driver – often, with a minimal or inexistent warning – in a disengagement event. Conversely, a level 3 driving automation system is able to negotiate more complex situations, so the system is expected to fail on fewer locations. In this case, the system is even expected to predict this failure in advance, transferring control to the driver in a Take Over Request (TOR) event. While level 3 presents a more complex performance, the time required for the driver to resume control is often beyond driver’s abilities, being reported as unsafe by many experts. In fact, there are many international efforts in reaching level 4 as soon as possible. Level 4 ensures performance without any need of human intervention under certain circumstances involving infrastructure, traffic, and environment. The different combinations of these circumstances are called Operational Design Domains (ODDs).

The new and better capabilities of automated vehicles should be in accordance to road technical features, such as geometry, sight distance, signs, and markings. However, the corresponding standards were developed for human driving, and therefore they must be adapted to the new systems without losing compatibility with lower automation levels.

Current semi-autonomous vehicles are equipped with a variety of sensors, including video cameras for environment identification (road markings, signs, vehicles, pedestrians, etc.) and radar for obstacle detection. Cameras are the basis for Lane Keeping Assist (LKA), and radars are the basis for the Adaptative Cruise Control (ACC) and emergency braking.

These devices aim at substituting human sight, but their location differs from driver’s eyes (and also among vehicles), which impacts on how sight distance should be calculated and checked. The new semi-autonomous vehicles should be included for carrying out RSA and RSI as a new point of view for their different sensors (radar, cameras, etc.).

There are other limitations for existing semi-autonomous vehicles. Some studies have recently focused on identifying the limitations of autonomous vehicles regarding line marking and road signs (Austroads, 2019; US TRB, 2018; EuroRAP and EuroNCAP, 2018).

These studies revealed that the quality, position, and consistency of line markings and traffic signs are critical to the performance of automated driving and driver assistance functions. Likewise, it is recommended to use line widths between 100 and 150 mm, a maximum lane width of 4.50 m, and a minimum road marking retroreflection of 150 mcd/lux/m2.

Other studies have explored the limitations of AVs related to road geometry (García, 2017; García et al., 2019; García and Camacho-Torregrosa, 2019; García and Camacho-Torregrosa, 2020). They found that there are still many limitations associated to horizontal and vertical alignment, as well as cross-section and road markings to ensure an adequate performance of semi-autonomous vehicles.

Finally, the coexistence of AVs with non-automated vehicles and other users leads to a complex mixed traffic scenario. The European Parliament resolution of January 15th, 2019 on autonomous driving in European transport (European Parliament, 2019b) highlighted the necessity of incorporating safeguard systems right for this transition phase; stressing the importance of driver assistance systems as a step towards fully automated driving, even now to prevent road crashes by means of active safety systems or reduce the severity of accidents by means of passive safety systems.

2. OBJECTIVES

The main objective of this study is to highlight previous findings on how AVs are constrained by road infrastructure (horizontal and vertical alignment, cross-section, road marking continuity, and pavement condition), by analyzing when AVs might disengage and transfer control to drivers. Based on these findings, new questions will be proposed to be included in Road Safety Audit and Inspection checklists.

However, this paper does not intend to define specific thresholds to be considered in AV-RSA’s, but to stablish a framework on which parts of road infrastructure should be compared to the performance of existing and oncoming vehicles.

3. ROAD INFRASTRUCTURE AND LOW-AUTOMATED VEHICLES

Although each car manufacturer equips different sensors and programs its own Active Cruise Control (ACC) and Lane Keeping Assist (LKA), the technical features of their sensors and CPU are similar because they share parts suppliers.

Therefore, the differences in vehicle performance are minimum. Based on this hypothesis, the authors decided to use a BMW 520d from 2017, equipped with the "Driving Assistant Plus" package, which gives it a level 2 of automation, as the car that can properly represent most of semi-autonomous vehicles on our road networks.

The vehicle was driven by a single driver along a total of 3,000 km in the Region of Valencia (Spain). Once both ACC and LKA systems have been activated, which requires the selection of the cruising speed, the car takes control of the accelerator, brakes, and steering wheel, being able to keep the vehicle within the lane as a result of the detection of road markings through two video cameras located in the interior rear-view mirror.

If the system cannot process the gathered information by the cameras, the system transfers control of the vehicle to the driver showing a warning message on the dashboard, without any acoustic signal. The driver is also asked to be in permanent contact with the steering wheel so as to take over control, if needed.

The vehicle performance was recorded through a Garmin Virb Elite HD video camera, which was placed next to the driver's head. The resulting video recordings included road, navigation system, dashboard, and comments of the driver and passengers. To prevent bias, all tests were carried out in daylight conditions, dry pavement surface, and road markings in good condition.

Traffic volume and operation might influence the performance of the assistance systems. However, a Road Safety Audit aims at detecting safety issues regarding road design, so it should be developed to identify the limitations of autonomous vehicles operating under free flow conditions. To allow reaching a reasonable operating speed, the data used in the following studies were collected during non-peak hours.

The horizontal alignment of the road sections was recreated by means of the procedure proposed by Camacho-Torregrosa et al. (2015), whereas the vertical alignment was extracted through Autodesk Civil 3D using LIDAR data provided by the National Plan for Aerial Orthophotography (PNOA, 2016).

3.1 Horizontal curves

This part of the study aimed at analyzing the capacity of the road infrastructure to host semi-autonomous driving systems on isolated horizontal curves (García, 2017). Particularly, the maximum speed at which a semi-autonomous vehicle can travel along this type of road element was identified for each studied horizontal curve.

A total of 132 isolated horizontal curves were considered in the analysis, which were located in motorways, freeways, multilane highways, and two-lane rural roads. Among different geometric features (radius, deflection angle, length, and Curvature Change Rate), the radius resulted in the most influential variable in the studied phenomenon. Specifically, the radii of the observed horizontal curves varied from 172 m to 3,858 m, with an average of 858.8 m.

The automated speed (Va), which was defined as the maximum speed at which the semi-autonomous vehicle was able to perform automatically, was identified for each horizontal curve by traveling along them at different speeds. This way, if the speed is greater than Va, the system is not able to process the gathered information and transfers the lateral control of the vehicle to the driver. It should be noted that Va could not be determined for those horizontal curves presenting a radius lower than 172 m.

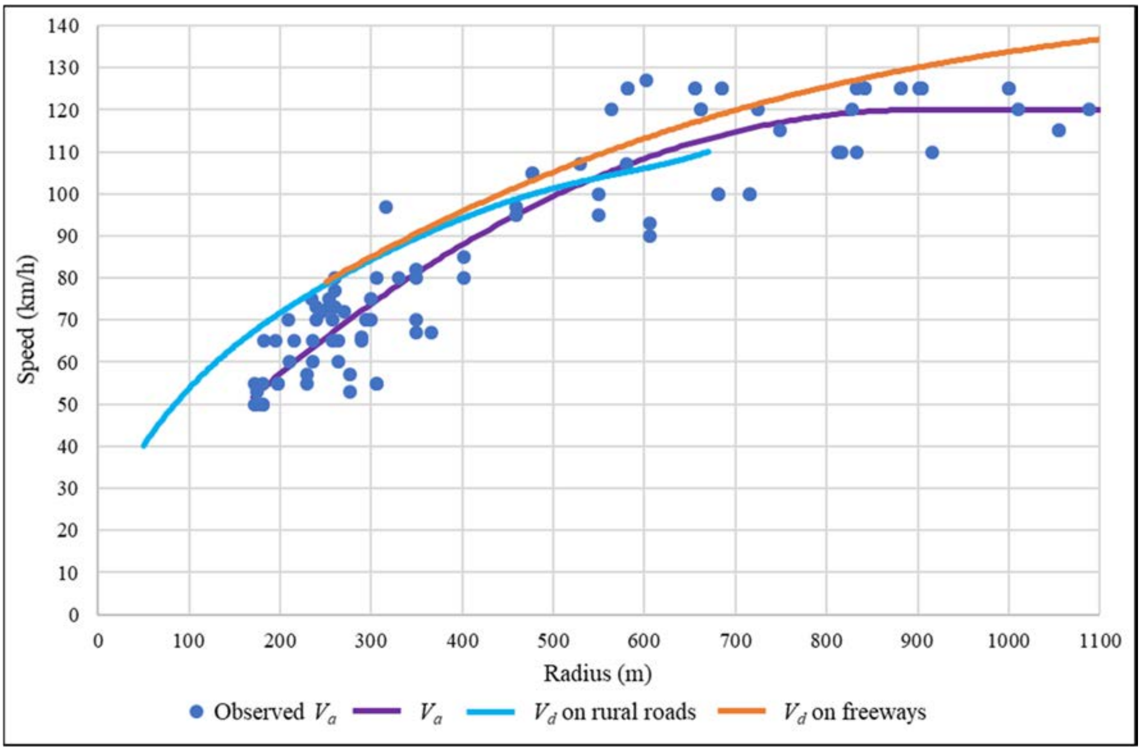

Figure 1: Relationship between the automated speed and the radius of the horizontal curve.

Figure 1 shows the relationship between the radius (R) and the automated (Va) and design (Vd) speeds for each horizontal curve. As expected, the automated speed increases with the radius.

In addition, the automated speed was only greater than the design speed for a few horizontal curves, so an automated driving performance, from the point of view of the road design, is not currently possible mainly along horizontal curves with a radius lower than 500 m.

3.2 Crest vertical curves

Another critical issue related to the automated driving performance of semi-autonomous vehicles is the influence of the vertical alignment. Thus, the objective of this part of the research was to examine the automated driving experience along 42 vertical crest curves overlapped with tangent sections, thus avoiding the influence of the horizontal alignment (García et al., 2019).

It should be noted that the driver tried to go along all studied crest vertical curves at its posted speed limit, but in some cases the operating speed was lower. The K values of these vertical curves ranged between 2.7 m/% and 65.5 m/%, whereas the algebraic difference in grades (A) varied from 0.36% to 11.85%. As a result, 18 of the studied crest vertical curves required the driver to take control of the vehicle. According to the Green Book (AASHTO, 2018), the vertical curve parameter (K) defines its sharpness (Figure 2). It is calculated as the ratio between its length (L) and the algebraic difference in grades (A). Given a parameter K, the stopping sight distance (SSD) can be calculated as follows (Figure 2, top right):

$$SSD = \sqrt{(L/A \cdot 100 \cdot (\sqrt{2 \cdot h_1} + \sqrt{2 \cdot h_2})^2)} \quad (1)$$

where:

- SSD is the Stopping Sight Distance (m); L is the length of the vertical curve (m)
- A is the algebraic difference in grades (%)
- h1 is the height of eye above roadway (1.08 m)
- h2 is the height of object onto the roadway surface (0.60 m).

This expression is only valid when SSD is lower than L.

This SSD can be tagged as available SSD (i.e. SSD_A), since it represents the road length that can be seen for a certain crest vertical curve design.

In addition, a biunivocal correspondence exists between design speed (Vd) and SSD. For a given design speed, SSD can be determined using Equation 2, which is divided into two terms:

- driver perception-reaction distance (dPRT)
- braking distance (dMT) (Figure 2, top left).

$$SSD = d_{PRT} + d_{MT} = 0.278 \cdot V_d \cdot t + 0.039 \cdot V_d^2/a \quad (2)$$

where Vd is the design speed (km/h); t is the perception-reaction time (2.5 s); and a is the deceleration rate (3.4 m/s2).

This is the required SSD (i.e. SSD_R), since it indicates which is the minimum length needed to stop the vehicle, driving at a certain speed. The Green Book assumes that vehicles are performing at the design speed, so $SSD_R \leq SSD_A$ indicates an adequate design, from this perspective.

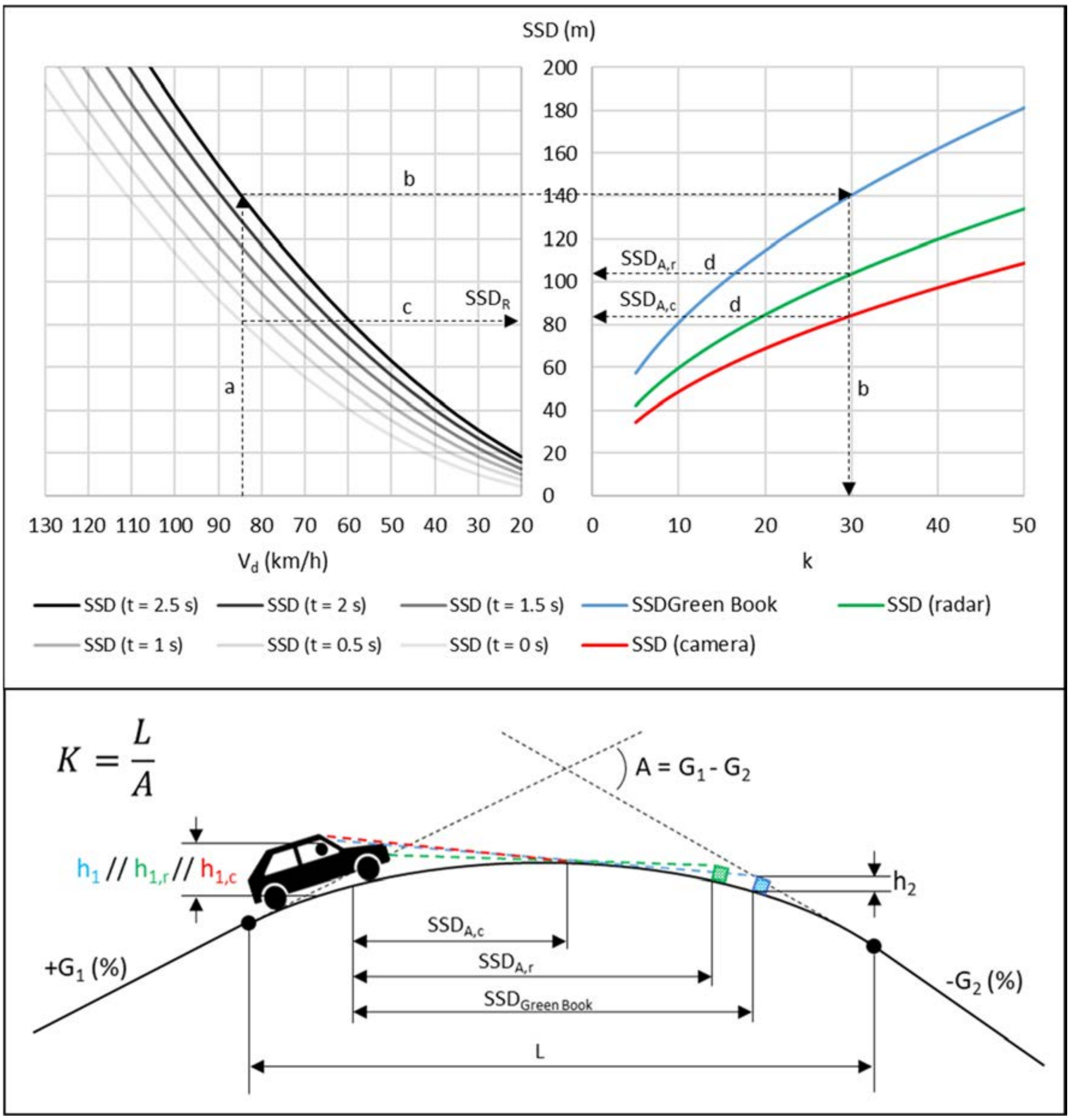

Figure 2: Relationship between SSD, K, and V_d. Left side: relationship between required SSD and design speed (reversed horizontal axis). Right side: relationship between available stopping sight distance and vertical curve parameter K.

The AASHTO Green Book assumes specific values for SSD, but these values must be changed for the devices equipped in the semi-autonomous vehicle: video camera and radar. Therefore, $SSD_{A,r}$ is the available sight distance for the radar, and $SSD_{A,c}$ for the video camera (Figure 2, top right).

The video cameras are usually located in the interior rear-view mirror and are responsible for lane keeping, so h1 can vary from 1 m (passenger cars) to more than 2 m (heavy vehicles), while h2 is 0 m (road markings). On the other hand, the radar is usually placed in the bumper and aims at detecting objects on the carriageway, so h1 ranges from 0.25 to 0.45 m and h2 is 0.60 m according to the Green Book (AASHTO, 2018).

On the other hand, perception and reaction time also changes with these automated systems. This new required distance (SSDR) will be determined considering perception-reaction times ranging from 0 to 2.5 s, since current autonomous vehicle manufactures do not provide the lag that these devices require to process the information and take a decision.

Again, a curve is well designed if the required SSD is lower than the available one for both systems, i.e.: $SSD_R \leq SSD_{A,r}$ and $SSD_R \leq SSD_{A,c}$ (lines c and d in Figure 2). All curves are assumed to be designed according to standards, so $SSD_R \leq SSD_A$ is always true.

As an example, the SSDR for 85 km/h design speed is 140 m (Figure 2: a). According to the Green Book, the minimum parameter K that allows this sight distance is 30 m/% (Figure 2: b). Assuming that the vehicle can perform automatically (i.e., perception-reaction time = 0 s), the SSDR would decrease up to 80 m (Figure 2: c). Likewise, the $SSD_{A,r}$ and $SSD_{A,c}$ would be approximately 105 and 85 m, respectively (Figure 2: d). Therefore, the vertical curve might be travelled in an autonomous way.

However, vehicles need a period of time to gather and process the information, so the success of the system mainly depends on how quick the vehicle system can operate. In the previous example, if the perception-reaction time required by the vehicle is 1.0 s, the driving experience would be manual.

It was hypothesized that the system might shift from automatic to manual in case of having insufficient time to process all information originating from the video camera. Thus, a new parameter called Available Processing Time (APT) was defined as the ratio between the available sight distance for the video cameras (SSDA,c) and the operating speed during the observation.

Figure 3 depicts the relationship between K and APT. First of all, it can be observed that the system tends to transfer the lateral control of the vehicle for K values lower than 20-30 m/%, which is usually associated to a big grade differential.

In addition, those crest vertical curves which required human intervention presented APT values lower than 3 s, whereas the minimum APT associated to an automated driving experience was 2.5 s.

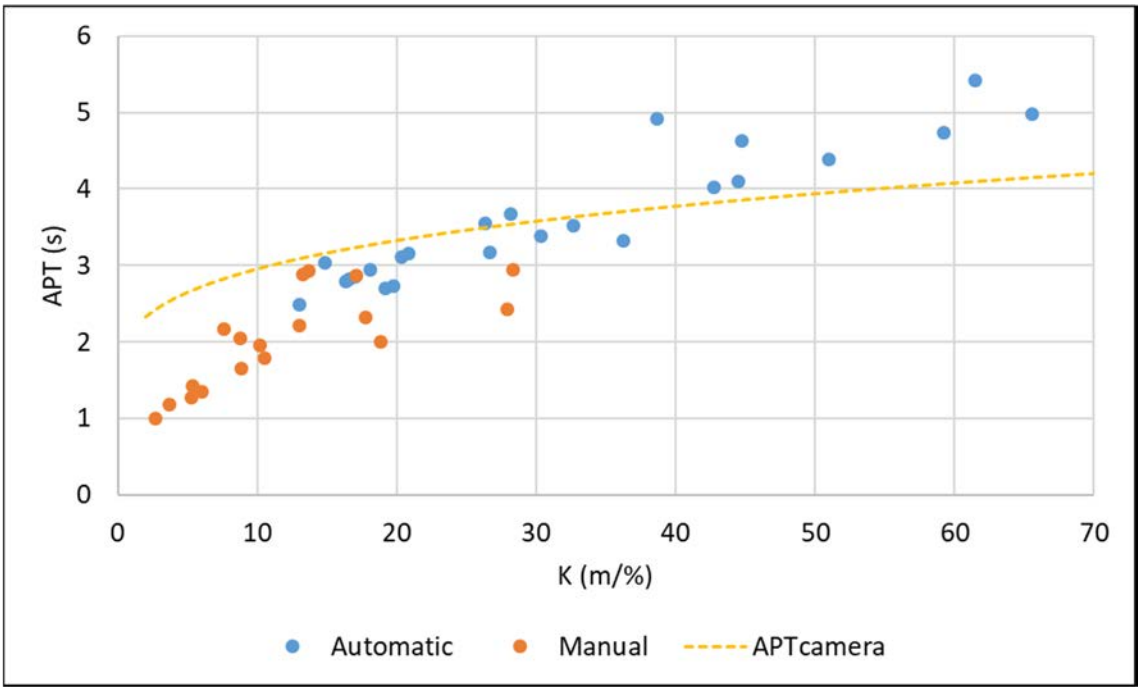

Figure 3: Relationship between *K* and *APT* depending on driving experience.

Therefore, the system needs more than 2.5 s to process the gathered information and take a decision. This processing time includes video recording, algorithms processing, and the time needed to control the vehicle. This *APT* was determined driving at the speed limit (or slightly lower, if posted speed could not be reached).

Figure 3 also shows the theoretical available processing time if the driver travelled at the design speed (dashed yellow line). As can be seen in Figure 4, operating/posted speeds are normally higher than the design speed on sharp crest vertical curves (thus leading to lower APT). Conversely, operating/posted speeds are generally lower than the design speed for smooth crest vertical curves, hence producing higher *APT* than the design-based and enabling more time to process the information and take a decision.

In this case, the automated speed (Va) is estimated as the ratio between the available stopping sight distance for the cameras (SSDA,c) and the minimum available processing time (APTmin). Figure 4 depicts the relationship between the operating speed and the vertical curve parameter (K) for the studied crest vertical curves. Likewise, thresholds for an automated speed considering APTmin equal to 2.5 and 3.0 s (dashed red lines) as well as the curve associated to the design speed (blue line) have been plotted. Additionally, the dashed green lines represent the automated speed for lower APTmin. Therefore, the automatic speed model will be located between both dashed red lines.

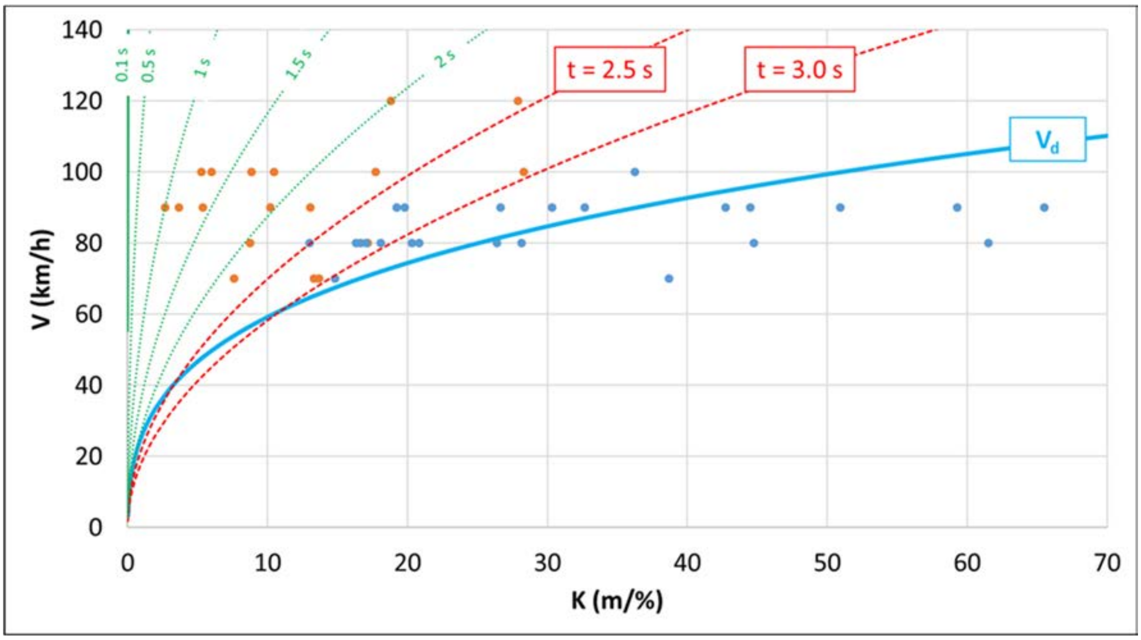

Figure 4: Relationship between the automated speed and the vertical crest curve parameter.

3.3 Lane width

In addition to the horizontal and vertical alignment, the characteristics of the cross-section, mainly lane width, have a great impact on the automated driving performance of semi-autonomous vehicles. To study the influence of this geometric feature on the automatic lane keeping system, an experimental field data collection was performed in an urban environment using the semi-autonomous vehicle described above (García and Camacho-Torregrosa, 2020).

Given that most narrow lane widths are associated with low-speed and urban roads, the data collection was carried out travelling at 50 km/h which is the usual speed limit along these roads. In addition, the use of a constant speed avoided introducing the influence of the speed on the phenomenon.

A total of 12 arterial tangent sections, belonging to a 5.4 km long urban arterial ring road in Valencia (Spain), were selected to be analyzed. This urban road is bi-directional, with several lanes with diverse lane widths, ranging between 2.28 and 3.80 m, with an average value of 2.70 m. The total number of studied lanes was 81 and the minimum number of passes along each lane was 10.

To study the influence of lane width on the automated driving performance, two parameters were defined: the automatic lateral control rate and the manual lateral control rate. The first one was calculated as the ratio between the observed number of passes in an automatic way and the total number of passes, whereas the second one was the number of passes in a manual way divided by the total number of passes.

Figure 5 clusters these rates in 5 cm intervals. As expected, the automatic lateral control rate increases with lane width and, on the contrary, the manual lateral control rate decreases as the lane width is greater. Specifically, the system was always able to perform in an automatic way for lanes wider than 2.75 m, whereas a lane width lower than 2.5 m always led to a manual driving. Additionally, a critical lane width can be estimated as the intersection of both driving performances, determining the same probability for manual and automatic lateral control at a width of 2.72 m.

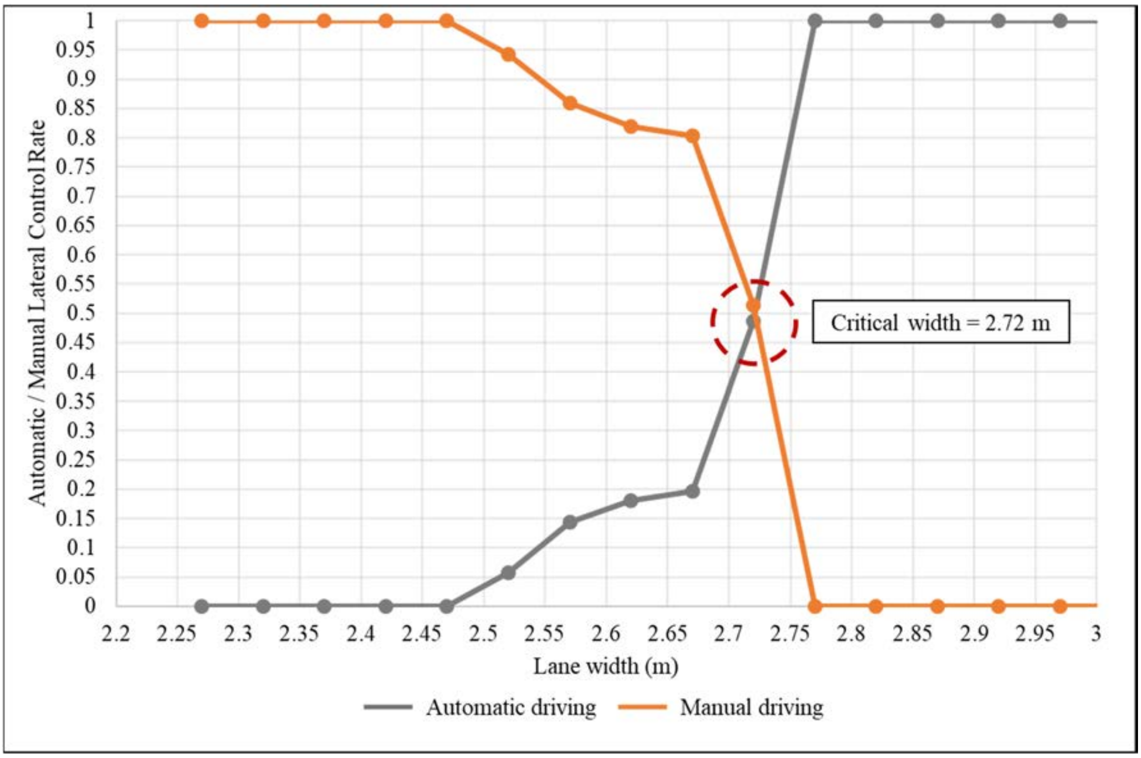

Figure 5: Influence of lane width on driving experience.

Taking into account the observed automatic lane width and the width of the experimental vehicle, the tested vehicle needs a free lateral space of 0.44 m. Since the study only focused on the observed disengagement events and not on the underlying causes, more insight is needed to determine the potential consequences on driving safety and performance. If this limitation arises from the capability of the system to process the visual information, similar limitations for other vehicle types are expected

Conversely, if the remaining lateral space is needed for vehicle maneuvering, it might imply a serious limitation to heavy vehicles, since the minimum width to support automation with current technology is inferred to 3.43-3.48 m. Moreover, these findings clearly define 2.50 m to 2.75 m as an Operational Design Domain threshold, which is not compatible with most low volume roads and some urban environments.

These findings can be complemented with those obtained by Austroads (2019). To this regard, the maximum lane width that allows an automated driving is 4.50 m.

This threshold was established by analyzing autonomous vehicle performance on 25,000 km of different road types in Australia and New Zealand.

3.4 Road marking

When comparing technical capabilities of autonomous vehicles with road infrastructure, a common thought is that signals in good condition establishes an adequate operational domain for semi-autonomous vehicles. Special mention deserves road markings, which are expected to have a good visibility and contrast. However, there might be some cases in which a good infrastructure with good road markings is not enough for semi-autonomous driving (García and Camacho-Torregrosa, 2019).

Thus, this research examines the system capability of the above mentioned semi-autonomous vehicle along different road marking configurations in 25 km of freeway. Particularly, the driving experience was studied on 25 exit ramps and 27 entrance ramps so as to determine the impact of the marking gap, i.e., the absence of the edge road marking at the beginning of the exit ramp and at the end of the entrance ramp. To this regard, Spanish regulations for road markings establish that the broken extension line must begin or finish when the acceleration or deceleration lane becomes 1.5 m wide. This results in a zone with a gap or edge line discontinuity. Its length depends on the cotangent of the corresponding taper. These assumptions are correct as long as the road marking was adequately set up.

At the studied locations, information on the station, ramp type (entrance/exit), existing gap (yes/no), width of the acceleration and deceleration lane (m), horizontal alignment (left curve/right curve/tangent), vertical alignment (upgrade/downgrade/crest curve/sag curve), and driving experience (manual/automatic) was collected. It should be noted that the semi-autonomous vehicle travelled at the speed limit, which was 120 km/h at most locations, and always located on the right lane.

Then, the automatic and manual lateral control rates were calculated for both exit and entrance ramps (Figure 6). As a result, 32% of the exit ramps and 19% of the entrance ramps led to a transference of the lateral control of the vehicle to the driver. In this way, it seems that the analyzed semi-autonomous system is more sensitive to exit ramps, since the lateral control is transferred at a greater frequency.

Similarly, most lane-reductions or additions also caused the system to fail. As said above, this is mainly due to the gap with no channelizing lines that the Spanish guidelines set for these sections. For these configurations, a longer discontinuity of the edge line exists.

Another observed issue was related to road-splits and road merging sections. If the sum of the lanes at the separated sections differ from the merged one, a large zone without any road marking appears, thus impeding any guidance by the semi-autonomous system.

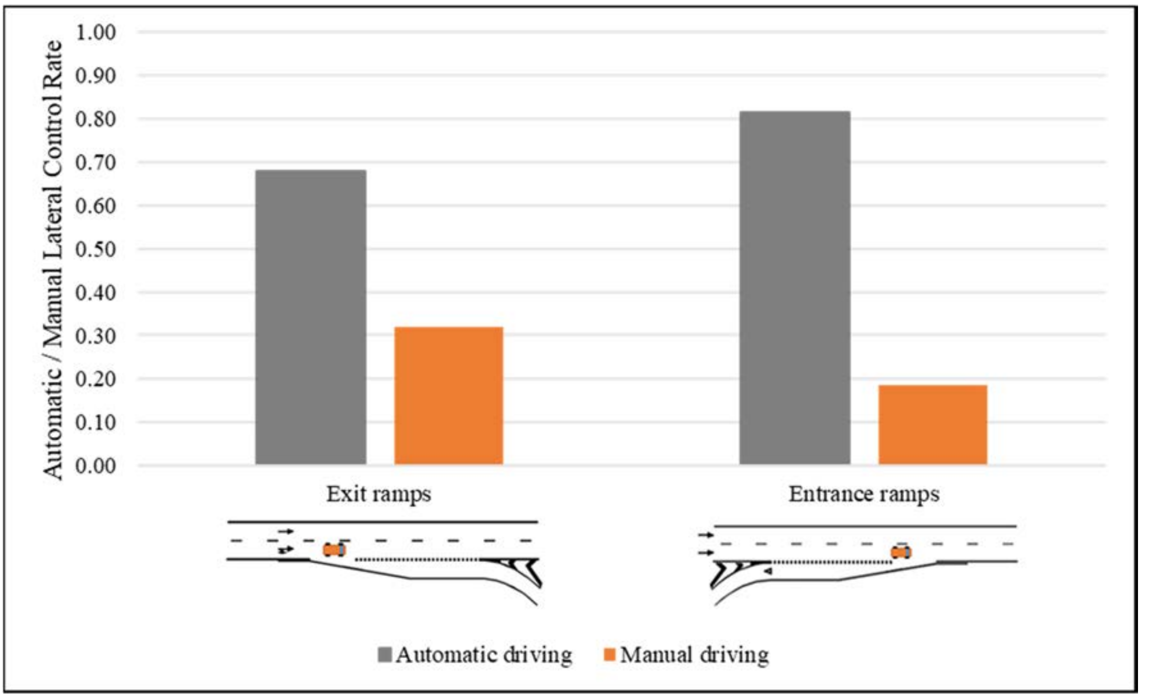

Figure 6: Influence of road markings on driving experience.

3.5 Pavement

In addition to the geometric design and road markings, another important factor affecting the effectiveness of the system of semi-autonomous vehicles is the road surface. As a result of the data collection described in the previous sections, some issues related to the condition of the pavement were also identified.

It was observed that the system often transferred the vehicle control to the driver when the pavement presented longitudinal cracking sealing along East-West sections. Regarding this, the reflection of the sun on this type of surfaces led to confusion to the vehicle system, which could not properly identify the lane markings.

Another feature of the pavement that showed a substantive influence on the performance of semi-autonomous vehicles was the road surface evenness. Particularly, those road segments with sharp unevenness caused a manual driving performance, so road maintenance is becoming more important as the number of automated vehicles increases.

Finally, a special mention should be given to work zones. Although these type of road sections have not been studied yet, they usually present a lack or deficiency of road markings, which will most likely result in the failure of the vehicle system leading to a manual driving performance.

4. NEW CRITERIA FOR ROAD SAFETY AUDITS

In view of these findings, some new criteria have been defined for both Road Safety Audit (RSA) and Road Safety Inspection (RSI), to determine whether a road segment is compatible with existing AVs.

Regarding RSA, the following criteria should be incorporated:

- minimum radius of horizontal curves (Rmin)
- minimum K-value of crest vertical curves (Kmin)
- minimum lane width (wmin)
- continuity of edge road markings.

On the other hand, the following issues should be taken into account in Road Safety Inspection:

- road marking performance, referred to visibility
- cracking sealing
- unevenness
- temporary road marking and pre-marking.

Taking into account that the current automated vehicles reach automation levels 2 or 3, the following thresholds to minimize disengagements are defined:

- Rmin = 500 m.
- Kmin = 30 m/%.
- wmin = 2.75 m.
- wmax = 4.50 m.

According to these geometric thresholds, it is expected that the existing Spanish motorways with a design speed greater than 100 km/h allow an automated driving to the current semi-autonomous vehicles.

Finally, Table 1 shows some questions that should be included in RSA and RSI checklists. These questions are preferred to be included in a new chapter or block of questions, which is proposed to be called “Autonomous driving performance”.

Based on the outcomes of this chapter, the capability of the road to hold autonomous vehicles might be determined. It should be noted that question block 4 only applied to existing roads, i.e., for RSI.

Issue	Yes	No	Comment
1. Horizontal and vertical alignment			
1.1 Does the road alignment have: • horizontal curves with a radius lower than 500 m? • crest vertical curves with a *K* parameter lower than 30 m/%?			
1.2 Is the curvature profile continuous?			
1.2 Is the automated speed lower than the design speed at: • horizontal curves? • crest vertical curves?			
2. Cross-section			
2.1 Is the width of traffic lanes constant?			
2.2 Is the lane width between 2.75 m and 4.50 m?			
3. Road markings			
3.1 Are edge line road markings continuous on: • entrance ramps? • exit ramps? • intersections? • transition sections?			
3.2 Is there any gap on: • entrance ramps (m) • exit ramps (m) • intersections (m) • transition sections (m)			
3.2 Are road markings in good condition?			
4. Pavement condition			
4.1 Does the pavement have cracking sealing?			
4.2 Does the road section consist of an uneven pavement?			
4.3 Are there any temporary road marking or pre-marking along the road?			

Table 1: Questions to be included in RSA and RSI.

Additionally, Table 1 should be complemented with the questions proposed by Austroads (2019) regarding line marking and road signs. Among all these questions, it should be highlighted those presented in Table 2.

Issue	Yes	No	Comment
1. Line marking			
1.1 Are the following lines present? • Left edge • Lane dividing line/s • Right edge • Centerline			
1.2 Are line widths nearing 150 mm, no narrower than 100 mm?			
1.3 Line contrast with surrounding roadway, • As relevant to machine vision during dry daytime conditions? • As relevant to machine vision during wet daytime conditions? • As relevant to machine vision during dry night-time conditions? • As relevant to machine vision during wet night-time conditions?			
2. Road signs			
2.1 Are there: • Static speed limits? • Electronic speed limits?			
2.2 Are road signs of good readability in daytime?			
2.3 Are road signs of good retro-reflectivity in night-time?			
2.4 Are road signs in their expected position?			
2.5 Are road signs obscured?			

Table 2: Questions for RSA and RSI proposed by Austroads (2019).

5. DISCUSSION

Fully automated vehicles (SAE level 5) will ensure an automated experience to their passengers, without the need to take control of the vehicle from any infrastructural condition. This technology is far from being reached, so existing technology is only able to produce partial automated experience. An adequate automated experience should ideally comply with:

- safe, meaning that no disengagements are produced without previous awareness or request to the driver
- reliable, meaning that the driving automation system is able to provide valuable information on how well it is performing (or whether a Take Over Request (TOR) is expected
- comfort, i.e. the frequency of disengagements/TOR should not be so high that drivers preferred to disconnect the system.

Comfortable speed and speed transitions should be met as well. Road infrastructure – combined with vehicle technology – can act on safety and comfort, while reliability can only be addressed with vehicle technology.

Therefore, a RSA/RSI including automated vehicles should explore how safe and comfortable is automation along a road segment, which can be done by analyzing how and how frequent disengagements are produced. A road segment whose geometry ensures performance without any disengagement, combined with adequate environmental conditions, defines an Operational Design Domain (ODD) able to support SAE level 4, which would be extremely safe and comfortable. On the contrary, a road segment with very frequent disengagements is not comfortable, but it would probably be safe from a driving automation perspective. This is because too many disengagements would discourage drivers from connecting the system thus staying in manual driving.

The worst scenario is, in fact, a road segment that causes a low number of disengagements. In this case, drivers might be willing to use the driving automation system, which will probably lead to distractions while the vehicle is performing the driving task (level 3). This increases perception-reaction time, which would be critical in case a disengagement/TOR arrives.

This research, beyond proposing specific thresholds which might be influenced by the vehicle used, aims at identifying the geometric-related aspects that might be the cause of these disengagements. Therefore, its major contribution is the proposal of the new speed concept named automated speed (Va) and the proposed methodologies to address semi-autonomous vehicle disengagements.

RSA should not focus on detecting whether the thresholds defined in the previous section are met or not, but on ensuring that these violations are not isolated, taking place after kilometers of automated driving. Auditors should pursue that high-end road segments meet all requirements for automation and ensure that adequate countermeasures are set in segments where a few disengagements are expected. Some examples of countermeasures might be an adequate signing (e.g. “Warning: Disengagements expected”), texturized pavement, etc. Specific electronic signs could also be proposed, if vehicles are adapted to read them and inform the driver about an oncoming disengagement. These measures would also be valid for transitions from ODDs valid from level 4 to other ODDs not compatible with this automation level. It is important to highlight that these measures must be reliable too, i.e. they should not be too conservative or relaxed. Too frequent signs warning about a possible oncoming disengagement without further becoming true would result in lower trust and, finally, in lower effect when actual disengagements take place.

While these measures would ensure a better performance of automated vehicles, there are two important shortcomings that affect their application:

- a) the diversity of driving automation systems
- b) their technological evolution.

The disparity of driving automation systems – which includes sensors, processing, and Human Machine Interfaces – makes it impossible to define an automated speed threshold that applies to all driving automation systems. In other words, a system might be able to perform autonomously along a horizontal curve of 400 m of radius, but another system might fail. Thus, the thresholds to define clear level 4 ODDs for most driving automation systems should be very conservative, set where the design speed of the road segment is clearly below the automated speeds measured for a wide range of driving automation systems. The main reason of proposing conservative thresholds is to avoid an overconfidence in drivers. As previously mentioned, when the road is prone to cause a lot of disengagements, manual driving might become safer than an automated driving.

In addition, these systems are evolving very fast. Existing limitations might be overcome in months, which hinders defining adequate ODDs, since these might be outdated soon and therefore become ineffective.

Defining the operational thresholds for the driving automation systems therefore becomes necessary. Given the plethora of technologies, harmonized testing protocols focused on determining the limitations of driving automation systems in real world should be developed by Administrations. These tests, combined with adequate thresholds, could be used to certify driving automation systems, ensuring that these will not disengage under some given circumstances. These limitations could also be used as an aim for Vehicle Original Equipment Manufacturers (OEMs) and their suppliers.

The above mentioned limitations would be present while the road infrastructure is only physical, which is barely resilient to changes. A Digital Infrastructure and an adequate communication between road infrastructure and CAVs could provide vehicles information about the ODD, allowing these to adopt and inform the driver about oncoming TORs. This would allow ODDs to change in definition, extension, and incorporate parameters such as traffic and weather conditions. An important effort should be done in advance to define harmonized and standardized vehicle limitations and ODDs. Thanks to it, the automated driving system, combined with HD map, would be able to anticipate the geometric-related disengagements and therefore inform about TOR with sufficient time.

If the digital infrastructure is not present, Variable Message Signs could inform the drivers about road readiness for AVs. Given the variety of vehicle technologies, some pictograms should be developed to show how the road interacts which each of them.

A standardization effort will be required as well to match road infrastructure with vehicle technology, provided that the number of pictograms should be limited since they have to be interpreted by drivers. Moreover, a driver should easily adapt to different vehicles which might obey to different of these pictograms.

In this scenario the role of auditors becomes challenging, since they should check adequacy of the pictograms to the different automation types, which implies readability of the signs, their frequency, and variation in time.

Finally, auditors should also be trained in V2X communications. New possibilities of CAVs, especially vehicle platoons and automated intersections would benefit from these communications but could generate new – and very important – problems if these fail. Degradation of Cooperative Active Cruise Control (dCACC) has been proven to suddenly increase decelerations on the traffic stream, which might not be supported by all autonomous technologies. Hence, auditors should check the strength of these communications and the possibilities of their blackout.

6. CONCLUSIONS

This study identifies some needs for improvement on current RSA/RSI procedures to host semi-autonomous vehicles. These are urgent needs, due to their fast market growth. Limitations regarding road design, road markings, and pavement condition have been identified, and some insight on how these should be incorporated is provided.

A new concept, the Automated Speed (Va), is introduced as the maximum speed at which semi-autonomous vehicles can perform autonomously. The relationship between this parameter and the design speed is of great importance, since a road feature in which the design speed exceeds the automated speed would result in massive disengagements and, therefore, hazards.

Several research of the authors on geometric and cross-section limitations of AVs have been summarized, highlighting how these should be applied by road safety auditors. At first, RSA/RSI should be based on conservative thresholds to ensure that a road feature produces no disengagements to any marketed semi-autonomous vehicle. Vehicle technological development and a better characterization of road-AV interaction will allow to define dynamic ODDs that will be transferred to vehicles via V2X. By doing so, RSA/RSI should adapt to ensure that these dynamic conditions are in line with all vehicles, regardless their automation level.

Existing RSAs already require the intervention of multidisciplinary teams to assess the road quality from different perspectives. Thus, adding autonomous vehicles to the picture might either require specialization of the team or increasing its number with more specialists.

Therefore, efforts must be made to gradually introduce new training on AVs and V2X communications to auditors. They should be able to analyze the potential shortcomings of communication failures, such as degraded CACC. A huge effort should be carried out first by Administrations, OEMs and suppliers to harmonize uniform communication, signage, and HMI protocols that are valid for current and further automation and infrastructure developments.

Further research should concentrate on determining the limitations of the different automation technologies, as well as on defining testing protocols to ensure their harmonization. These will establish a clearer goal for vehicle manufacturers in matching automation with road infrastructure, and a first step to group automation technologies and defining adequate ODDs. These ODDs, combined with the digital infrastructure, will ensure a safe scenario while transitioning from manual to fully-automated driving.

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CLASIFICACIÓN Y CARACTERIZACIÓN DE ELEMENTOS DEL RECORRIDO PEATONAL EN UN ENTORNO URBANO MEDIANTE DATOS LIDAR

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RESUMEN

La seguridad y calidad de la movilidad de los peatones en un ámbito urbano donde conviven con otros modos de desplazamiento debe ser una de las prioridades para cualquier gestor público. Para ello es fundamental disponer de una caracterización precisa de los recorridos peatonales y de los elementos urbanos que forman parte de estos recorridos, como pueden ser los pasos de cebra o los bordillos de separación entre diferentes espacios de movilidad, por ejemplo.

El presente trabajo presenta los avances en la clasificación y caracterización de algunos de estos elementos gracias al análisis de los datos obtenidos mediante un escaneado terrestre realizado por un *Mobile LiDAR Scanner* (MLS) en las calles cercanas a un colegio de la ciudad de A Coruña. Estos análisis se enmarcan dentro de las actividades desarrolladas en el proyecto BIG-GEOMOVE para el análisis de indicadores BIG GeoDATA sobre viarios urbanos para el diseño dinámico de caminos escolares seguros, y que fue financiado en 2017 por la Dirección General de Tráfico.

En este texto se muestran los procesos de tratamiento realizados sobre los datos LiDAR y los diferentes algoritmos desarrollados para clasificar la nube de puntos y diferenciar elementos urbanos importantes en los recorridos peatonales, en especial pasos de cebra y bordillos.

Además, se presentan los procesos de identificación, cálculo y análisis estadísticos de las caracterizaciones geométricas de los pasos de cebra reconocidos mediante los datos LiDAR. También se avanza en nuevas líneas de trabajo para analizar la calidad y el estado del firme de los recorridos. Los resultados alcanzados muestran un extraordinario potencial para definir con rapidez el estado de los elementos en los recorridos peatonales e identificar lugares y puntos donde es necesario realizar una actuación o mejora en comparación con el resto de elementos caracterizados.

1. INTRODUCCIÓN Y ANTECEDENTES DEL PROYECTO

Este estudio se integra dentro de los trabajos desarrollados en el proyecto denominado “Análisis de indicadores big geo-data sobre viarios urbanos para el diseño dinámico de caminos escolares seguros (BIG-GEOMOVE)” que recibió financiación de la convocatoria de 2017 de la Dirección General de Tráfico del Ministerio del Interior para subvenciones al desarrollo de proyectos de investigación en el área de tráfico, movilidad y seguridad vial. El equipo de investigación de este proyecto, además de los dos grupos redactores de esta comunicación, estaba formado por otros tres grupos de la *Universidade da Coruña* (del grupo de Ferrocarriles y Transportes, del grupo de Estudios Territoriales y del departamento de matemáticas), además del Dpto. de Sociología y Antropología de la *Universitat de Valencia*.

El objetivo principal de ese proyecto era obtener indicadores de caracterización de espacios peatonales en ámbitos urbanos para establecer rutas óptimas seguras y de calidad, centrándose especialmente en caracterizar espacios viarios para definir recorridos peatonales que permitan llegar andando a centros educativos. Su definición y desarrollo parte del proyecto previo “Estudio dinámico de la movilidad escolar mediante tecnologías web de geolocalización (GEOMOVE)”, también financiado por la DGT en la convocatoria de 2015 (Varela-García et al, 2018), completando y ampliando las líneas de investigación iniciadas entonces como se recoge en la web del proyecto http://geomove.es. Mientras en el primer trabajo se avanzaba en técnicas de recogida de información de hábitos de movilidad en los centros escolares mediante sistemas web de participación con mapas, en este segundo proyecto se profundiza en la integración de múltiples fuentes de datos para la parametrización de las características de los viarios urbanos. Se emplearon principalmente, además de la información adquirida mediante encuestas geolocalizadas sobre movilidad (como en el proyecto previo), datos procedentes de sensores LiDAR (*Light Detection and Ranging*), imágenes satelitales adquiridas por el sensor Worldview2 con 8 bandas espectrales y resolución espacial de 50 cm, así como imágenes del Plan Nacional de

Ortofotografía Aérea con una resolución espacial de hasta 25 cm, y otras fuentes de información vectorial y raster, como OpenStreetMap, Catastro, etc., que alimentan el análisis de accesibilidad peatonal que finalmente se realizaba.

Para el cálculo de los recorridos peatonales, además de identificar obstáculos a la movilidad, se observó la necesidad de poder diferenciar en los viales, los espacios destinados al peatón, como pueden ser las aceras o los pasos de cebra. En esta línea se estableció un trabajo específico entre el grupo de Arquitectura de Computadores de la Universidad de Santiago de Compostela (USC) y el grupo de investigación sobre Visualización Avanzada y Cartografía de la Universidade da Coruña (UDC) para desarrollar una metodología que pudiese identificar los bordillos que limitan la zona peatonal de la zona destinada a los vehículos motorizados, y también pudiesen caracterizar los pasos de cebra además de identificarlos, a partir de datos LiDAR, como describiremos en este texto.

La gestión y el mantenimiento adecuado de las carreteras, independientemente de su tipología y ubicación, requiere labores de inspección periódicas a fin de verificar su correcta conservación. Aunque a nivel tecnológico se ha avanzado significativamente, la mayor parte de las labores de inspección de viario siguen realizándose de manera subjetiva, frecuentemente mediante simples controles visuales que dependen de los criterios personales de los operarios encargados. En este sentido, las administraciones responsables del mantenimiento viario demandan cada vez más una información objetiva y actualizada a fin de asegurar su correcta conservación.

La llegada de la tecnología LiDAR ha facilitado notablemente estas labores de inspección gracias a la gran capacidad para capturar datos viarios con gran rapidez y precisión geométrica. LiDAR es un sensor de teledetección activo que emite pulsos de luz polarizada entre el ultravioleta y el infrarrojo cercano (Chuvieco, 2010) empleado tanto en el estudio y la exploración atmosférica (detección de aerosoles y partículas en suspensión, humedad, temperatura, etc.) como en el análisis de la topografía terrestre, ya que permite medir distancias desde un punto emisor.

Aunque su uso es más habitual en otros campos (inventario forestal, modelado del terreno, arqueología, conservación del patrimonio, etc.), en el área de infraestructuras viarias también existe un importante número de investigaciones que estudian la caracterización de carreteras mediante el empleo conjunto de datos LiDAR e información procedente de sensores pasivos y muchas de ellas emplean exclusivamente datos LiDAR, como pueden ser estudios sobre la construcción y el mantenimiento de viales (Akay, 2003; Collins y Sitar, 2010), la actualización automática de datos de navegación 2D y 3D para aplicaciones de consumo (Jaakkola et al., 2008), o la conducción autónoma de vehículos (Bendett y Aral, 1999; Kim et al., 2015; Lee et al., 2009; Park et al., 2011), además de una línea intensa en el control geométrico de infraestructuras singulares como puentes o túneles (Chen et al., 2014; Han et al., 2013; Martínez et al, 2014).

2. METODOLOGÍA

2.1 Datos

Para analizar físicamente los viarios se han escaneado múltiples calles de A Coruña del entorno de Colegio *Fogar de Santa Margarida*, que conforman un total de 12 km de viario, adquiriendo una nube de puntos LiDAR 3D mediante un sistema de captura de datos *Mobile Mapping* (MMS) ofertado por la empresa INSITU. El MMS empleado específicamente fue el Lynx Mobile Mapper M1 de la casa Optech. El sistema permite capturar nubes de puntos en coordenadas 3D a medida que se desplaza por el viario, y consta principalmente de dos sensores LiDAR y 4 cámaras RGB que permiten medir distancias a diferentes objetos del terreno para adquirir puntos en coordenadas X, Y, Z con un rango de precisión de 8 mm, además de información añadida, como valores de intensidad de retorno, tiempo de adquisición, ángulo de escaneo, etc., para obtener una nube de puntos densa que permite caracterizar el entorno analizado.

2.2 Tratamiento automático inicial de datos LiDAR

Para identificar los elementos de interés a partir de la nube de puntos LiDAR se ha desarrollado un método que en primer lugar clasifica los puntos en las clases “suelo” o “no suelo”, con el objetivo de obtener diferentes productos geomáticos a partir de ellas, que puedan servir como parámetros de entrada en sucesivos cálculos y análisis hasta la obtención de los indicadores de accesibilidad (que no son objeto de esta comunicación).

Este proceso parte de las nubes de puntos de los dos sensores en cada una de las escenas estudiadas, y se completa mediante cuatro etapas:

- segmentación grosera de la nube de puntos en suelo/no suelo
- depuración de la nube de puntos segmentada
- segmentación precisa de la nube de puntos
- generación de productos geomáticos.

Para realizar esta tarea se ha empleado la librería de tratamiento de nubes de puntos Point Data Abstraction Library (PDAL), sobre la que se han creado diferentes procesos y plugins para realizar el tratamiento de los datos y los análisis precisos para los cálculos de recorridos óptimos. Se muestra a continuación el modelo cartográfico empleado, que puede verse en la Figura 1, y se describe el procedimiento seguido. El código empleado con más detalles está disponible en el repositorio de código de cartoLAB: https://gitlab.com/cartolab. El código generado puede ejecutarse directamente desde la línea de comandos en cualquier ordenador que tenga instalada una versión de PDAL. Para hacer más sencilla la ejecución del algoritmo y que cualquier usuario no experto pudiese replicar los análisis, se ha optado por implementar el algoritmo en el software QGIS, por ser una herramienta de SIG muy extendida dentro da la comunidad geomática. De esta manera se dispone de todas las funcionalidades de PDAL dentro de QGIS, mediante el plugin PDALtools y el Geomove Processing Provider.

Una decisión alternativa hubiese sido crear un plugin de procesamiento a propósito para Geomove, ganando tiempo de análisis de datos, pero optamos por mejorar QGIS para un uso más estable en el futuro, y mayor beneficio para la comunidad de usuarios. Una vez aplicadas las mejoras pertinentes en el código fuente de QGIS, se implementa el algoritmo de Geomove mediante el plugin PDALtools y el Geomove Processing Provider. PDALtools permite instalar todas las herramientas necesarias para integrar PDAL dentro de Processing Toolbox, mientras que Geomove Processing Provider instala los modelos y algoritmos empleados en el proyecto Geomove dentro del Processing Toolbox. Para replicar los análisis realizados en este estudio es requisito imprescindible tener ambos instalados, así como una versión de PDAL en el ordenador.

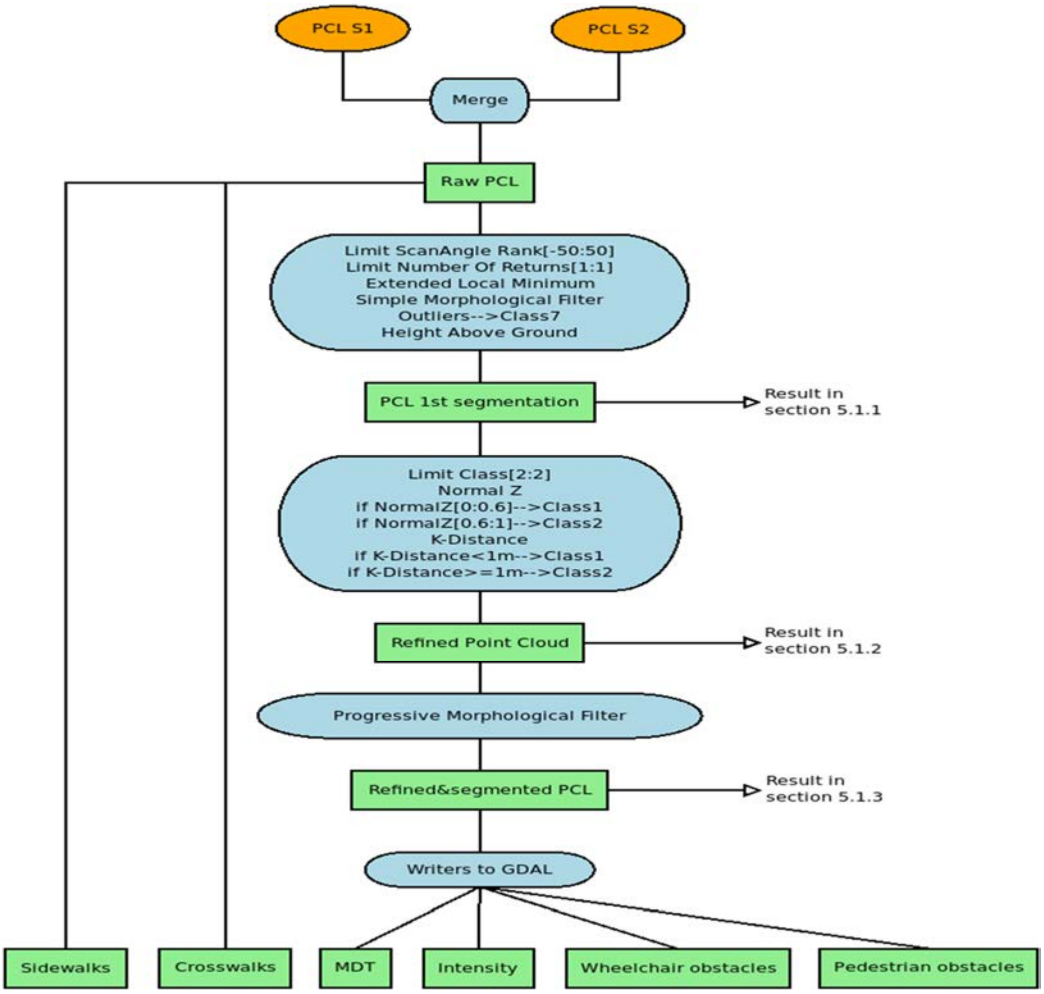

Figura 1: Modelo cartográfico empleado para la generación de la nube de puntos depurada y segmentada.

2.2.1 Segmentación grosera de la nube de puntos en suelo/no suelo

Los datos de entrada son las dos nubes de puntos crudas capturadas por los dos sensores S1 y S2 del sistema MMS, que tienen un formato de punto de tipo P={x,y,z,I,ts}, correspondientes a las coordenadas en 3D, un valor de Intensidad y otro de *time stamp*, respectivamente.

El objetivo de esta parte del algoritmo es segmentar de forma grosera puntos que pertenecen al viario de los que no. Para ello se agruparon los puntos de la nube analizada en dos categorías numéricas "2" y "1" correspondientes a *Ground* y *Unclassified points*, según las especificaciones del estándar ASPRS para las nubes de puntos puntos LiDAR (ASPRS las specification), a partir de ahora llamadas Class2 y Class1.

El proceso se inicia fusionando las dos nubes de puntos para conseguir una única nube [PCL]. Posteriormente se seleccionan sólo los puntos con un único retorno (se ha comprobado que pertenecen a áreas de vegetación, esquinas de edificios y retornos de cristales de vehículos, provocando problemas en la segmentación), y con un *ScanAngleRank* comprendido entre (-50,50), a fin de eliminar puntos demasiado altos que no interesan para la identificación de elementos viarios. Sobre estos puntos se aplican un *Extended Local Minimum Filter* (Chen, 2012) para identificar ciertos puntos como ruido y un *SimpleMorphologicalFilter* (Pingel, 2013) para obtener una nube segmentada en puntos de suelo y no suelo.

Se seleccionan los puntos pertenecientes a no suelo Class1, se les aplica un filtro *Outlier-Statistical Method* (Rusu, 2008) para identificar puntos con valores atípicos y se les asigna un valor de Class7 (*low point-noise*). Por último, sobre los puntos de Class2, se calcula la *Height Above Ground* (HAG), que es un valor de altura relativa desde cada punto respecto a sus vecinos. Este cálculo se realiza iterando sobre todos los puntos, encontrando el vecino más cercano en planimetría entre los puntos del terreno y calculando la distancia entre los dos valores de la componente Z.

2.2.2 Depuración de la nube de puntos segmentada

En este proceso se filtra la nube de puntos anterior, como paso previo a una segmentación más precisa. El primer paso es aplicar un filtro de normales. Se seleccionan sólo los puntos de suelo y se calcula el vector normal en las componentes x,y,z a cada punto en función de sus 30 vecinos más próximos. Con la aplicación del filtro de normales en la componente Z se identifican de manera clara los puntos de transición entre el terreno y los planos verticales. En la Figura 2 se muestran en color rojo los puntos pertenecientes al terreno Class2, en azul los no clasificados, Class1, y en verde las regiones de transición, que son el objeto de estudio en este paso del algoritmo.

Si la normal en la componente z está dentro del intervalo (0, 0.6) se considera que es bastante horizontal y por tanto el punto se asigna a un elemento vertical (fachada de edificio, obstáculo, etc.) con Class1. En el caso de que los puntos tengan una normal en la componente z prácticamente vertical (0.6, 1) se tomarán como puntos de terreno con Class2.

El siguiente paso es calcular *K-distance*. Sobre los puntos Class2 se calcula la distancia euclidea desde cada punto analizado a sus "k" vecinos (en este caso k=300) mediante el filtro *K-distance*.

Se establece que si esta distancia entre ellos es inferior a 1m, los puntos pertenecen a una misma clase (Class2) y si la distancia es superior, pertenecerán a clases diferentes y por tanto se asignan a Class1.

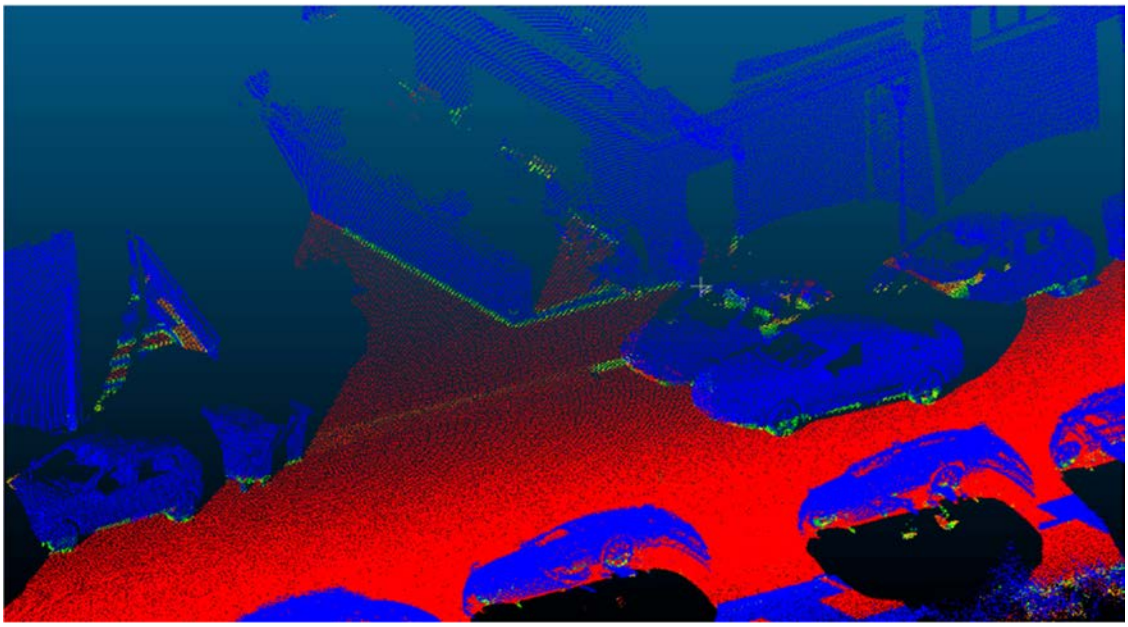

Figura 2: Cálculo del vector normal en la componente Z de cada punto de la nube.

2.2.3 Segmentación precisa de la nube de puntos

Se realiza la última segmentación de la nube de puntos ya filtrada mediante la aplicación de un *Progressive Morphological Filter* que permite segmentar puntos de suelo y no suelo mediante la implementación del método descrito en (Zhang, 2003).

2.2.4 Generación de productos geomáticos

Con la nube de puntos filtrada y adecuadamente segmentada se generan diferentes productos geomáticos, que son la base para crear las superficies de fricción al desplazamiento peatonal en el análisis de accesibilidad. Se generan cuatro archivos en formato raster con un tamaño de pixel de 18 cm: MDT, raster de intensidad, raster de obstáculos para peatones y raster de obstáculos para usuarios de sillas de ruedas. El MDT y el raster de intensidades tienen como valores de pixel las alturas e intensidades medias, respectivamente, de los puntos que se encuentran sobre dicho pixel. En ciertas escenas existen gran cantidad de vehículos aparcados en los laterales de la calzada que provocan zonas de sombra en las nubes de puntos LiDAR y que dificultan enormemente la labor de identificar con precisión la geometría de las aceras. Para solucionar este problema se ha optado por realizar una interpolación cuyo procedimiento no es objeto de esta comunicación.

Para generar los rasters de obstáculos para peatones y usuarios sillas de ruedas se han identificado y rasterizado todos los puntos cuyos valores de HAG están comprendidos entre 5 y 220 cm. Se ha considerado que todos los puntos con HAG >= 5 cm son obstáculos para usuarios de sillas de ruedas y HAG >= 25 cm para peatones.

Además de estos productos generados a partir de la nube de puntos filtrada y depurada, también se ha identificado la ubicación de los pasos de peatones y de los bordillos o delimitaciones calzada-acera, en este caso directamente desde las propias nubes de puntos LiDAR, como detallaremos a continuación.

2.3 Tratamiento automático específico de datos LiDAR

El tratamiento de los datos LiDAR ha sido sin duda el que ha significado un mayor número de horas de trabajo y esfuerzo realizado en este proyecto BIG-GEOMOVE, tanto en los procesos ya comentados, como en otros análisis pormenorizados de los parámetros ofrecidos por la nube de puntos de escaneo láser.

Entre ellos cabe destacar los implementados especialmente para la detección de pasos de peatones y la identificación de bordillos que delimiten convenientemente las aceras y ayuden a definir la zona de desplazamiento peatonal diferenciada de la calzada para los vehículos motorizados.

Los avances realizados han sido muy significativos en ambos casos, así como en otros procesos de detección e identificación de elementos de interés para los desplazamientos a pie, y por ello se han generado y se están generando distintos TFG y TFM con magníficos resultados en distintas líneas de investigación. Aquí expondremos brevemente una parte de estos estudios.

Un reto de estos análisis es la reducción del alto coste computacional del procesamiento de nubes de puntos LiDAR terrestre, donde se pueden alcanzar fácilmente densidades de varios cientos de puntos –e incluso miles– por metro cuadrado.

Debido a la propia naturaleza de los datos, el tratamiento de los mismos implica realizar un gran número de operaciones para llevar a cabo las tareas de segmentación y clasificación, por lo que se recurre a técnicas del ámbito de la computación de altas prestaciones, y se utiliza la infraestructura del Centro de Supercomputación de Galicia (CESGA) para realizar algunos de los procesamientos.

El punto de partida de este trabajo es un código secuencial que recibe como entrada los datos obtenidos tras la segmentación de la nube de puntos LiDAR, a partir de los métodos ya comentados, así como de los análisis de segmentación de datos LiDAR terrestre aplicada a seguridad vial implementados por (Soutullo, 2018) dentro del grupo de la USC.

El programa implementado se encarga de procesar los datos para realizar labores de detección de pasos de cebra y bordillos en entornos urbanos siguiendo un flujo de trabajo basado en la aplicación de distintas etapas de procesamiento consecutivas, obteniendo dos nubes de puntos (*bounding boxes* y elementos viales), que son:

- Algoritmo de adyacencia: Algoritmo que itera sobre la nube de puntos y marca aquellos que son susceptibles de pertenecer a un bordillo. Se basa en la suposición de que los bordillos son adyacentes a terreno (puntos cuya planaridad hace suponer que pertenecen a aceras o carreteras).
- Cálculo de línea virtual: Obtención de una línea compuesta por puntos ajenos a la nube de puntos que se ajusta a la geometría de un bordillo dado.
- Proporcionalidad por tipo de punto: Etapa que descarta grupos etiquetados como señales horizontales cuya proporción de puntos propiamente de señal supera un umbral dinámico.
- Generación de datos de bounding boxes: El principal uso de las bounding boxes consiste en envolver las señales horizontales para realizar un análisis local de las mismas, gracias al cual es posible identificar individualmente las franjas de los pasos de cebra.
- Generación de datos completos: Transformar los datos de pasos de cebra y bordillos a un formato interpretable para su visualización (especialmente usándose el visualizador "Olivia" desarrollado por el grupo de la USC).
- Otros procesamientos: Cálculo de diferentes parámetros asociados a los elementos identificados, como por ejemplo datos geométricos de los mismos (longitud, ancho, pendiente, etc.) para la caracterización final de los elementos clasificados.

En la Figura 3 se observa la nube de puntos LiDAR en una escena del viario estudiado, mostrando la zona según intensidad en la figura de la izquierda, y en la figura de la derecha se identifican con color morado las bandas del paso de cebra y con color blanco la alineación de los bordillos.

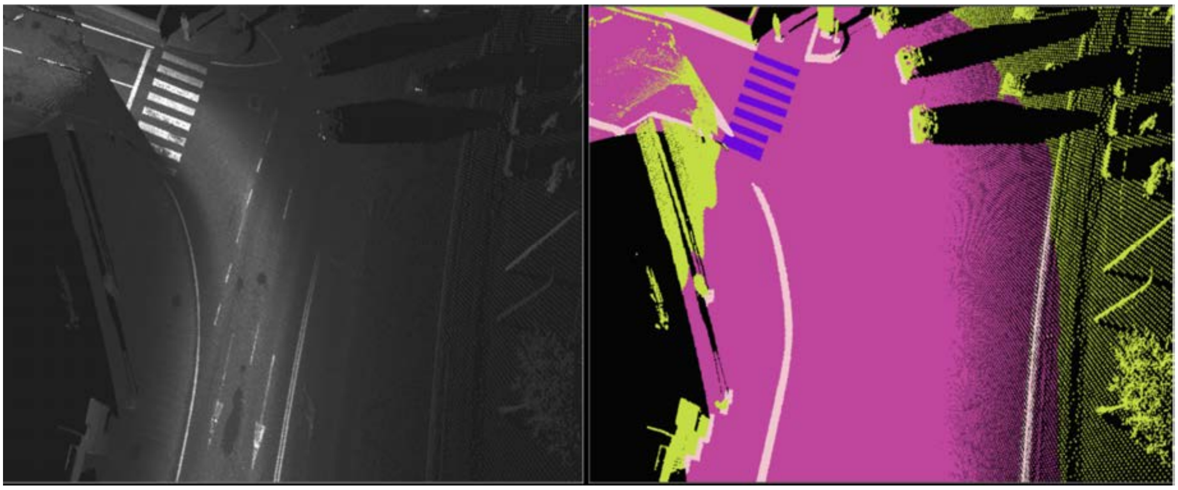

Figura 3: Ejemplo de identificación de paso de cebra y bordillos.

3. RESULTADOS

Aunque seguimos trabajando en la mejora técnicas ya se han obtenido resultados satisfactorios en diferentes entornos geográficos, a partir de distintas escenas de nubes de puntos LiDAR. En el caso de las calles del entorno del colegio de A Coruña, se han conseguido identificar los 37 pasos de cebra existentes, aunque las características de los mismos han hecho que su caracterización no siempre pudiese corresponderse con las geometrías de los mismos. En la Figura 4 puede verse la localización de estos pasos de peatones, identificando aquellos que presentan mejores resultados en cuanto a la geometría final obtenida de forma automática en el proceso de clasificación.

Figura 4: Mapa de localización de los 37 pasos de cebra identificados. En verde aparecen los que consiguen una geometría final similar a la existente y en morado los que presentan algún tipo de problema.

Los problemas de definición final de los pasos de cebra hemos comprobado que no son debidos a deficiencias en el proceso de identificación empleado, sino a las irregularidades y deficiencias presentes en estos elementos de señalización vial, como podemos observar en los ejemplos mostrados en la Figura 5. En general se deben a pérdida de calidad en la pintura de las bandas del paso de cebra, pero también nos encontramos con problemas adicionales cuando hay un cambio de pavimento en el entorno del paso de cebra, o en parte de él, lo que provoca intensidades muy altas de alguna zona del firme.

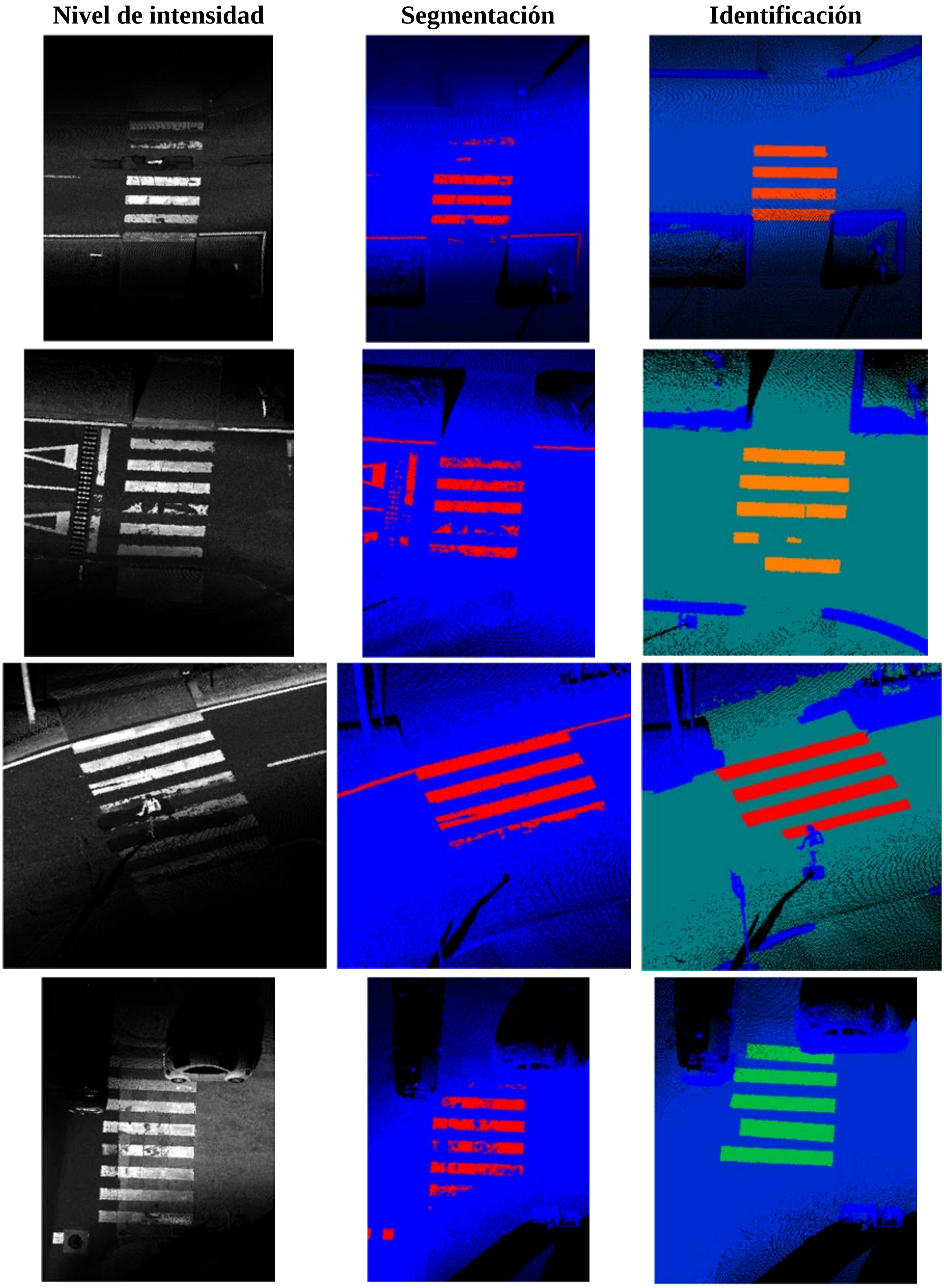

Figura 5: Ejemplos de pasos de cebra no caracterizados en su globalidad debido a distintos factores. Se presentan 3 imágenes de cada paso de cebra, para ver su nivel de intensidad, su segmentación y la detección final realizada.

Además, podemos observar como la presencia de un peatón, o de un vehículo sobre el paso de cebra, imposibilita la reconstrucción completa de parte de este elemento.

Sin embargo, lo que podría considerarse un problema en una primera interpretación de los resultados, creemos que esta circunstancia permite que con el sistema de análisis empleado, no sólo se puedan identificar los pasos de cebra de forma automática en una nube de puntos LiDAR, sino que se puedan clasificar automáticamente aquellos pasos de cebra que presentan irregularidades en su estado. Este hecho, sin duda es de especial interés para cualquier gestor o administrador de la integridad de la señalización viaria, especialmente en ámbitos urbanos, para conocer el grado de calidad de los pasos de cebra de una forma eficiente y objetiva, y poder plantear con ello medidas paliativas para solucionar los problemas detectados.

Pero el proceso de identificación automática de los pasos de cebra, también nos ha permitido caracterizar ciertos parámetros de cada uno de estos elementos de señalización viaria horizontal. Estos parámetros se corresponden tanto con los valores de los datos obtenidos directamente por el LiDAR, como la intensidad o el ángulo de incidencia, como de las métricas calculadas a partir de las coordenadas X, Y, Z de los puntos que caracterizan un paso de cebra, y cada una de sus bandas. Así, podemos obtener el ancho y la longitud de cada paso de peatones, y de cada una de sus bandas de pintura, la pendientes longitudinal y transversal de estos elementos, la diferencia de altura con las aceras de sus extremos, los valores estadísticos (medio, máximo, mínimo, desviación, etc.) de cada valor de intensidad o ángulo de incidencia de todos los puntos LiDAR que forman cada elemento, indicadores calculados a partir de esos datos, como la rugosidad o calidad de la pintura, y un largo etcétera. A modo de ejemplo, se incluye una Tabla 1 con las características más significativas de los pasos de cebra que se consideraron bien clasificados con respecto a los existentes.

PARÁMETRO CALCULADO	VALOR
Media del área real medida	31,85
Media del área calculada	32,19
Longitud media del paso de cebra	7,88
Ancho medio del paso de cebra	4,07
Relación media entre longitud y anchura	1,93
Número medio de barras	8,15
Longitud entre el número de barras	0,97
Longitud máxima de una barra	4,05
Ancho máximo de una barra	0,65
Longitud mínima de una barra	1,49
Ancho mínimo de una barra	0,38
Longitud media de una barra	3,82
Ancho medio de una barra	0,54
Relación media entre longitud y anchura por barra	7,04
Calidad media de la pintura por barra (máx 1)	0,91
Intensidad media por barra	2197,34
Intensidad máxima por barra	3446,03
Intensidad mínima por barra	400,84
Desviación estandar de la intensidad por barra	491,59

Tabla 1: Resumen de parámetros obtenidos sobre los 18 pasos de cebra bien caracterizados.

Además de estos análisis, también se iniciaron procedimientos para la identificación de obstáculos en el recorrido peatonal (farolas, árboles, papeleras, etc.) con el objetivo de definir espacios donde el peatón pueda desplazarse, y lugares donde la movilidad es imposible o presenta limitaciones. En este sentido, también se está estudiando la identificación de deficiencias en el pavimento mediante el análisis de la nube de puntos LiDAR, observándose incluso ligeras anomalías en ciertas zonas de las calles, por lo que sería posible no sólo detectar baches consolidados, sino también aquellas regiones del pavimento donde están empezando a formarse desperfectos significativos, y calcular las características de los mismos (longitudes, profundidades, volúmenes de deterioro, etc.).

4. CONCLUSIONES

La integración de diferentes fuentes de datos para el análisis y gestión de las infraestructuras viarias debe ser una línea de investigación importante en los próximos años, pues las posibilidades que ofrecen los nuevos sensores de captura de datos geográficos mediante técnicas de teledetección (LiDAR, radar, imágenes multiespectrales, etc.) amplían enormemente las posibilidades de identificación, clasificación y caracterización de cualquier elemento territorial. La coordinación de diferentes grupos de investigación, combinando conocimientos en tecnologías diversas y experiencias y capacidades compatibles para abordar estudios diferentes sobre infraestructuras viarias, debe ser también potenciada para encontrar nuevas líneas de análisis.

El ejemplo mostrado en este texto, es sólo una muestra de las iniciativas que con tiempo y recursos, se podrían conseguir para disponer de métodos rápidos y eficaces para aumentar las capacidades de gestión de los siempre complicados procesos de conservación y mantenimiento de las infraestructuras, especialmente las viarias.

Los resultados alcanzados en la identificación y caracterización de bordillos y pasos de cebra, así como de otros elementos relacionados con los recorridos peatonales en zonas urbanas, muestran unos niveles de eficiencia de alto interés para seguir avanzando en las líneas de investigación marcadas desde un proyecto financiado inicialmente por la DGT. Además, los problemas identificados abren líneas de mejora en las características de obtención de los datos, que podrían ser implementadas en futuros trabajos.

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DIFFERENCES IN ROAD-TRAFFIC CRASH RATES DURING CONSTRUCTION AND NON-CONTRUCTION TIMES ON ARTERIAL STREETS: A COMPARATIVE STATISTICAL ANALYSIS

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ABSTRACT

Different studies over the past 30 years have shown an increase in the rates of crash frequencies during road construction time, but this trend is not reported as valid for all cities. A question is raised whether higher rates are observed in arterial roads in Bogotá, Colombia. It is possible to apply descriptive statistics and hypothesis tests to prove them and identify the variables that affect the accident rate during road construction. Our research aims to verify the incidence of high impact construction zones, in the crash rate at the arterial road network of Bogotá. We use descriptive statistics and inferential statistical tests to analyze whether crash rates are statistically higher during construction time than during non-construction time at the same highway sections considering different crash severities (damages-only, injuries, and fatalities). Our database considered 871 road links that make up 68 artery corridors for the city of Bogota, and 5.450 road construction zones, from 2015 to 2019. An analysis by corridor was performed, in which we identified seven patterns in the behavior of accident rates influenced by the presence of a road intervention in the corridor. Within the patterns, it was evident that some corridors reported an increase in the accident rate during the time of construction, while others showed a decrease in the same comparison. We used the Wilcoxon test to establish the statistical significance of our conclusions, with a significance level of 10%. We also found that those construction interventions that do not require excavation of more than half a meter there was a decrease in the accident severity, as damages-only crashes, diminished during the construction time, while for those interventions that include excavation greater than half a meter there was an increase in overall accident rates during construction time.

1. INTRODUCTION

According to the World Health Organization, road crashes are the first leading cause of death and disabling injury among children and young adults between the ages of 5 and 29 and are the 8th leading cause of death in the world at all ages, with 1.35 million deaths each year. It is also a problem that affects 3 times more the countries of emerging economies than the countries with advanced economies (World Health Organization, 2018).

Traffic crashes in construction sites are continuing a problem in many countries around the world. For example, 87,606 crashes occurred in work zones, which led to over 37,000 injuries and 576 fatalities in 2010 in the US (National Highway Traffic Safety Administration, 2013). Large cities in the developing world carry out large-scale construction projects continually e.g., approximately 45% of the roads will be under construction in the next 4 years in Bogota Colombia. The main safety concerns are the road users and the construction workers.

The findings of previous studies that examine the safety impacts of work zones varied significantly because of the differences in locations, data size, data quality, and analysis approaches. Traffic-related crash rates and behavior depend on city-specific conditions such as drivers' behaviors, safety regulations and standards during construction, environmental conditions, and soon (Yang, Ozbay, 0zturk and Xie, 2015).

Road construction safety regulation requires that contractors take sufficient safety measures to protect human lives. Construction works always affect mobility conditions, even when a large part of the work aims to improve the conditions of the existing roads and the city mobility in general, but contractors are required to maintain safety and smoothness in traffic flow on the road construction site, (Instituto de Desarrollo Urbano IDU, 2016).

Construction of new infrastructure and building projects in Bogota are required to present a traffic management plan -PMT (for its words in Spanish) to the local mobility authority. A PMT should include strategies and technical alternatives to provide safe, and operational conditions to the different road users through optimized planning, scheduling, and operating mechanisms. In the particular case of Bogotá, those plans are classified into two main categories COI (Consolidation of infrastructure works) and COOS (Consolidated public service infrastructure works) (Movilidad, 2021).

To establish whether the PMT mechanisms implemented in the working zone are efficient and effective in mitigating work zone safety impacts on the traveling public and the workers we perform a long-term analysis for arterial roads in Bogota. We were interested in investigating changes in vehicle crashes by three different severities, questioning whether the rates of registered road crashes are higher during construction periods and non-construction time.

Several studies have been carried out at the global level to develop an understanding of the potential risk factors associated with work zone crash occurrences (Di, Shi, Zhang, Svirchev, & Hu, 2016; Jin, Saito, & Eggett, 2008; Rao, Wu, Xia, Ou, & Kluger, 2018; Rouphail, Yang, & Fazio, 1988; Theofilatos, Ziakopoulos, Papadimitriou, Yannis, & Diamandouros, 2017; Ullman, Finley, & Ullman, 2004; Zhang & Hassan, 2019).

The findings from these studies varied significantly because of the differences in data availability, locations, methods of analysis, but there is a general agreement about accident rates being higher during construction time when compared to non-construction rates in most advanced economies (Yang, Ozbay, 0zturk and Xie, 2015).

However, there is very little research on this topic in large Latin-American cities as is the case of Bogota, Colombia. Considering that Bogota has a vision zero plan towards road safety to reduce the number of crashes with fatalities by the year 2038, and in addition, during the next few years the city will begin the construction of multiple high-impact projects including the first Metro line, regional light rail (REGIOTRAM), new BRT corridors our research takes relevance.

Our study focuses on comparing long-term traffic crash rates in the arterial road network of the city of Bogota during construction and non-construction time using data for 2015 to 2018. Different statistical methods are applied to test statically significant differences of central trend measures.

We used non-parametric tests such as the Wilcoxon test (Wilcoxon, 1945), to test our hypothesis discriminating by different crash severities, different road types, and for different arterial corridors in the city of Bogota.

2. METHOD

2.1 Research framework

This study uses statistical techniques to identify patterns of behavior in accident rates during construction and non-construction time in Bogotá, Colombia. This statistical analysis is carried out through descriptive statistics (minimum, maximum, mean, standard deviation) and non-parametric statistical tests such as the Wilcoxon test. Crash rates were calculated using per million vehicle miles traveled (MVMT).

Our research consisted of two phases: First, the construction of the database needed; second one the statistical data analysis and hypothesis testing. From this point forward, a brief description of the process is made considering the main components of our research framework: road infrastructure description, types of construction zones, crash severity and time windows, the data sources, data grouping, and methods of analysis.

2.1.1 Road Infrastructure

The road subsystem in the city of Bogota is divided into 4 main types of the road network, the first one refers to the main arterial road network, which is responsible for providing accessibility and connection for the city with the region and the country. The second type is the complementary arterial road network, which is intended for medium and long-range travel within the city.

These first two networks add up in total 2.634 km. The third type is the intermediate road network, which functions as an alternative to decongest the city and has a total length of 3.204 km. Finally, there is the local road network to connect the housing units with the other arterial roads and is composed of 6.134 km of small streets. Our research analyses included the main and intermediate arterial networks with a total of 68 road corridors, and 400 kilometers (figure 1).

Figure 1: Main and complementary arterial network included in research analysis.

2.1.2 Types of construction interventions and their traffic management plan

As stated before, the traffic management plan (PMT) is a technical tool used to propose the strategies, alternatives, and different activities needed to reduce the impacts on traffic flow and safety during construction time. PMT contains actions required to deal with infrastructure closures and displacement of road users, as pedestrians, cyclists, transit buses, trucks, and light-duty vehicles.

All actions contained in the PMT must favor the road safety of all users and construction workers. These traffic management plans are classified according to the type of intervention which can be works or events.

They are also classified by the intensity of the impacts and the complexity of the construction process as high, medium, and low. In our investigation, three different types of PMT were considered, which are:

2.1.2.1 COI-ALTA

The Consolidated Works of Infrastructure (COI) is a standard regulation instruction manual designed by the District Secretariat of Mobility of Bogota for those PMT that does not require an excavation license for their execution. A total of 3708 COI PMT were included for our study.

COI-high denomination used in our research refers to the type of complexity. Impacts include traffic lights on road corridors, partial or total closure of lanes, partial or total use of the access platform, partial or total closures to pedestrian bridges, and total closures of bike paths located on the road.

2.1.2.2 COOS-ALTA

The Consolidated Public Service Infrastructure Works (COOS) is the PMT instruction manual developed by the District Secretariat of Mobility of Bogota for works that require an excavation license with a depth greater than 0.5. In this type of works, the width and depth of the excavation must be specified to determine the safety distances and type of element to be used for the enclosure.

COOS-high denomination refers again to the impact or level of affectation explained for the COI-ALTA. There were 1729 PMT considered for this investigation.

2.1.2.3 COI-TRONCAL

The Consolidated Works of Infrastructure (COI) is the type of PMT that applies to construction zones in Bogota´s BRT system - TransMilenio There were only 13 COI-TRONCAL PMT included in our analysis.

2.1.3 Crash severity and time windows

Crashes were classified by severity into 3 categories, the crashes that caused fatalities were defined as "Fatalities (DE)". If the crash caused injuries, or injuries and material damage, the severity will be defined as "Injuries (WO)". If only material damage occurred, the severity of the crash will be defined as "damage only (DO)".

Three different time windows of analysis were defined: Before construction time (BF), corresponding to crash rates before a road intervention happened and a work zone was established. During construction time labeled as PMT), corresponding to crash rates while the work zone was active. After construction time (AF), corresponding to crash rates after road intervention was finished.

The before and after time windows had the same duration as every intervention, to avoid bias. They were also placed immediately before and after each intervention for a better understanding of the direct impact they have on road safety conditions.

2.2 Data sources

2.2.1 IPAT

The Police Report on Traffic Accidents (Informe Policial de Accidentes de Tránsito, IPAT) is an official record used in Bogotá by the specialized bodies of Urban Traffic Police, as a tool that allows the primary collection of crash data. This report is aimed at allowing clear and probable identification of causes hypotheses and at facilitating the implementation of actions related to road safety for the national, departmental, municipal, or local government and representatives of civil society. (For more information about IPAT, its manual is available online)

2.2.2 SIGAT

SIGAT is the acronym for Sistema de Información Geográfica de Accidentes de Tránsito (Geographic Information System for Traffic Accidents). This database is linked to Registro Nacional de Accidentes - RNAT (National Registry of Traffic Accidents, in English) and its main function is to consult if a vehicle is reported in the database of Police Reports of Traffic Accidents (IPAT) registered in the District Secretary of Mobility of Bogotá. We used this database as our main source to compute crash rates between 2015 and 2018.

2.3 Grouping of data for construction and non-construction time

The database used to make the descriptive statistics and run the nonparametric test had 22 variables, and 5.450 entries, corresponding to the number of PMT or construction work zones in the 68 road corridors that were considered for the study. Table 1 shows the variables considered in our analysis.

VARIABLE	DESCRIPTION
COD	Corresponds to the number or key assigned to each PMT.
ADDRESS	Place where the PMT is developed, and the accident record is kept.
CORRIDOR	Name of road corridor.
PMT TYPE	Typology of the PMT that was carried out.
SECTION	Code assigned to each road section belonging to a particular corridor.
START	Start date of PMT implementation.
END	End date of PMT implementation.
DURATION	Time in days when the PMT was applied.
LENGHT	Distance in meters in which the PMT was applied.
VOL VEH	Corresponds to the average daily hourly traffic (TPDH).
BF_DO	Accidents before construction time with damages only.
BF_WO	Accidents before construction time with wounded people.
BF_DE	Accidents before construction time with deceased people.
BF_TO	The total number of accidents before construction time.
PMT_DO	Accidents during construction time with damages only.
PMT_WO	Accidents during construction time with wounded people.
PMT_DE	Accidents during construction time with deceased people.
PMT_TO	The total number of accidents during construction time.
AF_DO	Accidents after construction time with damages only.
AF_WO	Accidents after construction time with wounded people.
AF_DE	Accidents after construction time with deceased people.
AF_TO	The total number of accidents after construction time.

Table 1: Attributes of the database.

2.4 Method of analysis

We used R Studio, a statistical software (Gentelman and Ihaka, 1993) with packages as dplyr (Wickham and François, 2020), ggplot2 (Wickham, 2016), lubridate (Wickham and Grolemund, 2011), reshape2 (Wickham, 2011), nortest (Gross and Ligges, 2015), car (Fox and Weisberg, 2019), MVN (Korkmaz, Goksuluk, and Zararsiz, 2014) among other packages to analyze the crash rates associated with the 5450 construction work zones. We developed a descriptive statistical analysis, including mean, standard deviation, minimum value, and maximum value. We used Wilcoxon test (Wilcoxon, 1945) a non-parametric test to perform hypothesis testing, to probe statistical significance difference between crash rates in different time windows, discriminating t by severity, (Damage Only (DO), Injuries (WO), Fatalities (DE), and total (TO)). We used Wilcoxon for the hypothesis testing at the city level, by the corridor, and by type of PMT.

The Wilcoxon test used is also known as the Wilcoxon range sum test or Mann-Whitney test and represents a non-parametric alternative to the t-test of two unpaired samples, where it is checked whether two samples come from equidistributed populations. Some conditions that must be considered for the application of this test are that the data must be independent, ordinal, and the phenomenon of homoscedasticity must be presented among the groups to be compared.

For the Wilcoxon test, the equality in the averages of the accident rates during construction times and not construction was adopted as a null hypothesis, which would mean that there would be no statistically significant evidence that the rates were different; in addition, two alternative scenarios were adopted, the first of which was determined by greater, in which, if the null hypothesis was rejected, the hypothesis that the accident rate of the non-construction time was higher was accepted, compared to the accident rate in construction times; the second alternative hypothesis consists of less and is the opposite of the first because in this case there would be a statistically significant difference in the rates which would lead to the conclusion that the crash rates at construction time are lower than the rates under construction.

3. RESULTS

Our results are presented in tables by city level, by corridors, and by PMT type. These results are presented as follows. First, descriptive statistics and Wilcoxon test results for the entire city. The second will follow the Wilcoxon test results of crash rate difference sorted by corridors. Third, we present descriptive statistics and Wilcoxon test results of crashes sorted by PMT.

Tables 3, 4, 5, 6, 9, and 10 present a summary of the results of the Wilcoxon tests for two different alternative hypotheses: i) depending on the case one of the rates (before or after the construction zone) is greater than the crash rate during construction; ii) one of the rates (before or after the construction zone) is less than the crash rate during construction.

The columns of all tables show the previously described accident rates, and its rows vary according to the classification of accidents used. At the city level, there is only one row corresponding to its name: Bogotá D.C. In the case of accidents sorted by corridors, each row corresponds to the name of the 58 corridors that make part of the arterial network of Bogotá. In the case of accidents sorted by PMT, each row corresponds to the type of traffic management plan.

3.1 City level

Table 2 shows a summary of the descriptive statistics for the previously described crash rates, according to the defined classification of accidents. These statistics show the range, mean, standard deviation, and sum of these variables.

Bogotá	BF_DO	BF_WO	BF_DE	BF_TO	PMT_DO	PMT_WO	PMT_DE	PMT_TO	AF_DO	AF_WO	AF_DE	AF_TO
Minimum	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	3344.999186	5163.536933	395.9703834	5163.536933	3297.470898	1584.079157	2059.077505	3297.470898	15733.43452	1374.36379	271.3092127	15733.43452
Mean	22.71796736	9.743536421	0.484200592	32.94570438	22.801404	9.761602591	0.833701646	33.39670824	23.67714855	8.616248479	0.317818644	32.61121567
Standard deviation	104.0366236	80.99744194	9.505221487	137.4338887	99.17866335	49.84571701	29.43411908	119.7213343	226.1061631	42.7806412	5.061184979	232.010722
Sum	123812.9221	53102.27349	2638.893227	179554.0889	124267.6518	53200.73412	4543.673968	182012.0599	129040.4596	46958.55421	1732.111611	177731.1254

Table 2: Results of descriptive statistics at the city level.

At the city level of the city, the Wilcoxon test was run with a total of 5,450 work zones in arterial corridors. In general, we could not find statistical differences in crash rates during construction and non-construction times. We observed a raised in Damages Only (DO) crash rates after the construction zone is lifted but this test is considered inconclusive. Therefore, we decided to analyze by Corridor and by type of PMT.

CITY LEVEL	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
Bogota DC	5450	0,206	0,096	0,223	0,105	0,177	0,662	0,751	0,413	0,206	0,139	0,106	0,247

Table 3: Wilcoxon test results at a city level for alternative hypothesis where the crash rate in non-construction is greater than the crash rate during construction.

Note: Values shown are p-values. The green value corresponds to p-values less than 0.1. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

CITY LEVEL	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
Bogota DC	5450	0,794	0,904	0,777	0,894	0,823	0,338	0,250	0,588	0,795	0,861	0,894	0,753

Table 4: Wilcoxon test results at a city level for alternative hypothesis where the crash rate in non-construction is less than the crash rate during construction.

Note: Values shown are p-values. The yellow value corresponds to p-values bigger than 0.9. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

3.2 By corridor

We perform the hypothesis analysis in 58 arterial corridors. Table 5 shows, the p-value of the Wilcoxon test, performed to find statistically significant differences between the crash rates of the different time windows considering the three levels of crash severities.

Tables 5 and 6 shows p-values smaller than 0.1 in green color, and p-values bigger than 0.9 in yellow color. P-values equal to 1 are shown in red color as this was an indication that the hypothesis was completely rejected. Cells without color correspond to those p-values that do not fit any of the previously described categories.

CORRIDOR	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
AUTONORTE	321	0,478	0,319	0,336	0,341	0,464	0,534	0,949	0,292	0,029	0,394	0,194	0,217
AV.AMERICAS	215	0,587	0,060	0,069	0,869	0,976	0,936	0,882	0,929	0,682	0,699	0,480	0,345
AV.CARACAS	462	0,035	0,236	0,571	0,956	0,519	0,061	0,709	0,228	0,103	0,441	0,359	0,230
AV.CIRCUNVALAR	105	0,702	0,006	0,003	0,153	0,033	0,138	0,500	0,815	0,977	0,483	0,001	0,002
AV.CORDOBA	8	0,899	0,708	0,428	0,815	0,815	0,977	1,000	1,000	1,000	0,909	0,819	0,500
AV.P.MAYO	169	0,561	0,058	0,062	0,046	0,085	0,568	0,050	0,147	0,963	0,105	0,046	0,267
AV.SUBA	66	0,769	0,772	0,530	0,711	0,089	0,021	0,500	0,977	0,789	0,891	0,514	0,119
CL1	7	0,605	0,815	0,789	1,000	1,000	1,000	1,000	1,000	1,000	0,605	0,815	0,789
CL100	52	0,072	0,730	0,988	0,422	0,556	0,368	1,000	1,000	1,000	0,173	0,714	0,950
CL116	46	0,252	0,305	0,581	0,053	0,140	0,963	1,000	1,000	1,000	0,133	0,132	0,639
CL11SUR	46	0,929	0,583	0,400	0,853	0,013	0,005	0,186	0,211	0,977	0,938	0,030	0,011
CL127	80	0,602	0,443	0,201	0,032	0,101	0,735	0,977	1,000	0,500	0,351	0,291	0,303
CL13	173	0,338	0,076	0,114	0,889	0,437	0,124	0,292	0,186	0,186	0,742	0,185	0,024
CL134	41	0,599	0,318	0,348	0,708	0,606	0,606	1,000	1,000	1,000	0,534	0,269	0,348
CL147	50	0,394	0,233	0,211	0,180	0,164	0,583	1,000	1,000	1,000	0,219	0,043	0,241
CL170	73	0,918	0,923	0,676	0,280	0,545	0,714	1,000	0,969	0,969	0,776	0,898	0,853
CL19	80	0,227	0,069	0,186	0,204	0,722	0,871	0,572	0,500	0,395	0,189	0,090	0,278
CL24	125	0,464	0,694	0,820	0,001	0,296	0,976	0,789	0,500	0,211	0,041	0,585	0,921
CL26	215	0,322	0,773	0,808	0,174	0,222	0,475	0,977	0,899	0,860	0,266	0,775	0,848
CL26SUR-KR78K	15	0,050	0,962	0,993	0,977	0,899	0,899	1,000	1,000	1,000	0,091	0,989	0,993
CL32	6	0,950	0,969	0,295	0,500	0,899	0,394	1,000	1,000	1,000	0,911	0,953	0,428
CL34	25	0,550	0,062	0,054	0,102	0,143	0,990	1,000	1,000	1,000	0,301	0,085	0,066
CL43SUR	13	0,663	0,864	0,791	0,071	0,899	0,363	1,000	1,000	1,000	0,394	0,946	0,946
CL45	30	0,695	0,312	0,131	0,380	0,361	0,278	0,815	0,815	0,500	0,699	0,297	0,117
CL53	57	0,174	0,023	0,180	0,793	0,723	0,853	1,000	0,977	0,977	0,431	0,059	0,141
CL57	16	0,982	0,605	0,054	0,264	0,534	0,630	0,815	0,815	0,815	0,819	0,637	0,265
CL6	48	0,431	0,084	0,033	0,592	0,748	0,934	0,978	0,963	0,292	0,567	0,337	0,228
CL63	37	0,105	0,056	0,524	0,164	0,620	0,500	0,815	0,500	0,500	0,098	0,135	0,743
CL66A	6	0,186	0,963	0,969	0,977	1,000	0,888	1,000	1,000	1,000	0,395	0,963	0,950
CL68	39	0,225	0,147	0,335	0,270	0,775	0,977	1,000	0,978	0,978	0,138	0,444	0,826
CL7	10	1,000	0,963	0,963	0,500	1,000	0,122	1,000	1,000	1,000	0,500	0,963	0,963
CL72	166	0,549	0,919	0,965	0,365	0,164	0,769	0,102	0,201	0,860	0,181	0,804	0,830
CL80	229	0,247	0,184	0,482	0,385	0,706	0,050	0,400	0,075	0,201	0,214	0,393	0,452
CL85	26	0,977	0,966	0,500	0,663	0,209	0,541	1,000	1,000	1,000	0,974	0,916	0,228
CL92	65	0,202	0,704	0,942	0,228	0,377	1,000	1,000	1,000	1,000	0,121	0,500	0,910
CL94	6	0,977	0,969	0,963	1,000	1,000	0,547	1,000	1,000	1,000	0,977	0,969	0,963
DIAG16	33	0,610	0,608	0,408	0,723	0,541	1,000	0,211	0,292	0,909	0,525	0,294	0,510
K15	21	0,500	0,500	0,500	1,000	1,000	0,796	1,000	1,000	1,000	0,500	0,500	0,500
KR10	44	0,258	0,066	0,312	0,930	0,973	0,777	0,708	0,417	0,400	0,741	0,902	0,662
KR11	101	0,611	0,484	0,147	0,596	0,823	0,031	1,000	1,000	1,000	0,619	0,739	0,390
KR13	83	0,644	0,503	0,503	0,998	0,942	0,958	1,000	1,000	1,000	0,975	0,619	0,061
KR15	80	0,636	0,195	0,065	0,481	0,985	0,572	0,977	0,977	0,500	0,586	0,655	0,334
KR17	17	0,780	0,500	0,092	0,209	0,223	0,500	1,000	1,000	1,000	0,743	0,361	0,172
KR17-KR19	15	0,963	0,909	0,605	0,977	1,000	0,313	1,000	1,000	1,000	0,969	0,909	0,428
KR19	105	0,720	0,666	0,565	0,842	0,685	0,406	1,000	1,000	1,000	0,812	0,785	0,496
KR24	64	0,085	0,391	0,737	0,301	0,322	0,444	1,000	1,000	1,000	0,047	0,423	0,713
KR27	46	0,257	0,731	0,946	0,362	0,225	0,053	1,000	0,977	0,977	0,332	0,610	0,891
KR36	19	0,898	0,572	0,047	0,969	0,500	0,882	1,000	1,000	1,000	0,929	0,605	0,030
KR50	52	0,985	0,951	0,693	0,147	0,883	0,969	0,977	1,000	0,500	0,941	0,960	0,835
KR60	19	0,606	0,292	0,292	0,500	0,708	0,981	1,000	1,000	1,000	0,417	0,292	0,500
KR68	182	0,443	0,813	0,843	0,005	0,167	0,870	0,204	0,078	0,292	0,030	0,512	0,942
KR7	232	0,865	0,950	0,781	0,294	0,699	0,529	0,312	0,277	0,383	0,606	0,817	0,842
KR72	496	0,737	0,442	0,207	0,719	0,619	0,820	0,517	0,397	0,336	0,903	0,401	0,231
KR80	54	0,779	0,460	0,292	0,182	0,223	0,503	0,292	0,500	0,899	0,449	0,402	0,402
KR86	194	0,067	0,188	0,638	0,414	0,350	0,605	0,730	0,915	0,773	0,096	0,200	0,654
KR9	38	0,675	0,232	0,201	0,909	0,815	0,650	0,977	1,000	0,500	0,778	0,431	0,308
NQS	395	0,002	0,139	0,791	0,041	0,080	0,500	0,952	0,516	0,066	0,003	0,165	0,819
TV39-TV42	6	0,977	1,000	0,500	0,815	0,395		0,500	0,500	1,000	0,815	0,395	0,186

Table 5: Wilcoxon test results at by arterial corridor for alternative hypothesis where the crash rate in non-construction is greater than the crash rate during construction.

Note: Values shown are p-values. The green value corresponds to p-values less than 0.1. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

CORRIDOR	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
AUTONORTE	321	0,523	0,682	0,665	0,661	0,539	0,469	0,063	0,819	0,979	0,607	0,807	0,784
AV.AMERICAS	215	0,415	0,941	0,932	0,132	0,024	0,065	0,143	0,092	0,361	0,302	0,521	0,656
AV.CARACAS	462	0,965	0,764	0,429	0,044	0,481	0,939	0,300	0,781	0,902	0,559	0,641	0,771
AV.CIRCUNVALAR	105	0,301	0,995	0,997	0,853	0,969	0,871	0,977	0,500	0,500	0,520	0,999	0,998
AV.CORDOBA	8	0,181	0,428	0,708	0,500	0,500	0,500	1,000	1,000	1,000	0,211	0,292	0,606
AV.P.MAYO	169	0,441	0,943	0,939	0,954	0,916	0,435	0,978	0,896	0,186	0,896	0,954	0,734
AV.SUBA	66	0,239	0,238	0,480	0,301	0,918	0,981	0,815	0,500	0,395	0,112	0,496	0,884
CL1	7	0,605	0,500	0,395	1,000	1,000	1,000	1,000	1,000	1,000	0,605	0,500	0,395
CL100	52	0,932	0,278	0,014	0,608	0,472	0,651	1,000	1,000	1,000	0,835	0,294	0,053
CL116	46	0,775	0,722	0,459	0,971	0,911	0,186	1,000	1,000	1,000	0,885	0,883	0,406
CL11SUR	46	0,104	0,500	0,664	0,164	0,990	0,996	0,963	0,909	0,500	0,071	0,975	0,991
CL127	80	0,406	0,565	0,806	0,972	0,908	0,288	0,500	1,000	0,977	0,656	0,716	0,706
CL13	173	0,665	0,925	0,887	0,113	0,567	0,878	0,819	0,963	0,963	0,260	0,816	0,977
CL134	41	0,425	0,699	0,668	0,428	0,500	0,500	1,000	1,000	1,000	0,489	0,746	0,668
CL147	50	0,616	0,778	0,800	0,846	0,853	0,472	1,000	1,000	1,000	0,790	0,960	0,772
CL170	73	0,088	0,081	0,333	0,734	0,470	0,308	1,000	0,091	0,091	0,233	0,106	0,152
CL19	80	0,776	0,932	0,818	0,808	0,286	0,135	0,572	0,977	0,789	0,813	0,911	0,726
CL24	125	0,540	0,309	0,183	0,999	0,709	0,025	0,395	0,815	0,909	0,960	0,417	0,080
CL26	215	0,680	0,229	0,193	0,829	0,782	0,531	0,500	0,181	0,209	0,736	0,227	0,153
CL26SUR-KR78K	15	0,978	0,054	0,011	0,500	0,181	0,211	1,000	1,000	1,000	0,969	0,017	0,011
CL32	6	0,101	0,047	0,791	0,977	0,181	0,181	1,000	1,000	1,000	0,140	0,078	0,708
CL34	25	0,475	0,946	0,953	0,925	0,882	0,705	1,000	1,000	1,000	0,715	0,923	0,942
CL43SUR	13	0,417	0,176	0,295	0,953	0,181	0,015	1,000	1,000	1,000	0,705	0,071	0,071
CL45	30	0,333	0,736	0,889	0,658	0,682	0,688	0,500	0,500	0,815	0,318	0,733	0,895
CL53	57	0,835	0,979	0,829	0,238	0,318	0,748	1,000	0,500	0,500	0,583	0,946	0,867
CL57	16	0,030	0,605	0,960	0,779	0,534	0,201	0,500	0,500	0,500	0,221	0,417	0,799
CL6	48	0,586	0,926	0,969	0,428	0,282	0,388	0,050	0,186	0,819	0,448	0,675	0,782
CL63	37	0,901	0,948	0,492	0,853	0,419	0,074	0,500	0,977	0,977	0,907	0,872	0,269
CL66A	6	0,963	0,186	0,091	0,500	1,000	0,977	1,000	1,000	1,000	0,789	0,186	0,101
CL68	39	0,801	0,866	0,685	0,762	0,252	0,128	1,000	0,050	0,050	0,872	0,572	0,189
CL7	10	1,000	0,186	0,186	0,977	1,000	0,500	1,000	1,000	1,000	0,977	0,186	0,186
CL72	166	0,453	0,081	0,035	0,637	0,837	0,880	0,925	0,853	0,209	0,820	0,197	0,171
CL80	229	0,754	0,817	0,520	0,617	0,296	0,233	0,664	0,946	0,853	0,787	0,608	0,549
CL85	26	0,028	0,041	0,541	0,417	0,860	0,978	1,000	1,000	1,000	0,030	0,094	0,795
CL92	65	0,805	0,302	0,061	0,795	0,647	0,500	1,000	1,000	1,000	0,884	0,507	0,094
CL94	6	0,500	0,091	0,186	1,000	1,000	1,000	1,000	1,000	1,000	0,500	0,091	0,186
DIAG16	33	0,417	0,422	0,612	0,336	0,500	0,500	0,909	0,819	0,211	0,500	0,724	0,510
K15	21	0,815	0,977	0,977	1,000	1,000	1,000	1,000	1,000	1,000	0,815	0,977	0,977
KR10	44	0,752	0,939	0,712	0,075	0,028	0,212	0,428	0,663	0,664	0,267	0,103	0,348
KR11	101	0,393	0,521	0,855	0,415	0,185	0,231	1,000	1,000	1,000	0,385	0,264	0,613
KR13	83	0,361	0,503	0,503	0,003	0,061	0,970	1,000	1,000	1,000	0,026	0,386	0,941
KR15	80	0,370	0,810	0,937	0,538	0,016	0,045	0,500	0,500	0,815	0,420	0,350	0,670
KR17	17	0,257	0,583	0,929	0,860	0,824	0,572	1,000	1,000	1,000	0,297	0,682	0,857
KR17-KR19	15	0,186	0,211	0,605	0,500	1,000	0,977	1,000	1,000	1,000	0,091	0,211	0,708
KR19	105	0,294	0,348	0,448	0,173	0,335	0,699	1,000	1,000	1,000	0,194	0,223	0,514
KR24	64	0,919	0,618	0,271	0,714	0,693	0,612	1,000	1,000	1,000	0,955	0,586	0,294
KR27	46	0,761	0,281	0,062	0,667	0,801	0,583	1,000	0,500	0,500	0,684	0,404	0,118
KR36	19	0,136	0,572	0,970	0,091	0,815	0,971	1,000	1,000	1,000	0,092	0,605	0,985
KR50	52	0,019	0,054	0,322	0,896	0,147	0,143	0,500	1,000	0,977	0,066	0,044	0,174
KR60	19	0,500	0,819	0,819	0,977	0,428	0,091	1,000	1,000	1,000	0,663	0,819	0,606
KR68	182	0,559	0,188	0,158	0,995	0,834	0,020	0,828	0,938	0,819	0,970	0,490	0,059
KR7	232	0,136	0,051	0,220	0,710	0,305	0,132	0,736	0,777	0,661	0,395	0,184	0,159
KR72	496	0,263	0,559	0,793	0,282	0,382	0,472	0,500	0,619	0,678	0,098	0,599	0,769
KR80	54	0,225	0,546	0,714	0,823	0,783	0,188	0,819	0,583	0,181	0,556	0,603	0,603
KR86	194	0,933	0,813	0,364	0,589	0,653	0,499	0,305	0,098	0,243	0,904	0,801	0,347
KR9	38	0,345	0,789	0,818	0,211	0,500	0,605	0,500	1,000	0,977	0,239	0,597	0,714
NQS	395	0,998	0,861	0,210	0,959	0,920	0,351	0,051	0,516	0,938	0,997	0,836	0,182
TV39-TV42	6	0,500	1,000	0,977	0,500	0,789	0,977	0,977	0,977	1,000	0,500	0,789	0,963

Table 6: Wilcoxon test results at by arterial corridor for alternative hypothesis where the crash rate in non-construction is less than the crash rate during construction.

Note: Values shown are p-values. The green value corresponds to p-values less than 0.1. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

3.3 By PMT type

Tables 7 and 8 show a summary of the descriptive statistics for the previously described crash rates, according to the defined classification of accidents. These statistics show the range, mean, standard deviation, and sum of these variables.

COI-ALTA	BF_DO	BF_WO	BF_DE	BF_TO	PMT_DO	PMT_WO	PMT_DE	PMT_TO	AF_DO	AF_WO	AF_DE	AF_TO
Minimum	0	0	0	0	0	0	0	0	0	0	0	
Maximum	3344.99919	5163.53693	395.970383	5163.53693	3297.4709	1584.07916	490.330442	3297.4709	1985.78336	1374.36379	271.3092127	2045.01696
Mean	22.87013	10.12827	0.594041	33.59244	23.98458	10.30154	0.5601593	34.84628	20.27924	8.401647	0.3162106	28.9971
Standard deviation	117.27334	94.89802	11.276667	157.49235	109.75658	54.65265	10.909148	129.35503	71.61943	45.675955	5.5224075	92.11875
Sum	84802.45658	37555.62479	2202.703957	124560.7853	88934.81148	38198.1097	2077.070634	129209.9918	75195.43724	31153.30872	1172.509017	107521.255

Table 7: Results of descriptive statistics for COI-ALTA.

COOS-ALTA	BF_DO	BF_WO	BF_DE	BF_TO	PMT_DO	PMT_WO	PMT_DE	PMT_TO	AF_DO	AF_WO	AF_DE	AF_TO
Minimum	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	1064.67306	749.921325	76.2950083	1064.67306	1239.30942	749.921325	2059.077505	2059.0775	15733.43452	670.893258	77.2701849	15733.43452
Mean	22.35298	8.984521	0.2522784	31.58978	20.18608	8.677053	1.426607	30.28974	31.01735	9.141264	0.3236568	40.48227
Standard deviation	67.86485	36.972009	3.4676177	79.54107	71.63501	37.743989	49.760847	96.20247	387.45294	35.981352	3.9179715	389.14788
Sum	38648.30551	15534.23741	436.1892699	54618.73219	34901.74026	15002.62442	2466.603334	52370.96801	53629.00333	15805.24548	559.6025935	69993.8514

Table 8: Results of descriptive statistics for COOS-ALTA.

We perform the hypothesis analysis in 3 types of PMT. Tables 9 and 10 show, the p-value of the Wilcoxon test, performed to find statistically significant differences between the crash rates of the different time windows considering the three levels of crash severities.

Table 9 shows p-values smaller than 0.1 in green color, and p-values bigger than 0.9 in yellow color. P-values equal to 1 are shown in red color as this was an indication that the hypothesis was completely rejected. Cells without color correspond to those p-values that do not fit any of the previously described categories.

PMT TYPE	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
COI-ALTA	3708	0,010	0,067	0,652	0,016	0,005	0,467	0,573	0,088	0,073	0,002	0,005	0,482
COI-TRONCALES	13	0,500	0,500	0,277	0,977	1,000	0,500	1,000	1,000	1,000	0,605	0,500	0,201
COOS-ALTA	1729	0,968	0,561	0,047	0,779	0,962	0,753	0,796	0,940	0,756	0,977	0,938	0,187

Table 9: Wilcoxon test results by PMT type with the greater alternative hypothesis
Note: Values shown are p-values. The green value corresponds to p-values less than 0.1. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

Table 10 shows p-values smaller than 0.1 in green color, and p-values bigger than 0.9 in yellow color. P-values equal to 1 are shown in red color as this was an indication that the hypothesis was completely rejected. Cells without color correspond to those p-values that do not fit any of the previously described categories.

PMT TYPE	N	PMT_DO/BF_DO	PMT_DO/AF_DO	BF_DO/AF_DO	PMT_WO/BF_WO	PMT_WO/AF_WO	BF_WO/AF_WO	PMT_DE/BF_DE	PMT_DE/AF_DE	BF_DE/AF_DE	PMT_TOT/BF_TOT	PMT_TOT/AF_TOT	BF_TOT/AF_TOT
COI-ALTA	3708	0,990	0,933	0,348	0,984	0,995	0,533	0,428	0,913	0,927	0,998	0,995	0,518
COI-TRONCALES	13	0,815	0,583	0,777	0,500	1,000	0,977	1,000	1,000	1,000	0,605	0,583	0,853
COOS-ALTA	1729	0,032	0,439	0,953	0,221	0,038	0,248	0,211	0,062	0,248	0,023	0,062	0,813

Table 10: Wilcoxon test results by PMT type with the less alternative hypothesis
Note: Values shown are p-values. The green value corresponds to p-values less than 0.1. Damage ONLY (DO), Wounded (WO), Deceased (DE), and Total (TO) severities are considered when comparing each of the temporary windows: Before (BF), During (PMT), and After (AF).

4. DISCUSSION

The results of the hypothesis testing, using the Wilcoxon test allow us to identify a total of 7 patterns when considering the behavior of the crash rates during construction and non-construction periods. Patterns describe growth or decrease in the crash rates, influenced by work zone in the arterial corridors. Figure 2 shows a diagram that describes the seven different patterns:

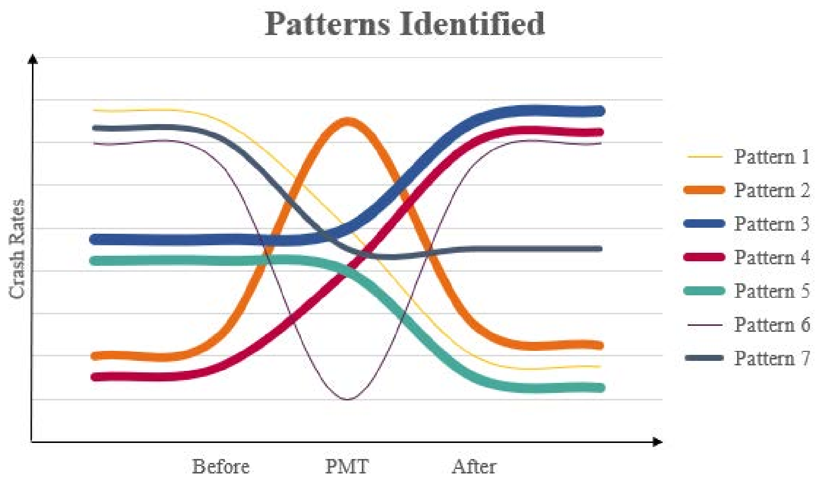


Figure 2: Patterns identified in crash rates during construction time.

The first pattern is represented in yellow in Figure 2. Includes the behavior observed in the CL26SUR-KR78K corridor, where it is evident that during the application of the PMT (construction time) the crash rate is lower than the rate observed before the intervention. Besides, there is also a downward trend in the crash rates, compared with the rates before and during construction time.

The second pattern Figure 2 (orange) includes the behavior observed in 5 corridors with two different severity (DO and WO). We observed a higher crash rate during construction time than the rates observed during periods of non-construction, whether before or after the road intervention.

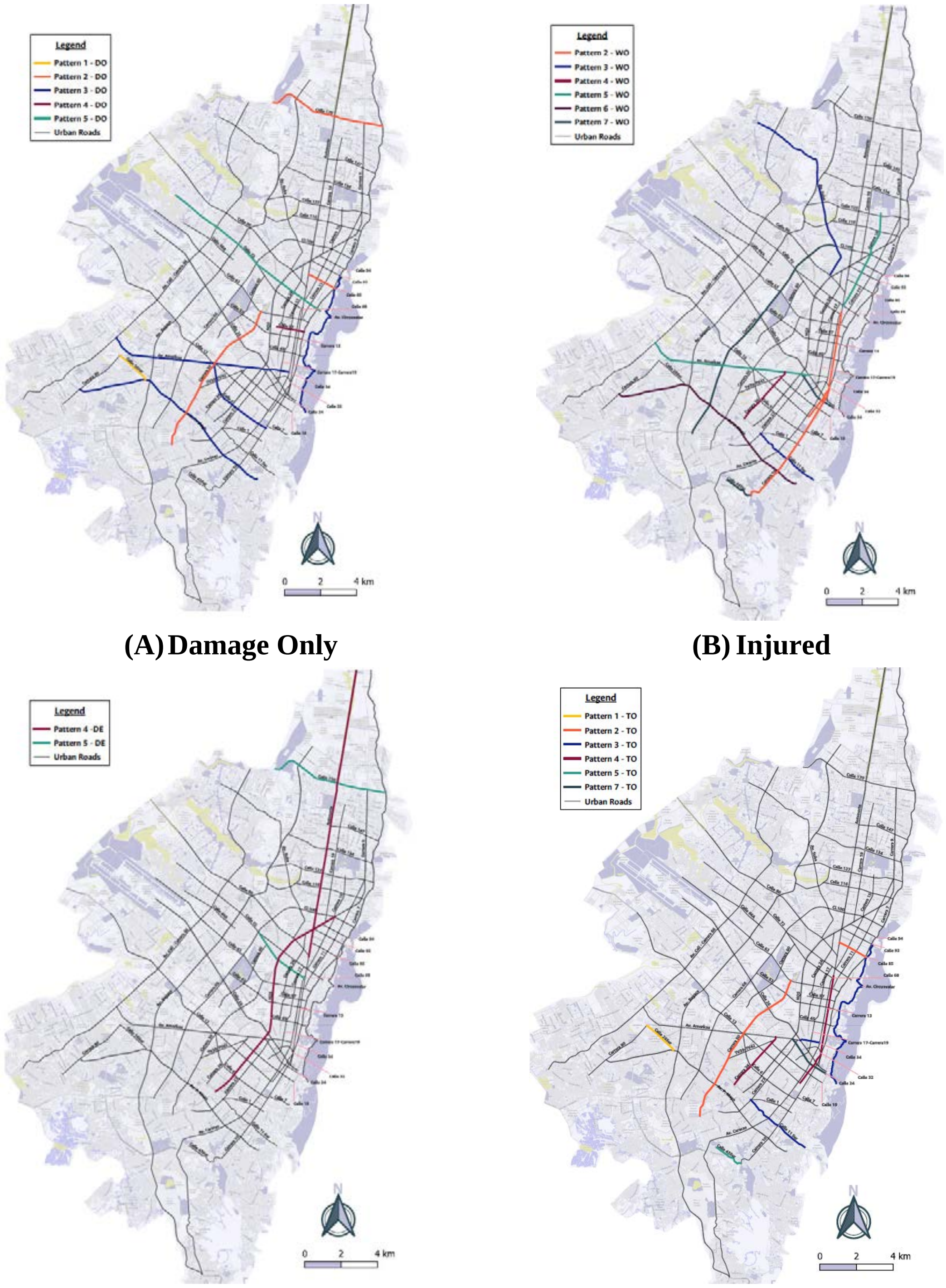
The third pattern, represented in blue in Figure 2 and includes seven arterial corridors, in different severities. These corridors show an increase in the crash rates after construction, and those rates are higher than the rates from before the construction.

A fourth pattern, represented in burgundy in Figure 2, includes the behavior of five arterial corridors. We observed an increase in crash rates, during and after the construction time.

The fifth pattern groups those corridors with smaller crash rates during and after construction. We found six corridors whit this pattern marked in green mint color in Figure 2.

A single arterial corridor presented the sixth pattern when we observe crash rates are significantly lower during construction, and greater crash rates before and after construction (Figure 2 dark purple color).

In the seventh and last pattern crash rates during the construction time decreased compared to before the intervention started, and after the construction zone was lifted these remained lower than before the constructions (Figure 2. dark grey).



(A) Damage Only **(B) Injured**

(C) Fatalities **(D) Total crashes**

Figure 3: Maps of crash rates behavioral patterns in arterial corridors for Bogotá.

Figure 3 shows the map with the arterial streets of the city of Bogota, where the different patterns of crash rates during construction and non-construction time are highlighted, according to the severity of the accident (Damaged Only(A), Injuries (B), and Fatalities (C)) and in all records(D). Pattern one was depicted with a yellow color, pattern two with an orange color, pattern three with blue, pattern four with burgundy, pattern five with mint green, and pattern seven with a dark blue tone.

4.1 By PMT type

Performing the Wilcoxon test by type of PMT, we find results and p-values that allow us to reject the null hypothesis of equality in the crash rates and suggest a statistically significant difference among the crash rates, at least in two out of three types of intervention.

For the typology of COI-ALTA (construction that does not require excavation) it is evident that, for the severity of OD, WO, and TO there was a decrease in the accident rates during the construction time, compared to before and after the work began, this behavior resembles pattern 6 identified for the corridors. This result might be associated with a lower speed that is common during construction. Besides, for the severity of DE, there is behavior pattern 3, being greater the accident rate once the construction is finished.

For interventions that required a PMT of type COOS-ALTA (construction that does require excavation), we found a lower crash rate during construction for damage-only crashes. Injuries and fatalities crash rates after the intervention are lower than during the active construction period. For all construction types considering all crash severities, a behavior pattern 2 was identified, in which the average of accidents is greater during the construction than in times of non-construction.

We choose to use a non-parametric hypothesis test method because we did not assume normality on crash rates, as the articles in the literature did (Jin, Saito, and Eggett, 2008). Assuming normality can bring a clear bias towards lower rates, due to most of the city traffic is channeled through a few sections of the arterial network, leaving a lot of corridors with zero accidents in the time windows defined.

Some of the corridors with high traffic volumes and therefore high crash rates are Avenida Ciudad de Cali, Avenida Boyacá, Carrera 68, Calle 80 and Avenida Las Américas. According to Bogotá´s Secretary of mobility, “these five corridors gather nearly 25% of traffic in Bogota´s arterial streets ”.

As to the statistical tests used, instead of using a paired t-test, two-way ANOVA, and Tukey test, our research team decided to use the Wilcoxon test as these were a better suit for the properties of the studied population (Zimmerman and Zumbo, 1993).

5. CONCLUSIONS

Our research focused on the descriptive analysis of crash data to explore long-term work zone characteristics such as crash severity, crash rate, type, and location using the non-parametric Wilcoxon test to explore differences in accident rates on arterial roads in the city of Bogotá between 2015 and 2019.

A total of 5.450 works were analyzed in 58 arterial road corridors of the city, where it was found that for the severity of damage only, 3 corridors within them the Calle 170 and the Calle 85, show an increase in accident rates during the construction time, which is presumed to be a direct result of the intervention on the road, also presenting this same phenomenon with the severity of injuries for the corridors of Carrera 10 and Carrera 13.

A completely different behavior was found for the Primero de Mayo Avenue, where for crash with injuries it was statistically demonstrated that the accident rates were lower during construction time, which can be associated with a correct design and application of the PMT. The corridors of Calle 24, Calle 43Sur, and Carrera 68 also showed a correct application of the PMT, managing to reduce accidents with injuries in construction time and once the intervention is lifted.

As well as the patterns described above, a total of seven different patterns were found in the behavior of accident rates during construction time in a city as peculiar as Bogota, where its road planning was guided in a disorderly way by an inordinate growth in a very short time.

This study represents the first approach to understand the response of the city in terms of mobility, before a high-impact road intervention, whose importance lies in the current projection of the city to develop mega works for the next five years, such as the metro. Future research could include the study of crash characteristics before, during, and after the work zone periods to highlight both the safety similarities and differences between work zone and non–work zone locations. Additionally, undertaking analysis to explore the correlation of road conditions as determinants in the behavior of accident rates, or exploring if the problem lies in the structure of the traffic management plan.

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INFLUENCIA DEL GASTO EN CONSTRUCCIÓN Y MANTENIMIENTO DE CARRETERAS EN LA SEGURIDAD VIAL EN EL CONTEXTO EUROPEO

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RESUMEN

El presente artículo analiza la influencia de los recursos económicos invertidos en la red viaria, tanto en construcción como en mantenimiento, sobre el número de fallecimientos producidos en la misma. Dada la multitud de factores de los que depende el tema de estudio, además de los recursos económicos invertidos, se incluye una serie de variables explicativas que tratan de reflejar características de la red viaria, aspectos socioeconómicos, meteorológicos y legislativos. Para ello, se ha construido un modelo de datos de panel para 22 países europeos y para el período comprendido entre 1998 y 2016, para la red viaria interurbana. Los resultados muestran un efecto beneficioso del gasto en mantenimiento de carreteras sobre la mortalidad. También se han hallado resultados significativos para la construcción de carreteras, la proporción de vías de gran capacidad, el PIB per cápita y el carnet por puntos.

1. INTRODUCCIÓN

Las infraestructuras viarias han jugado un papel importante en el desarrollo económico de los países, así como en la cohesión territorial de los mismos. No obstante, el transporte por carretera lleva asociada una tasa de mortalidad que es necesario erradicar cuanto antes. En Europa, a pesar de contar con el menor índice de muertes por 100.000 habitantes en el mundo (9.3 según la WHO (2018)), la Unión Europea se reafirma en su ambicioso objetivo para 2050 de reducir el número de muertes en carretera a cero. Esto supone un gran reto, ya que, por una parte, esta última década ha estado marcada por varias crisis económicas que han afectado seriamente a los recursos económicos destinados a las carreteras, especialmente en los países del sur. Mientras tanto, la reducción en el número de muertes en carretera ha llevado un ritmo más lento de lo planeado: tan solo un 20% desde 2010 hasta 2017, estando planteado un objetivo de reducción del 50% de víctimas para 2020 (European Commission, 2018). Por todo ello, resulta de vital interés analizar la influencia de cualquier variable que influya en este problema del transporte. Así pues, en el estudio que se presenta a continuación, se analiza la influencia que los recursos económicos invertidos en carreteras (además de otros factores relacionados con el tema de estudio) puede tener sobre la mortalidad. Los resultados obtenidos pueden ser útiles de cara a planificar un gasto más eficiente en el contexto europeo, y como base en la que guiarse para cumplir objetivos de seguridad vial.

2. ESTADO DE LA CUESTIÓN

Existen multitud de factores que influyen en los accidentes de circulación, y generalmente, éstos se suelen englobar en tres categorías: imputables al factor humano, relacionados con el vehículo y relacionados con la carretera. De cara al estudio de su influencia en la seguridad vial, una forma de considerar los condicionantes de la carretera de forma aproximada y general, es a través de los recursos económicos invertidos en la infraestructura viaria. Así pues, una mayor inversión en construcción, y un mayor gasto en mantenimiento ayudan a conseguir una mejor y más segura red de carreteras, lo que necesariamente ha de influir en la mortandad en las mismas. Consecuentemente, existen estudios que incluyen este tipo de variables económicas en sus modelos de seguridad vial, tanto a nivel nacional, como a nivel internacional.

En este sentido, Fridstrøm e Ingebrigtsen (1991) incorporaron en su estudio sobre siniestralidad vial en Noruega la inversión en construcción y el gasto en mantenimiento de carreteras, encontrando un efecto favorable entre el gasto en mantenimiento y la mejora de la seguridad vial. Respecto a la inversión en construcción, hallaron resultados contradictorios en función de la titularidad de la vía. También obtuvieron correlaciones significativas para una serie de variables independientes relativas a la exposición, condiciones meteorológicas, luminosidad, longitud de la red de carreteras, partes de accidentes, inspección de vehículos, medidas legislativas y consumo de alcohol.

En España, Aparicio et al. (2011) identificaron una serie de factores que tenían influencia en el número de accidentes mortales y con heridos en España. Sin embargo, no obtuvieron resultados concluyentes respecto al gasto en mantenimiento y conservación de carreteras, ya que aparecía relacionado con disminuciones en los accidentes con heridos y aumentos en los accidentes con fallecidos. Sí que observaron que el aumento de la proporción de carreteras de gran capacidad estaba relacionado con una reducción del número de accidentes. Por su parte, Albalate et al. (2013) analizaron la influencia sobre la seguridad vial de los recursos económicos invertidos en construcción y mantenimiento de carreteras en España junto con otras variables, entre ellas los cambios normativos que afectan a la circulación. Hallaron una relación inversa entre la inversión en mantenimiento de carreteras y los fallecimientos, presentando también una relación negativa variables como la tasa de motorización, el nivel de desempleo y la ratio de doctores, mientras el porcentaje de personas mayores de 65 años dio una relación positiva.

Nguyen-Hoang y Yeung (2014) estudiaron los efectos de las inversiones realizadas en construcción y mantenimiento de carreteras en 48 estados de Estados Unidos sobre la mortalidad. Junto con las variables de recursos económicos invertidos en carreteras, añadieron otra serie de variables independientes con el fin de controlar los efectos de las características de los conductores, la normativa gubernamental, la exposición y las condiciones económicas de cada estado.

Los resultados obtenidos mostraron una relación inversa entre las variables de inversiones viarias, tanto en construcción como en mantenimiento, y el número fallecimientos. También hallaron relaciones significativas para los vehículo-milla, el porcentaje de vehículos pesados, la longitud de la red de carreteras, la velocidad máxima en carreteras interestatales, la legislación sobre el cinturón de seguridad, la edad mínima para comprar cerveza, el índice de precipitaciones y temperatura, la renta per cápita, la tasa de desempleo y la densidad de población.

Sánchez González et al. (2018), realizaron un estudio sobre la influencia de las características provinciales españolas en los accidentes de tráfico en vías interurbanas mediante el análisis de diferentes variables económicas, técnicas, sociales y legislativas. Como variables dependientes, consideraron tres indicadores de siniestralidad, los cuales definen en función de la gravedad del herido (leve, serio y fallecido) y el nivel de exposición (millón de vehículos-Km). Hallaron como significativas las relaciones de las inversiones realizadas tanto en construcción como en reposición de carreteras respecto a los tres indicadores. Sin embargo, dichas variables mostraban distinto comportamiento: negativo para la reposición y positivo para la construcción. También obtuvieron relaciones significativas para la implantación del sistema de penalización por puntos, el volumen de tráfico, la tasa de motorización, la variación anual de densidad de población, la tasa de desempleo y la proporción de carreteras de gran capacidad. Posteriormente, los autores realizaron un estudio similar y con los mismos indicadores de siniestralidad (Sánchez González et al., 2020), pero esta vez, utilizaron dos modelos para cada indicador: uno para provincias con renta per cápita alta y otro para los que tienen baja. También añaden como variables independientes una tasa del número de turistas, el porcentaje de vehículos con antigüedad superior a diez años, la proporción de población entre 20 y 29, la proporción de población mayor de 75 y la proporción de población con nivel educativo alto. Respecto a los resultados obtenidos para las variables de inversión de recursos económicos, se muestran relaciones significativas con diferentes efectos en función del indicador y de la renta per cápita de la provincia. Para la tasa de fallecidos, la inversión en construcción de carreteras muestra una relación inversa durante el año de ejecución del gasto y directa para el año siguiente. Para la tasa de heridos graves no se obtienen resultados significativos del gasto en reposición, pero sí se obtienen de la inversión en construcción, con una relación inversa. Por último, para la tasa de heridos leves, obtienen resultados significativos para el gasto en reposición durante el año de ejecución y los dos siguientes, con una relación inversa para las provincias de renta per cápita baja, sin embargo, para las provincias de renta alta, solo se obtiene como significativo el gasto durante el año siguiente, con relación directa.

En otro estudio en Chile, Sánchez-González et al. (2021) analizaron la influencia de las condiciones regionales sobre los accidentes de tráfico. Como variables dependientes utilizaron ocho indicadores de severidad, definidos según el número de víctimas, y dos medidas indirectas del nivel de exposición: el número de vehículos registrados y la población.

Como variables independientes incluyen recursos económicos invertidos en construcción y en reposición, reformas legislativas, tasa de motorización, densidad de población, tasa de desempleo, precipitaciones, proporción de carreteras sin pavimentar y proporción de vías de gran capacidad. Respecto a los resultados obtenidos para las variables de recursos económicos, el gasto en reposición resulta significativo en cuatro de los indicadores, mostrando relaciones inversas en todos ellos. Aunque en el caso de heridos graves por vehículo, refleja también una relación contradictoria: directa durante el año de ejecución del gasto e inversa para el retardo de dos años. Por otro lado, la inversión en construcción muestra una relación directa y significativa en tres de los ocho indicadores considerados.

A nivel internacional, numerosos estudios han tratado de identificar, utilizando datos agregados por países, los diversos factores que afectan a la seguridad vial. Así pues, Kopits y Cropper (2005) analizaron los efectos de la renta per cápita para un total de 32 países con un periodo de estudio comprendido entre 1963 y 2002, incluyendo también variables demográficas, sociales, de motorización y de longitud de la infraestructura. Los resultados no mostraron una influencia significativa de la renta per cápita. Sin embargo, el abuso de alcohol, la mejora de los servicios médicos y una menor cantidad de conductores jóvenes sí mostraron tener efecto en las tasas de mortalidad. Bishai et al. (2006), por su parte, analizaron la relación entre el desarrollo económico y la siniestralidad, utilizando datos de 41 países durante el periodo 1992-1996.

Estos autores hallaron una relación diferente según la renta per cápita del país: en países de baja renta per cápita un incremento de la misma induciría un incremento de la siniestralidad, mientras que en países con mayor renta per cápita se produciría el efecto contrario. También obtuvieron que un mayor consumo de petróleo y de alcohol estaban relacionados con mayores tasas de mortalidad en países ricos. Calvo-Poyo et al. (2020), realizaron un estudio acerca de la influencia de las inversiones en construcción y del gasto en mantenimiento sobre la mortalidad, con datos de 23 países europeos y para el período comprendido entre 1998 y

2016. Además, incluyeron una serie de variables de control de factores específicos del transporte, socioeconómicos y meteorológicos.

Los resultados obtenidos mostraron una relación directa para la inversión en construcción e inversa para el gasto en mantenimiento, siendo representativas ambas variables en el año posterior al de ejecución de los recursos económicos. También obtuvieron resultados significativos para la proporción de vías de gran capacidad, la tasa de motorización, el PIB, la proporción de personas mayores de 65 años y la precipitación media anual. Elvik (2021), utilizó una serie de indicadores democráticos y de gobernabilidad junto a otras variables explicativas (consumo de alcohol y tasa de motorización), para comprobar la relación de dichos índices con las tasas de mortalidad de 148 países. Aunque no justifica una relación causal, encuentra una relación estadísticamente significativa del nivel de democracia de un país, el índice de eficiencia de gobierno, la tasa de motorización, el consumo de alcohol per cápita respecto a la siniestralidad vial.

Por tanto, teniendo en cuenta lo anteriormente expuesto, no se han encontrado estudios a nivel internacional, que analicen, con datos de distintos países, la influencia que pueden tener los recursos económicos invertidos en carreteras sobre la mortalidad y que controlen posibles cambios legislativos. Por ello, con el presente estudio, se pretende aportar a la literatura un análisis que incluya este tipo de variables para el contexto europeo.

3. METODOLOGÍA

Para modelos de siniestralidad vial, Hakkert y Braimaister (2002) recomiendan utilizar una ratio en función del nivel de exposición como variable dependiente, por lo tanto, en el presente estudio se utiliza una tasa de mortalidad, definida como el número de fallecidos por cada mil millones de pasajeros-km. Por otro lado, se utilizan una serie de variables para controlar los efectos de los recursos económicos invertidos en carreteras, de las características de la red viaria, de las condiciones socioeconómicas, de la meteorología y legislativos.

Como principales variables independientes que controlen los efectos de las inversiones en carreteras sobre la mortalidad, se incluyen tanto las inversiones en construcción de carreteras por kilómetro de red, como el gasto en mantenimiento por kilómetro, ambas para el año en curso y para un retardo de un año. Como variables independientes que controlen los factores mencionados anteriormente se incluyen la proporción de vías de gran capacidad, la variación anual de la tasa de motorización (se ha diferenciado la serie para eliminar los efectos de la tendencia creciente en la serie), el PIB per cápita, el consumo de alcohol, la precipitación media y la existencia de un sistema de carnet por puntos.

La codificación de las variables, así como sus unidades de medida y los principales estadísticos descriptivos se encuentran en la Tabla 1. Todas las variables económicas han sido convertidas a valores constantes de 2015.

Código	Unidad	Media	dt	Min.	Mediana	Máx.
Fatal_pkm	Fallecidos/ mil millones de pkm	7.60	5.9	1.46795	5.43325	35.3
Road_inv	Miles de €/km	21.82	35.8	.03284	12.97648	279.8903
Road_maint	Miles de €/km	8.36	10.9	.246996	5.25882	83.75754
Prop_motorwa	%	2.43	4.0	0	1.06926	21.41859
Mot_index	Turismos/1000 habitantes	452.00	95.5	199.3854	456.6513	678.4133
GDP_Cap	Miles de €/km	31.23	18.8	4.26825	32.56199	94.84641
Alcohol	Litros per cápita (15+)	10.76	2.3	5.24	10.91	17.75
Precipit	Mm/año	915.78	283.3	445.6974	841.8867	2266.778
DPS	*(Dummy)*	0.59	0.5	0	1	1

Tabla 1. Codificación y descripción de las variables

Se han recopilado datos desde 1998 hasta 2016 de los siguientes países: Alemania, Austria, Bélgica, Dinamarca, Eslovaquia, Eslovenia, España, Estonia, Finlandia, Francia, Irlanda, Italia, Letonia, Lituania, Luxemburgo, Noruega, Países Bajos, Polonia, Portugal, Reino Unido, República Checa y Suecia. Dada la naturaleza de estos datos, con 22 países distintos y durante 19 años, se opta por formular un modelo de panel cuyo objetivo es explicar los fallecimientos ocurridos en carreteras a lo largo del tiempo y países seleccionados. De los países considerados, tan solo dos no forman parte de la UE: Noruega y Reino Unido. Se ha intentado incluir al resto de países de la UE (Bulgaria, Croacia, Chipre, Grecia, Hungría, Malta y Rumanía), pero no se han podido obtener datos suficientemente desagregados, bien del número de fallecidos en carreteras interurbanas o bien de los recursos económicos invertidos en carreteras.

Los modelos de datos de panel son ampliamente utilizados en la literatura sobre seguridad vial a nivel macro, sin embargo, cuentan con una serie de fenómenos propios que deben ser analizados con el fin de obtener estimadores robustos. Para ello, se han realizado una serie de test. El test de Levene (Levene, 1960) se utiliza para comprobar la homocedasticidad a lo largo del corte transversal, mostrando los siguientes resultados: W0 = 25.300 (p-valor = 0.000), W50 = 14.644 (p-valor = 0.000) y W10 = 24.438 (p-valor = 0.000). Por tanto, se rechaza la hipótesis nula de homocedasticidad. Para comprobar la correlación serial, se usa el test de Wooldridge (Wooldridge, 2007) en el que la hipótesis nula supone la no existencia de autocorrelación de primer orden. Los resultados del test, F = 173.54 (p-valor = 0.000), descartan la validez de dicha hipótesis nula. Y, por último, para comprobar la independencia de corte transversal, se utiliza el test de Pesaran (Pesaran, 2020), suponiendo dicha independencia en la hipótesis nula. El resultado del test, 31.575 (p-valor = 0.000), junto con el valor absoluto medio de la correlación de los residuos, 0.568, hacen rechazar la hipótesis nula. Como consecuencia de los resultados obtenidos en los test, se considera la existencia en el panel de heterocedasticidad grupal, de autocorrelación de primer orden, y de correlación contemporánea.

Por tanto, para solventar estos problemas y obtener una mejor inferencia del modelo lineal estimado a partir de datos de series temporales, se utiliza el método de errores estándar corregidos para panel (PCSE) propuesto por Beck y Katz (1995), con un autocorrelación de primer orden específica para cada país. Así, el modelo empleado de panel de datos adopta la siguiente forma:

$$y_{it} = \beta_0 + \beta_1 X_{1it} + \beta_2 X_{2it} + \cdots + \beta_k X_{kit} + \mu_{it} \quad (1)$$

en el cual, y_{it} representa la variable dependiente, con subíndices *i* para cada país y *t* por cada año. X_{Kit} son las variables independientes, β_K son los coeficientes estimables y μ_{it} el término de error:

$$\mu_{it} = \rho_i \mu_{it-1} + e_{it} \quad (2)$$

siendo ρ_i el parámetro de autocorrelación específico para cada país y e_{it} se corresponde con los errores independientes e idénticamente distribuidos. El software utilizado para estimar el modelo es STATA versión 12.1, el cual aplica una regresión de Prais-Winsten para estimar los parámetros.

De esta forma, el modelo queda de la siguiente manera:

$$atal\_pkm = \beta_0 + \beta_1\, Road\_inv + \beta_2\, Road\_inv_{lag1} + \beta_3\, Road\_maint + \beta_4\, Road\_maint_{lag1} + \beta_5\, Prop\_motorwa + \beta_6\, Mot\_index + \beta_7\, GDP\_Cap + \beta_8\, Acohol + \beta_9\, Precipit + \beta_{10}\, DPS + \mu it \quad (3)$$

4. RESULTADOS

4.1 Modelo

Los resultados obtenidos de la regresión se muestran en la Tabla 2.

		Panel-corrected					
Fatal_pkm	Coef. (β_k)	Std. Err.	z	P>|z|		[95% Conf. Interval]	
Road_inv							
--.	.0120614	.007856	1.54	0.125		-.0033361	.0274589
L1.	.0231607	.0077126	3.00	0.003	***	.0080443	.0382771
Road_maint							
--.	-.0226329	.0154456	-1.47	0.143		-.0529056	.0076399
L1.	-.0383305	.0162192	-2.36	0.018	**	-.0701195	-.0065415
Prop_motorwa	-.389789	.0818051	-4.76	0.000	***	-.5501241	-.2294539
Mot_index	.0056254	.0074999	0.75	0.453		-.0090742	.020325
GDP_Cap	-.1473763	.0250015	-5.89	0.000	***	-.1963783	-.0983742
Alcohol	-.1416466	.1596968	-0.89	0.375		-.4546466	.1713535
Precipit	-.0010549	.0006568	-1.61	0.108		-.0023423	.0002324
DPS	-1.113752	.3715196	-3.00	0.003	***	-1.841917	-.385587
$\_Cons(\beta_0)$	15.43535	2.625257	5.88	0.000	***	10.28994	20.58076

*** p<0.01, ** p<0.05, * p<0.1 | R-squared = 0.5571

Parámetro de autocorrelación por país (ρ_i):

Austria: 0.857086	Bélgica: 0.828970	Chequia: 0.774229
Dinamarca: 0.796525	Estonia: 0.716573	Finlandia: 0.920368
Francia: 0.903019	Alemania: 0.725165	Irlanda: 0.692969
Italia: 0.557741	Letonia: 0.867476	Lituania: 0.544753
Luxemburgo: 0.923186	Países Bajos: 0.907368	Noruega: 0.641941
Polonia: 0.884460	Portugal: 0.611798	Eslovaquia: 0.736251
Eslovenia: 0.679140	España: 0.867863	Suecia: 0.933459
Reino Unido: 0.851805		

Tabla 2. Resultados

4.2. Discusión de resultados

4.2.1 Inversión en construcción de carreteras (*Road_inv*)

En primer lugar, la variable de inversión en construcción de carreteras ha obtenido resultados significativos solo en el caso con un año de retardo. Los resultados muestran una relación de signo positivo para la variable de construcción, en consonancia con otros estudios (Fridstrøm e Ingebrigtsen, 1991; Sánchez González et al., 2018), y sugieren un aumento en la tasa de fallecidos de 0.0231607 por cada mil euros por kilómetro invertidos durante el año anterior al considerado. Este retardo en la influencia puede deberse al tiempo necesario para la ejecución de la obra y puesta en servicio de la misma, a partir de la cual empezarán a notarse los efectos.

Por otro lado, Albalate et al. (2013) señalaron la posibilidad de que el efecto de la inversión en construcción esté sobreestimado en los modelos en los que no se incluyen variables de control de cambios legislativos, y que al incluir éstas, la inversión en construcción pueda perder nivel de significancia. Sin embargo, en el presente estudio se ha incluido la introducción del sistema de carnet por puntos, sin que ello haya afectado al nivel de significancia de la variable.

4.2.2. Gasto en mantenimiento (*Road_maint*)

Los resultados muestran una relación de signo negativo para la variable de gasto en mantenimiento. Al igual que para la variable de inversión en construcción, solo se obtienen resultados significativos para el gasto en mantenimiento con un retardo de un año. Al igual que en la inversión en construcción, resulta lógico pensar que una parte de la ejecución del gasto en mantenimiento puede llevarse a cabo en el último periodo del año, con lo que sus efectos no son esperables inmediatamente, sino durante el año siguiente.

Según los resultados, por cada mil euros por kilómetro en gasto en mantenimiento se espera una reducción de -0.0383305 en la tasa de mortalidad. Este efecto beneficioso para la reducción de la siniestralidad vial también se encuentra reflejado en la literatura en estudios realizados en EE.UU (Nguyen-Hoang y Yeung, 2014), España (Albalate et al., 2013; Sánchez González et al., 2018) y Noruega (Fridstrøm e Ingebrigtsen, 1991).

4.2.3. Proporción de vías de gran capacidad (*Prop_motorwa*)

La proporción de vías de gran capacidad, como variable de control de las características generales de la red viaria, ha resultado significativa con signo negativo, es decir, que el aumento de la proporción de vías de gran capacidad contribuye a la disminución de la mortalidad en la carretera. Esta relación se halla en consonancia con resultados de estudios previos (Albalate et al., 2013; Sánchez González et al., 2018), y pone de manifiesto los beneficios que para la seguridad vial que conlleva la extensión de este tipo de red. En este sentido, Albalate y Bel (2012) señalaban que este tipo de vías son las únicas que pueden relacionarse con reducciones en la tasa de mortalidad.

4.2.4. Variación anual de la tasa de motorización (*Mot_index*)

Respecto a la primera de las variables socioeconómicas, la tasa de motorización se ha considerado como variación anual, con el objetivo de eliminar los efectos de tendencia creciente que presenta y transformar la serie en estacionaria (lo cual es conveniente para aplicar la metodología de PCSE). De todos modos, no se han obtenido resultados significativos para esta variable.

4.2.5. PIB per cápita (*GDP_cap*)

Siguiendo con las variables socioeconómicas, se obtiene un resultado significativo para el PIB per cápita y con relación inversa respecto a la tasa de mortalidad. Esta relación puede ser consecuencia de los mejores servicios sanitarios y de atención post accidente (Bishai et al., 2006), y de la mejor red de carreteras y mejor parque de vehículos inherentes al mayor nivel de riqueza de un país.

4.2.6. Consumo de alcohol (*Alcohol*)

El consumo de alcohol per cápita muestra una relación negativa con la tasa de mortalidad, similar a lo reflejado en estudios previos (Elvik, 2021), sin embargo no resulta significativa. Esta falta de significancia estadística suficiente puede deberse a que, el hecho de aumentar el consumo de alcohol anual en un país, no tiene por qué representar la predisposición de los usuarios de la vía a conducir bajo los efectos del alcohol. Hay otros factores adicionales (culturales, punitivos, …) que influyen en esta decisión por parte de los conductores.

4.2.7. Precipitación media (*Precipit*)

Como control de factores meteorológicos, la precipitación media anual ha resultado significativa y con signo negativo. Estos resultados se hayan en sintonía con estudios previos (Aparicio Izquierdo et al., 2013), y ponen de manifiesto la posibilidad de que se produzca un aumento de la precaución por parte de los conductores ante esta situación meteorológica adversa, reduciendo generalmente la velocidad y, como consecuencia de ello, la severidad de un posible accidente.

4.2.8. Carnet por puntos (*DPS*)

Por último, la variable que controla un cambio legislativo como es la introducción de un sistema de carnet por puntos ha resultado significativa y de signo negativo. Diversos autores han resaltado la influencia de este sistema en la reducción de la siniestralidad en estudios realizados en España (Albalate et al., 2013; Izquierdo et al., 2011; Sánchez González et al., 2018), el presente estudio constata dichos resultados, pero a nivel europeo.

5. CONCLUSIONES

El estudio ha puesto de manifiesto que el gasto en mantenimiento de carreteras tiene un efecto reductor de la mortalidad en las carreteras a nivel europeo, produciéndose este efecto principalmente en el año posterior al de ejecución del gasto. Como aportación a la literatura, destaca la obtención de resultados que reflejan este efecto beneficioso para 22 países europeos. Se corrobora así, a nivel internacional, la relación inversa entre gasto en mantenimiento y mortalidad que estudios previos habían hallado con datos de un solo país (Albalate et al., 2013; Fridstrøm e Ingebrigtsen, 1991; Nguyen-Hoang y Yeung, 2014; Sánchez González et al., 2018).

Además, otras variables han resultado significativas en el estudio realizado. Así pues, la inversión en construcción de carreteras ha mostrado una relación directa con la tasa de mortalidad, mientras que la proporción de vías de gran capacidad, el PIB per cápita y el carnet por puntos han mostrado una relación inversa con el número de fallecidos en carretera. Este artículo complementa el estudio publicado por Calvo-Poyo et al. (2020) al añadir las variables de consumo de alcohol per cápita (que no resulta significativa) y la de carnet por puntos.

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LOCALIZACIONES DE RIESGO MÍNIMO PARA VEHÍCULOS AUTOMATIZADOS Y CONECTADOS

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RESUMEN

Cada vehículo automatizado y conectado posee su propio Dominio de Diseño Operativo (ODD) debido a las particularidades de su sistema automatizado – sensores, algoritmos de percepción y decisión, y actuadores –. Para garantizar que este tipo de vehículos opere de forma segura es fundamental el diseño de Maniobras de Riesgo Mínimo (MRM) que permitan al sistema, cuando finalice un ODD, lograr una Condición de Riesgo Mínimo (MRC).

Hasta ahora, se han planteado, pero no concretado, distintas alternativas relacionadas con la configuración y el diseño de carreteras para facilitar a los sistemas automatizados alcanzar un MRC. Concretamente, este trabajo propone, para distintas tipologías de carretera – autopistas, autovías y carreteras 2+1 –, diferentes soluciones de apartaderos de emergencia y zonas de detención segura, analizando sus fortalezas y debilidades. La alternativa más segura y con mayor capacidad para una MRC será una zona de detención segura, localizada fuera de los ámbitos de las calzadas principales, aprovechando las conexiones, los ramales o las zonas intermedias de enlaces. Esta nueva necesidad ligada a los vehículos automatizados y conectados requiere indudablemente replantearse el diseño y configuración de la red de carreteras, especialmente de los nudos viarios, con el fin de fomentar una movilidad inteligente y segura.

1. INTRODUCCIÓN

Para un mismo tramo de carretera, cada vehículo automatizado puede tener sus propios Dominios de Diseño Operativo (Operational Design Domains, ODDs) que se manifestarán en diversas secciones inconexas de esa carretera que le permiten operar de forma automatizada. Son inconexas porque no tienen continuidad, es decir, se pueden producir desconexiones o cesiones al conductor, que se pueden deber a factores limitantes distintos, para luego volver a recobrar el control.

Ante la problemática de las finalizaciones de los ODDs por sus desconexiones, debidas a algunos de los factores limitantes, se hace muy necesario que el sistema automatizado aplique dos principios fundamentales: la monitorización continua de los factores subyacentes del ODD del vehículo y la capacidad de autoadaptación.

Si se detecta una alteración que comporta un ODD potencialmente restringido, algunos sistemas pueden ser capaces de adaptar dinámicamente su comportamiento para permanecer dentro de este dominio. En cualquier caso, si no le fuera posible, se espera que los niveles 4 y en muchas ocasiones también los de nivel 3 funcionen de manera segura incluso en el caso de fallos del propio sistema o con condiciones externas peligrosas, como una adversidad meteorológica importante.

Un sistema automatizado de nivel 4 debe poder lograr una condición de riesgo mínimo – como apartarse y detenerse en el arcén – si detecta algún problema con su propio funcionamiento o por condiciones externas que impidan una operación segura. Se trata, por tanto, de una detención segura, no una detención de emergencia.

La terminación de la tarea de conducción automatizada, por un fallo repentino del sistema automatizado, un cambio súbito de un factor ambiental o de entorno, o la finalización del ODD, supone el necesario desarrollo de una tarea dinámica de conducción (Dynamic Driving Task, DDT) para la retirada del vehículo a una Condición de Riesgo Mínimo (Minimal Risk Condition, MRC), donde se pueda producir su detención segura o que conlleve un riesgo mínimo. Luego se trata de localizaciones viarias.

El concepto es sencillo, pero el problema radica en de qué forma práctica y segura se pueden establecer y habilitar esas condiciones de riesgo mínimo sobre la infraestructura viaria. El sistema automatizado, en función de las condiciones que han ocasionado la necesidad de buscarlas, así como del estado del vehículo, carretera y entorno, decidirá de entre una serie de opciones posibles, cuál es la que conlleva el mínimo riesgo. Por ejemplo, detener el vehículo automatizado en el mismo carril por donde estaba circulando (activando de forma automática las luces de emergencia, como hacen los vehículos automatizados actuales de nivel 2) es una opción que presenta un riesgo importante y por ello únicamente debería ser activada bajo circunstancias extremas. Preferentemente, y si el vehículo lo permite, el sistema debería ser capaz de llevar el coche a zonas de aparcamiento seguro que se habiliten cada cierta distancia, fuera del ámbito de los arcenes.

Para llevar el vehículo automatizado a un estado o situación segura, las MRC se convierten en la base para definir las maniobras de riesgo mínimo (Minimal Risk Maneuvers, MRM). Luego, el sistema automatizado ha de ser capaz, en primer lugar, de analizar y decidir la mejor opción para alcanzar una MRC, entre todas las posibles en cada lugar y momento, en función de la causa, de las características de la sección de carretera y de las condiciones operacionales y ambientales.

Una vez adoptada la decisión de qué MRC se va a alcanzar, se han de analizar las distintas maniobras de riesgo mínimo (MRM) para optar por las más seguras.

Por tanto, se trata de un balance global para minimizar los riesgos, tanto de las maniobras evasivas (MRM), como de la situación o condición final (MRC).

2. ALTERNATIVAS VIARIAS PARA ACOGER CONDICIONES DE RIESGO MÍNIMO

Ante tanta incertidumbre relacionada con la nueva movilidad conectada y automatizada, tanto tecnológica como técnica y regulatoria, se sigue avanzando en los estudios y desarrollos, así como en las discusiones entre los diversos agentes o partes interesadas. Uno de los ámbitos principales de avance necesario es el de las interrupciones o finalizaciones de los ODDs, con las consiguientes maniobras de riesgo mínimo (MRM) para llevar al vehículo a una condición de riesgo mínimo (MRC).

De hecho, para aumentar la seguridad en estas maniobras de los sistemas automatizados, se están incorporando elementos y procesamientos redundantes relacionados con la tarea de conducción (como los relacionados con la frenada, el giro del volante, la detección de obstáculos, etc.).

Otro de los elementos en discusión está muy relacionado con la configuración y diseño de las carreteras. Se trata de las zonas donde poder acoger con seguridad los vehículos automatizados que necesiten alcanzar una MRC. Hasta ahora, se han planteado diversas alternativas, de menor a mayor seguridad: el uso del arcén exterior, la disposición de apartaderos de emergencia y el desarrollo de nuevas zonas de detención segura fuera de la plataforma viaria (Transport Systems Catapult, 2017; SAE, 2018; Liu et al., 2019). Estas medidas van, además, de mayor a menor proximidad respecto a la localización del vehículo en el momento de la activación de la causa.

En esta nueva necesidad viaria, lo primero que habría que tener en cuenta es la estimación de la posible demanda de alojamiento para las maniobras de riesgo mínimo (generadas por los vehículos con un alto nivel de automatización, de niveles 4 y 5 y ocasionalmente el 3), así como las necesidades para maniobras de mitigación de riesgo (algunos niveles 2 y 3, así como niveles superiores en condiciones excepcionales).

Estimar la demanda real de estas maniobras resulta especialmente complicado en la actualidad, pues los ODDs no están enunciados de forma explícita y por lo tanto no es posible determinar cuántos vehículos podrían verse afectados por una variación de un factor del entorno (como una inclemencia meteorológica, que podría provocar que muchos sistemas automatizados se salieran de sus ODDs).

Además, siempre habría cierta demanda ante fallos de funcionamiento del propio sistema automatizado, aparte de los fallos mecánicos que ya existen en los vehículos.

Por tanto, habría que hacer una provisión importante de plazas o posiciones de detención segura y uniformemente repartidas, para que los vehículos automatizados puedan alcanzar con facilidad una MRC para retirarse con un riesgo mínimo, en caso de no recibir respuesta por parte del conductor.

Para que el arcén pudiera servir para esta función, tendría que disponer de una anchura mínima de 2,5 m, aunque siempre sería una opción peligrosa, por la proximidad a la circulación en el carril adyacente. De hecho, el Protocolo de Auxilio en Carretera (DGT, 2015) califica de alto riesgo el que un vehículo averiado haya quedado inmovilizado en un arcén. Sin embargo, el arcén presenta la ventaja de su disponibilidad continua a lo largo de la carretera.

Según la Ley de Carreteras (2015), se define el arcén como la “franja longitudinal pavimentada, contigua a la calzada, no destinada al uso de vehículos más que en circunstancias excepcionales”. Por tanto, con la función establecida en la regulación actual, el arcén podría emplearse como MRC. Pero, ante una inclemencia ambiental intensa, los arcenes podrían ser ocupados de forma densa por lo que los vehículos automatizados detenidos podrían bloquear el paso necesario de vehículos de emergencia.

Todo ello hace necesario que se habiliten otras soluciones viarias que supongan unas localizaciones más seguras para los vehículos automatizados, sin ocupar ni bloquear los arcenes.

3. APARTADEROS DE EMERGENCIA

Los apartaderos de emergencia ya existen en algunas autovías y autopistas, donde el arcén no tiene una anchura suficiente (Figura 1). Se trata de un ensanche de la plataforma de la carretera destinado a permitir la detención o el estacionamiento temporal de los vehículos (Ministerio de Fomento, 2016).

Figura 1: Apartadero de emergencia.

Según la tipología de carretera, se podrían plantear diferentes tipologías de apartaderos:

- Autopistas y autovías:
    - Apartadero exterior para varios vehículos.
    - Apartadero exterior para un coche como ampliación del arcén.
    - Apartadero interior en la mediana para varios vehículos.
- Carretera 2+1:
    - Apartadero exterior para varios vehículos.
    - Apartadero exterior para un coche como ampliación del arcén.
    - Apartadero interior en las zonas de transición no críticas para varios vehículos.

3.1 Apartadero exterior para vehículos

Estos apartaderos exteriores existentes están diseñados para hacer posible la detención de vehículos averiados, como se menciona en la Instrucción 3.1-IC (2016). Antes de esta nueva versión de la Instrucción, se construyeron con dimensiones más reducidas.

La Instrucción de Trazado establece que el ancho total de estos apartaderos será al menos de 4,5 m, con la siguiente distribución: 3,5 m para el apartadero, propiamente dicho, y al menos 1,0 m de cebreado de separación de la calzada (Figura 2). Además, la longitud de los apartaderos y de la zona cebreada será de 30 m, con cuñas de transición al inicio y final, de longitud mínima 30 m, cada una.

Figura 2: Definición geométrica de un apartadero de emergencia según la Instrucción 3.1-IC (2016).

Además, se establece que el número de apartaderos necesarios y su ubicación será objeto de un estudio. Por tanto, refleja lo que esta nueva función va a requerir: un estudio detallado de la demanda, tanto del número de vehículos a acoger, como su distribución espacial y temporal. Para ello, habrá que esperar la evolución de los desarrollos de los sistemas automatizados de conducción para poder contar con las bases técnicas suficientes para poder hacer esos estudios.

En Inglaterra (Highways England, 2020), la regulación de las áreas de emergencia para autopistas inteligentes (con regulación variable de velocidad) es similar, pero con forma de trapecio escaleno, donde la cuña de entrada ha de tener 25 m de longitud y la de salida 45 m, mientras que la zona de parada ha de ser de 30 m. La anchura está establecida en 4,6 m. También se regula el espaciamiento máximo entre las áreas de emergencia, debiendo ser no mayor de 1,6 km y de forma recomendable cada 1,2 km. Todo ello es de aplicación cuando no exista un arcén exterior de 3 m de anchura mínima o cuando existiendo pueda ser abierto a la circulación en horas punta (Figura 3).

Figura 3: Área de emergencia en Inglaterra.

Uno de los parámetros que seguro habrá que ajustar, según las demandas estimadas, será la longitud de los apartaderos, no teniendo sentido que sean de esa longitud fija de 30 m. Tampoco está claro que tengan que reincorporarse por la cuña final, ya que el orden de regreso a la circulación no tiene por qué coincidir con el de entrada en el apartadero. Esta sería una de las limitaciones de esta alternativa, ya que no habría espacio para acelerar y entrar a una cierta velocidad, aumentando el riesgo de esas maniobras.

Esta necesidad de entradas y salidas a los apartaderos, sin un orden de posicionamiento, haría que las marcas viales de separación hubiera que replantearlas para que se permitiera su cruzamiento. Por ejemplo, se podrían disponer de forma paralela pero discontinuas, con una relación trazo/vano a estudiar.

Además, se podrían aprovechar las secciones en desmonte que cuentan con cunetas de seguridad amplias y suaves para adaptarlas como apartaderos para este fin, con la única necesidad de pavimentar las bermas para darle continuidad al pavimento, pero sin tener que regularizar la geometría de la zona de cuneta. En la fotografía de la Figura 4 se puede observar el resultado al haber pavimentado la berma y así garantizar la continuidad transversal de la superficie de rodadura para vehículos ligeros. Esta disposición tiene la ventaja adicional de su gran capacidad al ser tramos normalmente largos.

Figura 4: Apartadero exterior sobre cuneta de seguridad.

También se podría aprovechar para ubicar un apartadero exterior el sobreancho de estructuras de pasos inferiores que se construyeron previendo una futura ampliación de calzada, como se puede observar en la Figura 5.

Figura 5: Apartadero exterior sobre sobreancho de estructura de paso inferior. Fuente: Google.

Todas estas diversas tipologías de apartadero se podrían aplicar a cualquier otro tipo de carretera.

3.2 Apartadero exterior para un coche como ampliación del arcén

En algunos tramos de autopistas y autovías existen pequeños apartaderos para estacionar vehículos de conservación y explotación, así como de vigilancia y control (Figura 6).

Figura 6: Apartadero exterior reducido.

Suelen tener forma trapecial, con unas dimensiones reducidas: unos 20 m de longitud total y 2,5 m de anchura, incluyendo sendas cuñas de transición de 5 m cada una y dejando 10 m para la zona de parada. Hasta ahora se han desarrollado en secciones con disponibilidad y facilidad de espacio en el margen para reducir su coste.

La ventaja de este tipo de apartadero, para la nueva necesidad que va a surgir, radica en el bajo coste y su facilidad de ejecución, para poder ofrecer localizaciones de detención segura numerosas y muy uniformemente distribuidas, que compensen su capacidad unitaria con una mayor accesibilidad. No precisan de mayores dimensiones si se distribuyen con cierta regularidad y sus cuñas de transición no han de ser más largas porque se trata de que un vehículo automatizado que precise apartarse a una MRC pueda inicialmente reducir su velocidad, incorporarse y circular por el arcén a una velocidad de unos 30 km/h, hasta alcanzar el siguiente apartadero libre, entrando en él para su detención segura, dejando totalmente libre el arcén.

Estos apartaderos más reducidos pero frecuentes, se podrían desarrollar en cualquier otro tipo de carretera, siendo más fáciles de integrar que los anteriores en carreteras de calzada única.

3.3 Apartadero interior en la mediana para varios vehículos

Teniendo en cuenta que puede haber autopistas donde se asigne en exclusiva para los vehículos automatizados el carril izquierdo, no sería descartable la necesidad de disponer los apartaderos directamente en la mediana. Esta opción podría ser la preferida por vehículos que circulasen por el carril izquierdo. De este modo, aparcando en la mediana se ahorra cruzar los otros carriles para alcanzar el arcén o un apartadero exterior.

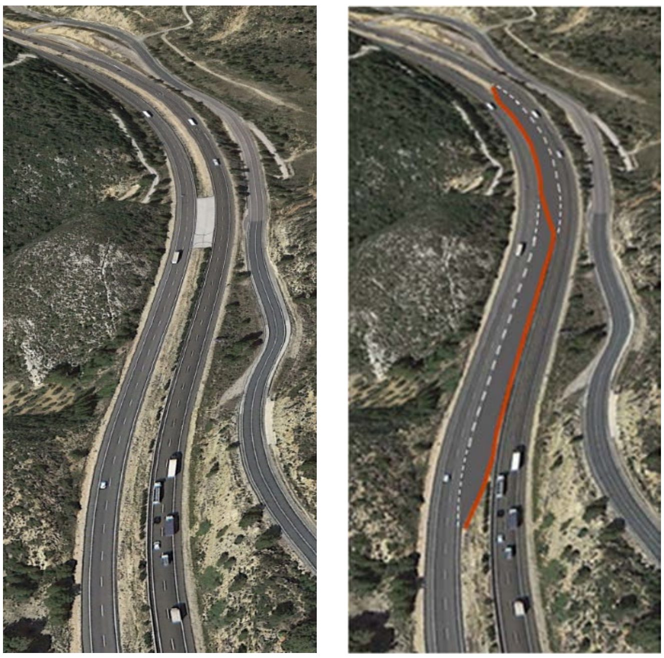

Figura 7: Apartadero interior en la mediana. Fuente: Adaptada de Google.

En este sentido, se podrían aprovechar los pasos de mediana, extendiéndolos como apartaderos para cada uno de los sentidos, siempre y cuando la mediana tenga anchura suficiente para poder acoger los apartaderos. En la Figura 7 se puede observar una posible solución para estos apartaderos de mediana.

Adicionalmente, se podrían utilizar estos apartaderos como pasos de mediana decalados para los dos sentidos, con la ventaja adicional de contar con sendos carriles de deceleración. Para ello, habría que añadir las cuñas finales triangulares pavimentadas que faciliten la incorporación final a la otra calzada. Para su apertura, habría que retirar o mover el sistema de contención de la parte final del apartadero.

3.4 Apartadero interior en las zonas de transición no críticas de carreteras 2+1 para varios vehículos

En las carreteras 2+1 surgen las zonas de transiciones no críticas acopladas para la apertura de los carriles de adelantamiento para cada uno de los sentidos (MITMA, 2021). Según las nuevas Recomendaciones para su diseño, "la longitud de cada carril adicional de adelantamiento debe ser tal que diluya la cola estimada en la hora de proyecto con una longitud en un rango estimado de entre 800 m y 2000 m, sin perjuicio de estudios más detallados al respecto". Luego, como es habitual, se diseñan para las mayores demandas de tráfico estimadas, por lo que habrá una mayoría de horas al año donde no sea necesaria tanta longitud de carril de adelantamiento para facilitar toda la demanda de adelantamiento que se haya podido acumular en el tramo anterior de un solo carril.

Por tanto, se podría plantear la posibilidad de darle un uso temporal al inicio de los carriles de adelantamiento para alojar vehículos automatizados que precisen alcanzar una condición o localización de riesgo mínimo. En la Figura 8 (adaptada de la Figura A1.1 de las Recomendaciones), se puede observar una propuesta para facilitar apartaderos interiores en el inicio de los carriles de adelantamiento.

Para diferenciar la zona correspondiente al apartadero, se podría emplear la marca vial M-1.4 establecida para la "delimitación de carril que pueda utilizarse en un sentido o en el contrario, solo cuando este regulado por medio de semáforo de carril" (MOPU, 1987). El borrador de la nueva Instrucción 8.2-IC define la función de esta marca vial: "delimita por ambos lados los carriles reversibles, en los que el sentido de circulación está reglamentado en uno u otro sentido mediante semáforos de carril u otros medios" (MITMA, 2020).

Aunque su función hasta ahora estaba orientada a la delimitación lateral de los carriles reversibles, teniendo en cuenta la prevención que transmiten a los conductores para su cruce y que habría que señalizar dinámicamente el uso o no de la zona inicial como carril de adelantamiento, sería una buena opción para la señalización.

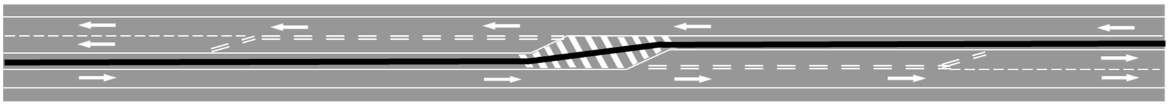

Fig. 8 – Apartaderos interiores en el inicio de carriles de adelantamiento de carreteras 2+1.

4. ZONAS DE DETENCIÓN SEGURA

La alternativa más segura y con mayor capacidad para una MRC será una zona de detención segura, localizada fuera de los ámbitos de las calzadas principales, aprovechando las conexiones, los ramales o las zonas intermedias de enlaces.

Para estas zonas de detención segura caben diversas alternativas según la tipología de carretera:

- Una vía colectora existente a la que se adose un apartadero lineal o una batería de aparcamientos. Si la vía colectora no tuviera suficiente desarrollo, cabría la posibilidad de adelantar la salida y extender la vía colectora de forma anticipada para poder disponer la zona de detención en esa zona nueva (Figura 9).
- Una nueva vía colectora que conecte un ramal de salida con un ramal de entrada (Figura 10).
- Un ramal de salida con apartadero de emergencia, preferentemente cuando los vehículos automatizados puedan tener continuidad en la intersección con la carretera secundaria para volver a reincorporarse a la calzada principal. Si el ramal no tuviera suficiente desarrollo, cabría la posibilidad de adelantar la salida y extender el ramal de forma paralela a la calzada principal para poder disponer la zona de detención en esa parte nueva (Figura 11).
- Un nuevo ramal específico para dar acceso a la zona de detención segura, que pueda tener continuidad en la intersección con la carretera secundaria para volver a reincorporarse a la calzada principal (Figura 12).

Figura 9: Zona de detención segura en una vía colectora existente con apartadero. Fuente: Google.

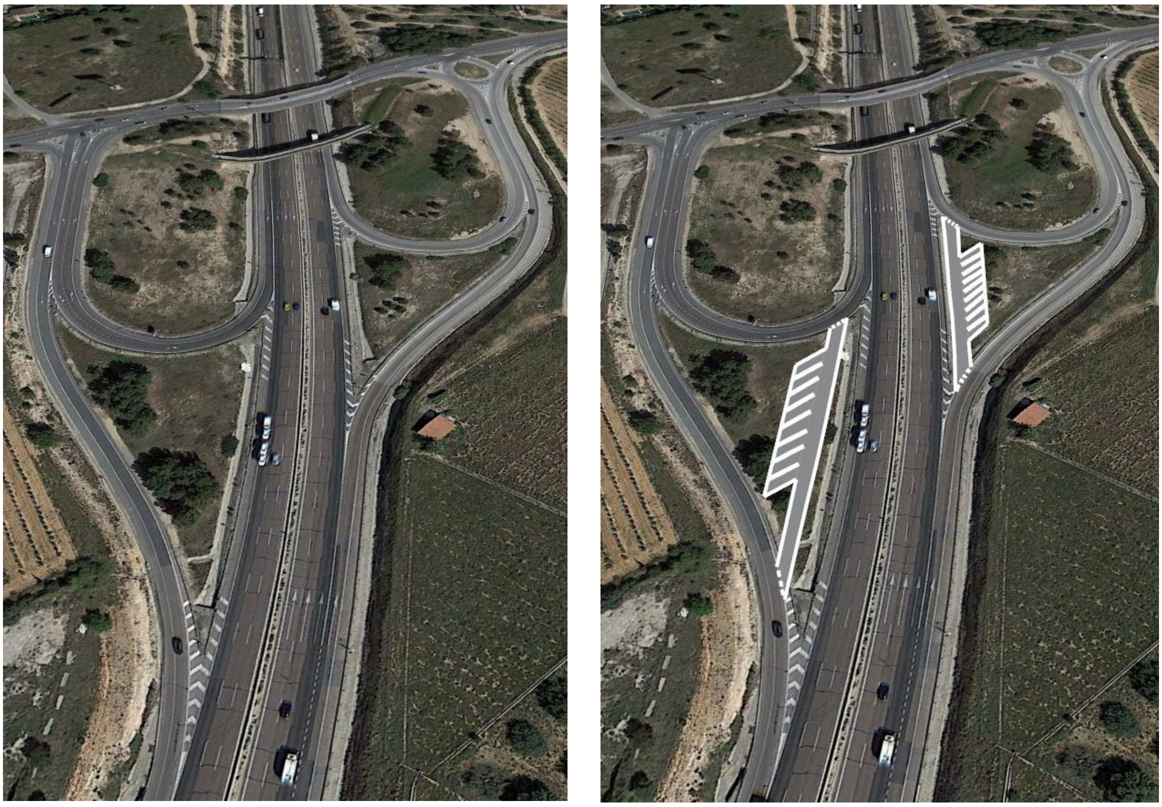

Figura 10: Zona de detención segura en una nueva vía colectora. Fuente: Adaptada de Google.

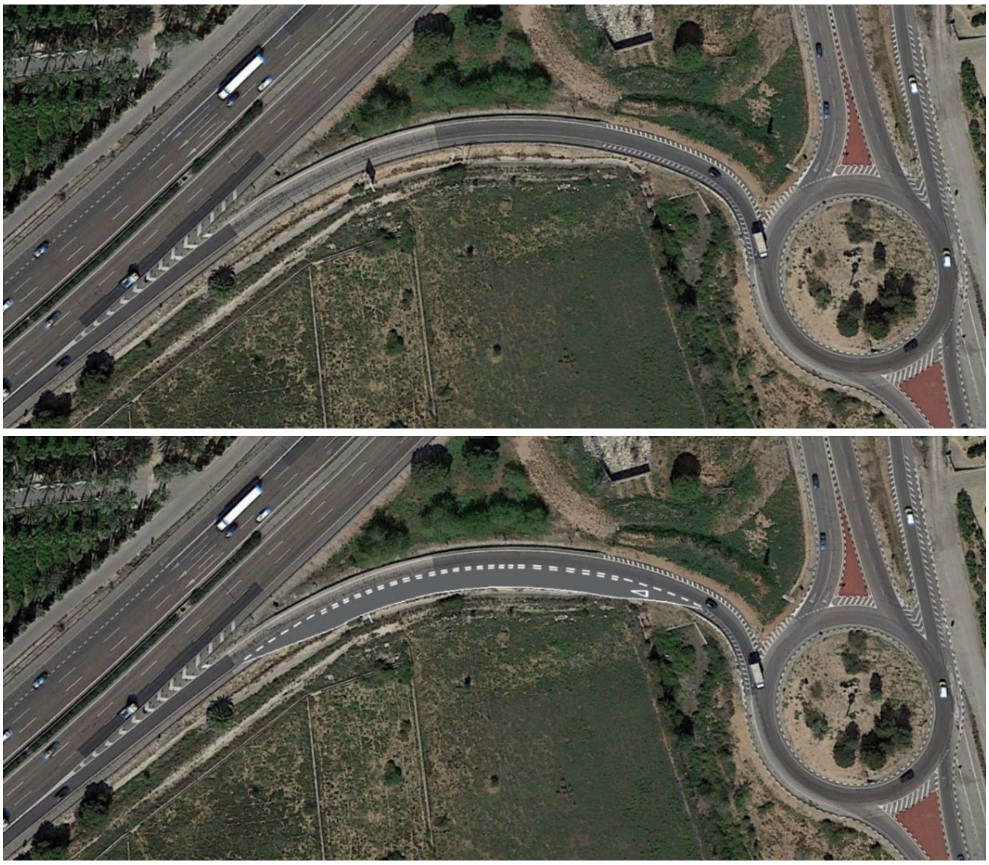

Figura 11: Zona de detención segura en un ramal de salida con apartadero. Fuente: Adaptada de Google.

Figura 12: Zona de detención segura en un nuevo ramal de uso específico. Fuente: Adaptada de Google.

5. NUEVOS CRITERIOS DE DISEÑO Y ORDENACIÓN

Ante la nueva necesidad que va a surgir y las diversas alternativas viarias para facilitar las zonas de detención segura de los vehículos automatizados, habrá que añadir este nuevo criterio a la hora de diseñar los nudos, especialmente los enlaces, pero también las intersecciones.

Uno de los posibles cambios será que en los enlaces difusores con una carretera secundaria se diseñen las intersecciones de los ramales con la misma empleando glorietas, que faciliten la reincorporación de los vehículos automatizados desde las zonas de detención segura a la carretera principal. Adicionalmente, se deberán separar más los ramales directos de giro a derecha para dejar espacios intermedios que permitan integrar en ellos las zonas de detención segura.

La necesaria señalización horizontal y vertical requerirá de un estudio amplio y armonizado, al menos, a nivel europeo, conjuntamente con la industria del automóvil. Igualmente, para la ordenación de su uso, incluyendo la necesaria conectividad V2I e I2V de tal forma que cada vehículo que adopte una posición MRC comunique su posición georreferenciada a un centro de control, para que, a su vez, sea comunicada al resto de vehículos que precisen localizar otra MRC en esa zona. Además, habrá que establecer una regulación clara que prevenga del mal uso de las zonas de detención segura.

6. CONCLUSIONES

Para el desarrollo de un sistema automatizado seguro, el diseño de las maniobras posibles para lograr una condición de riesgo mínimo cuando finalice un ODD sin que el conductor recupere el control, es una parte fundamental. Pero, se hace necesario el estudio, para cada tramo de carretera donde se habilite la circulación de vehículos automatizados de nivel 3 o superior, de las posibles localizaciones que cumplan los requisitos para las condiciones de riesgo mínimo.

Hasta ahora, se han planteado diversas alternativas, de menor a mayor seguridad, pero de mayor a menor proximidad respecto a la localización del vehículo en el momento de la activación de la causa, respectivamente: el uso del arcén exterior, la disposición de apartaderos de emergencia y el desarrollo de nuevas zonas de detención segura fuera de la plataforma viaria.

Los arcenes presentan la ventaja de su disponibilidad continua a lo largo de la carretera y serían posibles localizaciones, siempre que dispusieran de una anchura mínima de 2,5 m, aunque siempre sería una opción peligrosa, por la proximidad a la circulación en el carril adyacente.

Además, ante una inclemencia ambiental intensa, los arcenes pasarían a ser ocupados de forma densa por lo que los vehículos automatizados detenidos podrían bloquear el paso necesario de vehículos de emergencia.

Según la tipología de carretera, se han planteado diferentes tipologías de apartaderos de emergencia para servir como MRCs. En autopistas y autovías se pueden desarrollar: apartaderos exteriores para varios vehículos, como los actuales, pero también aprovechando zonas con cunetas de seguridad amplias y sobreanchos de estructuras en pasos inferiores; apartaderos exteriores para un solo coche como ampliación del arcén; y apartaderos interiores en la mediana para varios vehículos, que además pueden servir como pasos de mediana de mejores prestaciones que los actuales. En carreteras 2+1, además de los anteriores, se podrían integrar apartaderos interiores en las zonas de transición no críticas para varios vehículos.

La alternativa más segura y con mayor capacidad para una MRC será una zona de detención segura, localizada fuera de los ámbitos de las calzadas principales, aprovechando las conexiones, los ramales o las zonas intermedias de enlaces. Para estas zonas de detención segura se han propuesto diversas alternativas: una vía colectora existente a la que se adose un apartadero; una nueva vía colectora que conecte un ramal de salida con un ramal de entrada; un ramal de salida con apartadero de emergencia; un nuevo ramal específico para dar acceso a la zona de detención segura, que pueda tener continuidad en la intersección con la carretera secundaria para volver a reincorporarse a la calzada principal.

Ante la nueva necesidad que va a surgir y las diversas alternativas viarias para facilitar las zonas de detención segura de los vehículos automatizados, habrá que añadir este nuevo criterio a la hora de diseñar los nudos, especialmente los enlaces, pero también las intersecciones.

Además, la necesaria señalización horizontal y vertical requerirá de un estudio amplio y armonizado, al menos, a nivel europeo, conjuntamente con la industria del automóvil. Igualmente, para la ordenación y regulación de su uso, incluyendo la necesaria conectividad V2I y V2I de tal forma que cada vehículo que adopte una posición MRC comunique su posición georreferenciada a un centro de control, para que, a su vez, sea comunicada al resto de vehículos que precisen localizar otra MRC en esa zona. Habrá que establecer una regulación clara para prevenir el mal uso de las zonas de detención segura.

Todas las localizaciones para alojar vehículos automatizados, ya sean apartaderos o zonas de detención segura, deberán estar incorporadas en los mapas de alta definición dinámicos.

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ANALYSIS OF TRAFFIC VELOCITY UNDER DIFFERENT WEATHER AND TEMPORARY CONDITIONS

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ABSTRACT

The density of traffic within urban areas depends on multiple factors, and among those; one that has major impact is the weather. This paper presents a study that empirically analyzes the traffic flow velocity depending on the atmospherically conditions and the day schedule. The objective is to assess systematically to which extent there is a correlation between the vehicle velocity on an urban environment and the weather, depending on the time of day. The presented case of study uses a set of real data, specifically the trips made by taxis in the city of Porto (Portugal). First, the vehicle GPS routes are analyzed to identify departure and arrival points and estimate the route average velocity and adding weather and time conditions. The data is processed with different regressive techniques to obtain the influence of the variables on the velocity. The results show differences between days of the day and weekends, as well as differences in speeds with a favorable climate for driving compared to other more adverse ones.

1. INTRODUCTION

Traffic within cities can be considered as a living being that grows and evolves over time. Cities grow, and it is necessary to designs a good urban planning and road traffic management according to this evolution. Likewise, in recent years with the advancement of technologies and the appearance of concepts such as smart cities, the different municipal corporations invest large amounts of money in putting technologies at the service of their inhabitants to improve their quality of life.

Urban traffic management is a challenging problem nowadays; it is difficult to find a management system or a generic solution to this problem, as each urban area presents a different problem.

This is due to factors as diverse as the available infrastructures, the demography, geographical situation and orography of the city, issues such as the cultural customs of the inhabitants, the economic power or the vehicle fleet, among others.

A determining factor that affects the variation in traffic flow is the weather conditions (Cools, Moons et al. 2010). In the present work, a study is performed to see how different weather conditions affect the way in which users of urban roads move in the city of Porto (Portugal). With this, we want to observe how this behaviour varies at different times and days of the week and depending on the atmospheric climate and analyse if there are significant differences between some conditions and others. With this, it will be possible to make a forecast of the traffic state, which will facilitate its management, being able to avoid traffic jams and accidents (Maze, Agarwal et al. 2006).

The rest of the work is divided in, related work, dataset explanation methodology employed, experiment results, conclusions and future work.

2. RELATED WORK

Traffic flows within urban areas have been widely studied in the literature and encompass different problems that all affect the traffic of vehicles in cities. Examples of them can be found in traffic light management (Gupta, Kumar et al. 2017), accident prevention (Aldegheishem, Yasmeen et al. 2018), contaminant emissions reduction (Anjum, Noor et al. 2019), or traffic flow predictions to avoid traffic congestion (Hu, Wang et al. 2018).

In our specific case, we want to analyse the state and variation of traffic flows velocity depending on the atmospheric conditions due to it is one of the factors that most influence the behaviour of drivers.(Kilpeläinen and Summala 2007).

In this field one of the pioneering works in this field was (Tanner 1952) in which they analyse the correlation between the use of different vehicles under the effect of rain, distinguishing between working days and holidays. As technology advances, more scientific articles related to traffic and weather have appeared.

Golob and Recker (2003) demonstrate with multivariate statistical methods such as weather, traffic flow and lighting influence on accidents on the highways of California.

The effect of the snow or precipitations in the traffic flow congestion using video recordings is studied in (Asamer and Van Zuylen 2011). Tsapakis, Cheng et al. (2013), show the variation in the speed of London drivers under various conditions of snow, rain, and temperature.

Paying attention to snow and how it affects traffic we can find the case of Beijing (Weng, Liu et al. 2013) . Authors highlight the reduction in speed and capacity of urban roads, as well as the increase in travel times; in addition, these effects are noticeable in the following days due to the ice although no longer snow.

In (Stamos, Salanova Grau et al. 2016) the effect of heavy rains and how it affects the speed of vehicles in Thessaloniki (Greece) is analyze from data of 1,200-taxi fleet that contained GPS coordinates and speed information. under certain atmospheric conditions (Yasanthi and Mehran 2020), in this case traffic data is crossed with atmospheric data, including data such as temperature and the condition of the pavement or wind speed.

Finally, congestion is studied in Porto, (Portugal) with diagrams and probabilistic models (Silva, d'Orey et al. 2018), for this they use data obtained from taxis and the weather, but only focusing on a small central area.

3. DATA SET DESCRIPTION

The data set used contains GPS routes of taxis in the city of Porto (Kaggle 2018). The TRAVISANA software has been used to process it (Cogollos, Porras et al. 2020). In it the routes are pre-processed, filtered, and speeds are calculated. In Figure 1 the application pipeline process is shown.

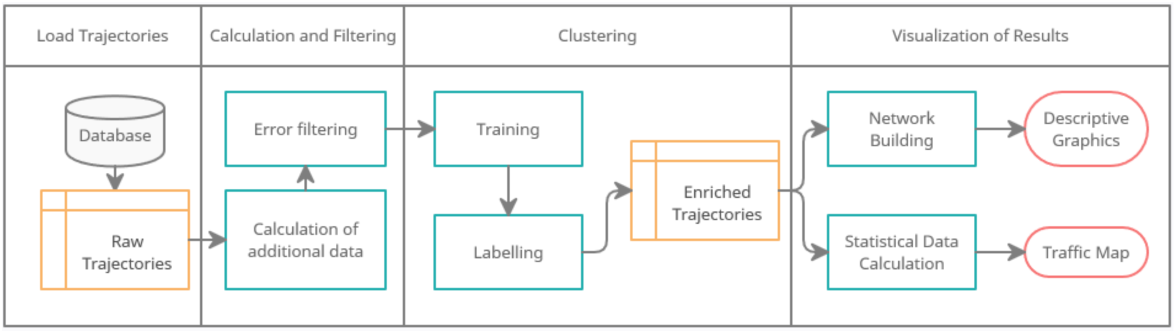

Figure 1: TRAVISANA Pipeline.

In this specific case, the atmospheric data, extracted from(Ltd 2020), are also added to the routes. All the data is combined in the application to obtain the complete data set with the speeds of each vehicle in each trip and the atmospheric conditions of that moment.

Specifically, the set consists of the following variables:

- Id: Route identifier.
- Velocity: Average speed of the vehicle during the trip in kilometers per hour.
- Day: Day of the week from 1 Monday to 7 Sunday.
- Temperature: Temperature at that moment in Celsius degrees.
- Precipitation: Amount of rain in milliliters.
- Visibility: Range of visible space in kilometers.
- Humidity: Grams of water for each cubic meter of air.

Finally, Weather: categorical variable, with 20 values: clear, cloudy, fog, heavy rain, heavy rain at times, light drizzle, light rain, light rain shower, mist, moderate or heavy rain shower, moderate or heavy rain with thunder, moderate rain, moderate rain at times, overcast, partly cloudy, patchy light drizzle, patchy light rain, patchy rain possible, sunny and torrential rain shower.

4. METHODOLOGY

To see the influence of each variable on t the vehicles velocity, the following regression techniques are used.

- Multiple regression: This method explains the variable under study as far as possible, using a group of variables that, directly and indirectly, participate in its value.
- Principal component regression (PCR): This method differs from the classical multiple linear regression in that first a principal component analysis is performed on the dependent variables and later the multiple regression is applied using the obtained factors.
- Partial least squares regression (PLS Regression): This technique combines the multiple regression ant the principal component analysis but is focused on reduce the multicolinearity and obtain more accurate predictions, as difference PCR is more focused on reduce the number of dependent variables.
- Regularized regression: Also known as regulated or constrained regression, specifically the elastic net regression has been used in this paper. This family of regression methods adds a penalty term to the best fit trying to obtain less variance achieve and restricting the influence the dependent variables over the independent one by compressing their coefficients.
- Multiple adaptative regression splines (MARS): It is an algorithm that automatically creates a piecewise linear model which provides an intuitive stepping block into nonlinearity. In order to identify the nonlinear relationships MARS assesses each data point for each predictor as a knot and creates a linear regression model with the candidate features.
- Bagged MARS: Bagging it is a machine learning technique that raises the stability of models by reducing the variance and improving the accuracy, avoiding overfitting.
- Bagged MARS with gCV Pruning: In this version, a generalized cross-validation is added to a Bagging MARS. In addition, a pruning step is executed in every iteration, removing the term in the model that gives the smallest increase in the sum of squared error.

5. EXPERIMENTS RESULTS AND DISCUSSION

To apply the methods to the data set, the caret package from R has been used(Kuhn 2008). All the techniques have been applied with a general cross validation process, with *k=10*. The root mean square error (RMSE) after the general cross validation process (GVC) and the root square sum of the errors (RSS) are used as performing metrics.

The aim of the study it is investigate the relationship between the velocity and the weather conditions in different days of the week.

Initially, all the data have been processes for a first approximation using MARS. Results can be observed, in Table 1 and Figure 2. According with them we can distinguish that the factor with more influence in the velocity are the sunny weather, humidity, and the weekend's days. Therefore, we can conclude that the daily days and weekends has an influence on vehicle velocity in weekends the velocity is higher than in daily days. For a further exploration and more accuracy study of weather influence, the data has been split in daily days and weekends.

Variable	GVC	RSS
WeatherSunny	100.0	100.0
Humidity	100.0	100.0
Day7 (Sunday)	68.0	68.2
Day6 (Saturday)	55.1	55.3
Temperature	48.0	48.3
Precipitation	37.9	38.2
WeatherCloudy	37.4	37.7
WeatherPartly cloudy	32.6	32.9
WeatherOvercast	27.2	27.4

Table 1: GVC and RSS Values for all data.

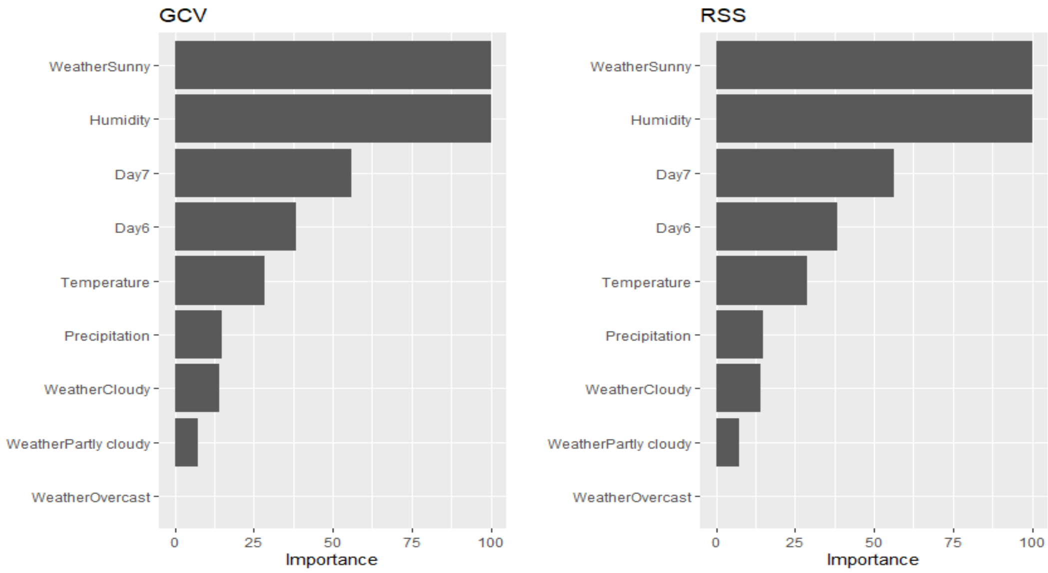

Figure 2: Variable importance according to the contribution to GCV and RSS values as predictors for all data.

In Table 2 the RMSE of predicted velocity for all methods are presented, according with them, the methods who best fit are MARS for daily days and PLS regression for weekends.

	RMSE	
Method	**Daily**	**Weekend**
Multiple regression	12.64511	12.77780
PCR regression	12.64583	12.94490
PLS regression	12.64511	**12.77776**
Regularized regression	12.64522	12.77780
Bagged MARS	12.67633	12.92724
Bagged MARS with gCV Pruning	12.67451	12.90767
MARS	**12.55634**	12.79040

Table 2: RMSE values for Daily days and weekends.

Daily days study: Figure 2 and Table 3 shows the variable importance. According with them it can be observed that sunny weather and humidity have a great influence over velocity as expected according to the initial analysis, but it is observed that between days the temperature and that the weather is cloudy contributes to a higher speed. Analysing the combinations of the variables in Table 4, it is noticeable that the speed increases with temperatures above 9 degrees, and humidity levels below 57 either with sunny or cloudy weather. On the other hand, when precipitation appears, speeds decrease.

Variable	GCV	RSS
WeatherSunny	100.0	100.0
Humidity	100.0	100.0
Temperature	54.7	55.1
WeatherCloudy	43.7	44.2
Precipitation	37.4	37.9

Table 3: GVC and RSS Values for daily data.

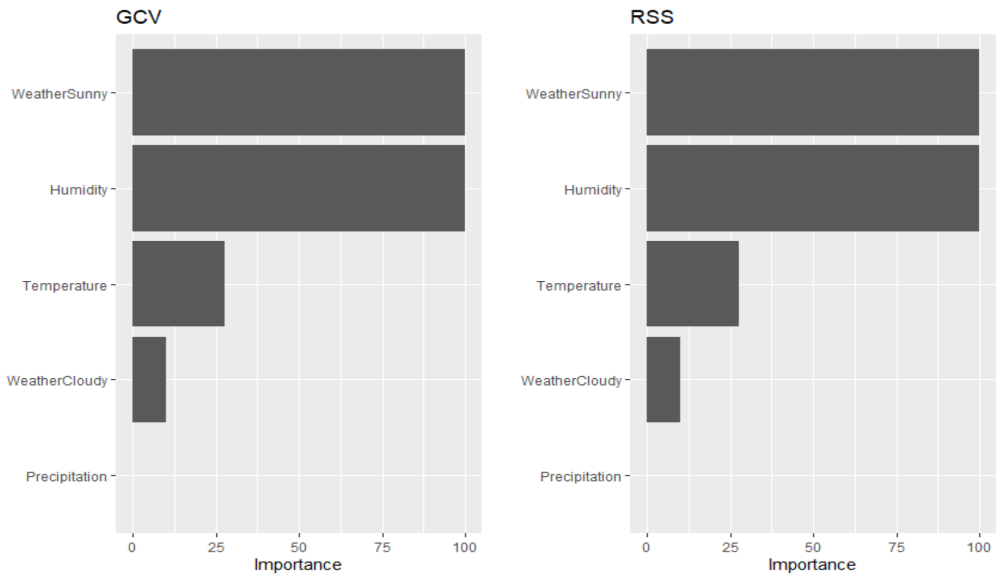

Figure 3: Variable importance according to the contribution to GCV and RSS values as predictors for daily days.

Variable	Coefficent
(Intercept)	22.95928
WeatherSunny	0.82939
WeatherSunny*h(Humidity-57)	0.55996
h(Temperature-9)	0.17940
h(9-Temperature)	12.73014
WeatherCloudy*h(Temperature-9)	1.42678
h(9-Temperature)*h(87-Humidity)	0.11849
h(9-Temperature)*h(Precipitation-0.8)	-5.37981
h(9-Temperature)*h(0.8-Precipitation)	-15.80329
WeatherCloudy*h(Temperature-9)*h(Humidity-97)	-1.34813

Table 4: Mars coefficients for Daily Days.

Weekend study: We used PLS as it is the method with less RMSE. In Table 5 can be seen as more atmospheric states influence the speed, as in the previous case, the most influential factors are sunny weather and humidity. However, visibility and rainfall are important; this can be related to rainy climates. Our PLS result only gives us one level and we do not see the iterations between the variables, but by analyzing the coefficients, we can say that the velocity is higher with sunny and cloudy weather and decreases with light rain or fog. The positive weight of rainfall suggests that speed increases with rainfall and the negative of visibility that decreases the more visibility there is. These factors seem contradictory and would require a more complete study.

Variable	GCV	RSS	Coefficent
WeatherSunny	100	100	3.05085
Humidity	27,9	27,9	0.19905
WeatherLight rain	25,8	25,8	-0.17142
Visibility	24,9	24,9	-0.06000
Precipitation	21,5	21,5	0.36494
WeatherOvercast	21,1	21,1	0.91770
Temperature	18,4	18,4	-0.72814
WeatherPartly cloudy	17,7	17,7	1.19975
WeatherModerate rain	15,4	15,4	0.63879
WeatherModerate or heavy rain shower	11,7	11,7	0.06692
WeatherTorrential rain shower	11,6	11,6	-0.22982
WeatherLight rain shower	5,1	5,1	0.728437
WeatherLight drizzle	2,6	2,6	-0.08700
WeatherMist	1,3	1,3	-0.12495
WeatherCloudy	1,29	1,29	0.43920
WeatherPatchy rain possible	0	0	0.67629

Table 5: PLS regression coefficients for Daily Days.

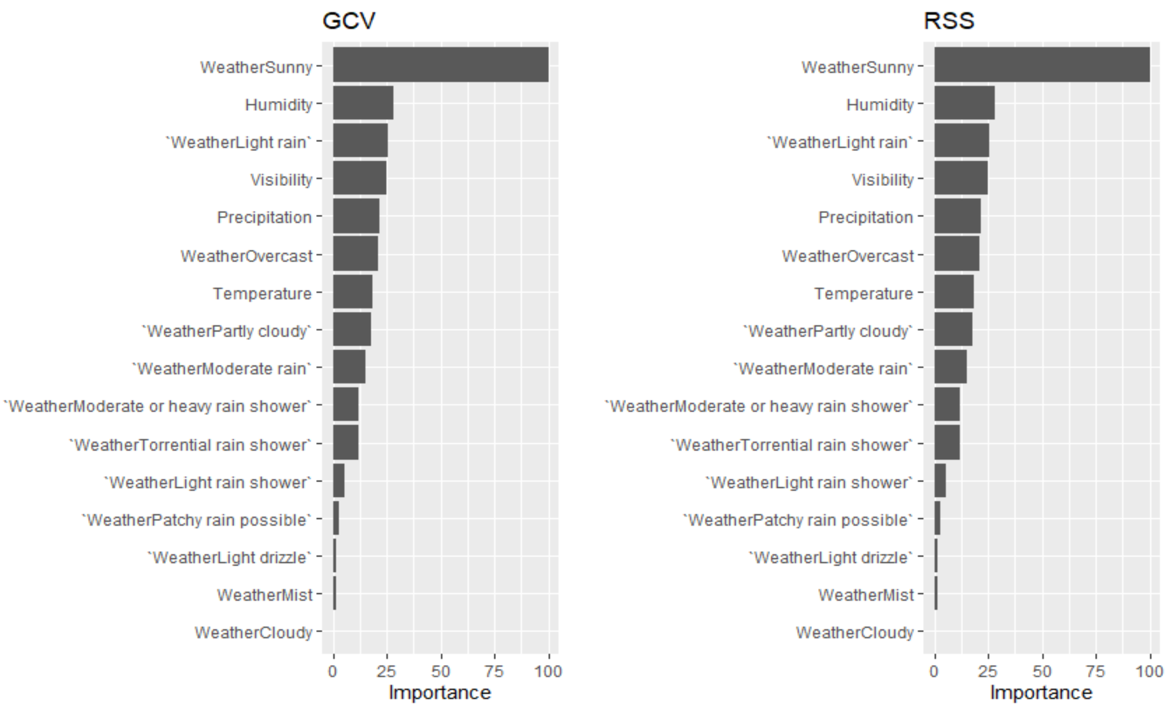

Figure 4: Variable importance according to the contribution to GCV and RSS values as predictors for weekends.

6. CONCLUSIONS AND FUTURE WORK

As seen in the results section, atmospheric conditions and the day of the week significantly influence the average speed at which Porto taxis circulation. It can be concluded that under sunny or cloudy days without rainfall, taxis travel at a higher speed, as conditions worsen the speed is reduced. For daily analysis, the speed is higher on weekends than on daily days, this could be due to a lower volume of circulation, regardless of the weather. We must highlight humidity importance; we assume that it will be due to the geographical situation of Porto.

This study has its limitations, evidently factors such as the volume of vehicles, the type of road, the speed limit, the lighting or the time of day also affect the flow of traffic. Collecting these data and obtaining data from different types of vehicles to build a better model is one future line of work in order achieve more precise results.

In addition, it is also limited by the characteristics and climate of Porto, as future work we plan to compare it with other cities with different climates and orography.

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WORKING HOURS AND TRAFFIC ACCIDENT INJURIES: CASE STUDY IN BARCELONA

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ABSTRACT

Working hours in Spain is generally last for 8 hours per day with a maximum of 40 hours per week. Working hours, therefore, can impact the traffic flow and characteristics due to the intensity of road usage by different road users. On the other side, traffic accidents can also be impacted by several temporal factors that may lead to a higher number of traffic accidents or may increase the level of injury alongside other risk factors. In this study, these timings are examined to comprehend the influence of the temporal factors represented by the working hours scheme on traffic accident injuries in Barcelona. Another temporal factor which is the season of the year is included to provide a wider and clearer image for the conducted results and the current situation. The data is collected from the open data service provided by the City Hall of Barcelona. Data preparation and segregation to include the categories of working hours that may lead to a different level of injury resulted from a traffic accident is, firstly, carried. Then, a machine learning model is applied to classify the correlations for both the temporal factors and traffic accidents. Eventually, a Tree Augmented Naïve Bayes model is applied. The results showed that both working hours timing and summer season have higher probabilities of having traffic accidents slight injuries with different medical care assistance provided compared to other timings.

1. INTRODUCTION

Spain has set a comprehensive labor law to organize and regulate the whole working employees' and employers' relationships with covering other aspects including health and safety at work, Social Security, the procedural law, and special relationships conditions for employment (de Vivero, 2019). As part of these regulations and rules, the maximum number of hours per week has been set to be 40 hours which is estimated based on an average over an annual period. Generally, the working time periods each day is set to start at 9:00 a.m. and end at 7:00 p.m. with having two hours break during the working period. This break period usually starts at 2:00 p.m. and ends at 4:00 p.m. for most employees. These timings, indeed, can be a reason for traffic congestion or flow intensity on different roads due to the fact that several groups of people are heading to different destinations at the same time throughout the day.

Real- time traffic data can be affected by different temporal factors similar to the working hours timings and other temporal factors besides the spatial factors. Several studies have examined the effect of the temporal factors on traffic real-time data. In some European countries, holidays' periods shown lower traffic compared to other seasons (Stathopoulos & Karlaftis, 2001). Peak hours have shown to be another influential factor related to traffic flow. Based on a study that is conducted to examine traffic flow patterns in Shanghai, China (Yang, Wu, Xu, & Yang, 2019), the results showed that peak hours had worse traffic congestion compared to non-peak hours.

Traffic accidents, on the other hand, can also be correlated with different temporal factors that can increase the occurrence of them or affect the level of injury. A study (Kashani & Zandi , 2020) shown that weekends can be correlated with a higher number of traffic accidents compared to weekdays.

The same study also revealed that hot timing had more accidents during weekdays. These timings were found to be 8 a.m. and 2 p.m. While for weekends, these timings differ from weekdays' hot timings. 1 p.m., 8 p.m., and 10 p.m. were the hot timings for accidents during weekends. Slight injuries accidents were found to be more likely to happen when the traffic flow is high (Quddus, Wang, & Ison, 2010). Similar to traffic flow, traffic accidents were found to vary according to the season of the year (Harirforoush, 2017) (Le, Liu, & Lin, 2019). Morning, afternoon, or late-night timings were found to have lower probabilities of having fatal injuries compared to early morning timing in Cartagena, Colombia (Cantillo, Márquez, & Díaz, 2020). Consistently, time was found to be an important independent variable related to traffic accidents severities (Li, Prato, & Wang, 2020). As mentioned earlier, traffic congestion can be highly affected by the timing of the day. Therefore, a study (Hyodo & Todoroki, 2018) showed congested and the mixed flow state can increase the risk of having traffic accidents different types including property damages and slight injury accidents.

The objective of conducting this study is to examine the influence of certain temporal factors represented by the working hours and the season of the year in Barcelona, Spain. Data collected and preparation process is carried. Then, a Bayesian network is applied to the exploited data to extract the results.

2. METHODOLOGY

2.1 Data description

The data the is exploited in this study is collected from the Barcelona open data service which is called Barcelona's City Hall Open Data Service (Ajuntament de Barcelona's open data service, 2019). The data that is gathered consists of different traffic injuries. In this study, slight injury levels with different categories are selected for this purpose that occurred in Barcelona in 2019.

Two temporal factors are selected for the objective of this study including the working hours timing and the season of the year. Beginning with the season potential temporal risk factor, the four seasons are included in the examined period and categorized based on their climate (The main climate data of Barcelona, 2020). The summer season is considered to start in May and end in August. Followed by the autumn season that begins in September and ends in November. The winter season is considered to start in December and end in February. Spring, therefore, is considered to start in March and end in April. For the working hours, two categories are included: during work and the other rest time. Working hours are considered to start at 9 a.m. and end at 7 p.m. with having two hours break. These two hours are considered to start at 2 p.m. and end at 4 p.m. with considering them with the other rest category when the initiation of the analysis part is established. However, during the data analysis, this time-period is considered to start from 2:01 p.m. to 4 p.m.

These previously mentioned categorizations are for the independent variables, while for the dependent variable, three categories are included. The first category is represented by the person who had a slight injury with medical assistance. The second category is represented by the person who had a slight injury but rejected health care. The third and last category is represented by the person who had a slight injury with having a hospitalization up to 24 hours. Table 1 is displaying the two different independent variables' general statistics. The total number for both predictors is 11620 accidents that occurred in 2019 in Barcelona and belonged to the slight injuries that required different levels of medical care. As mentioned earlier, the working hours variable consists of two categories, while the season has three categories. Both predictors are considered as categorical type variables alongside the dependent variable when the analysis part is carried.

	Count	Mean	Min	Max	Range	Variance	Standard Deviation	Standard Error of Mean
Working hours	11620	1.55	1	2	1	0.247	0.497	0.005
Season	11620	2.68	1	4	3	1.405	1.185	0.011

Table 1: Main independent variables statistics.

2.2 Bayesian network

Bayesian network is a member of probabilistic graphical models (GM)s that provides laconic descriptions of the distribution of joint probability for the given random variables. Two methods can be exploited when applying Bayesian network models when using IBM Watson Studio software platform with utilizing SPSS modeler. Tree Augmented Naïve Bayes and Markov Blanket estimation are both methods that can be utilized. In this study, Tree Augmented Naïve Bayes is implemented to classify the correlation between the two predictors and the level of medical care that is provided for persons that are involved in traffic accidents.

The reason for choosing Tree Augmented Naïve Bayes is for its simplicity as the number of variables is only two and the aim of this study is only to examine the correlation with considering the prediction part. Moreover, the two independent variables are classified under the same category which is the temporal variables category. The classifier of Tree Augmented Naïve Bayes that is exploited through the IBM software platform is based on this book (Friedman, Geiger, & Goldszmidt, 1997). The conditional probabilities are calculated, in general, by SPSS modeler as follows:

$$\{[Pr(Y_i|X_1 = x_1^j, X_2 = x_2^j, \dots, X_n = x_n^j) = (Pr(Y_i)(X_1 = x_1^j, X_2 = x_2^j, \dots, X_n = x_n^j|Y_i))/ (Pr(X_1 = x_1^j, X_2 = x_2^j, \dots, X_n = x_n^j))], [\propto \Pr(Y_i) \prod_{k=1}^{n} Pr(X_k = x_k^j|\pi_k^j, Y_i)]\} \quad (1)$$

For $d_j = (x_1^j, x_2^j, \dots, x_n^j)$ where d is the data set. d_j is the case that is classified to which it belongs to i^{th} target category, which in this study, the target Y_i is the medical care three levels provided for slightly injured persons. x is the predictor. n is the number of predictors which is two in this study. K is the number of non-redundant parameters. π_k is the parent set of the independent variable alongside the dependent variable, it maybe empty for Tree Augmented Naïve Bayes. The conditional probability is $Pr(X_k = x_k^j|\pi_k^j, Y_i)$ that is associated with each node, which in this study, there are two nodes for predictors.

2.3 Results and discussions

The structure of the applied Tree Augmented Naïve Bayes structure consists of three nodes including medical care level, season, and time which is the working hours as shown in figure 1. The parent node for the season independent variable is only the medical care level. For the time node, this node is linked to two nodes including medical care level and the season. This makes sense since the fact that working hours are already part of the season of the year. Time has a higher importance value compared to season based on the applied model.

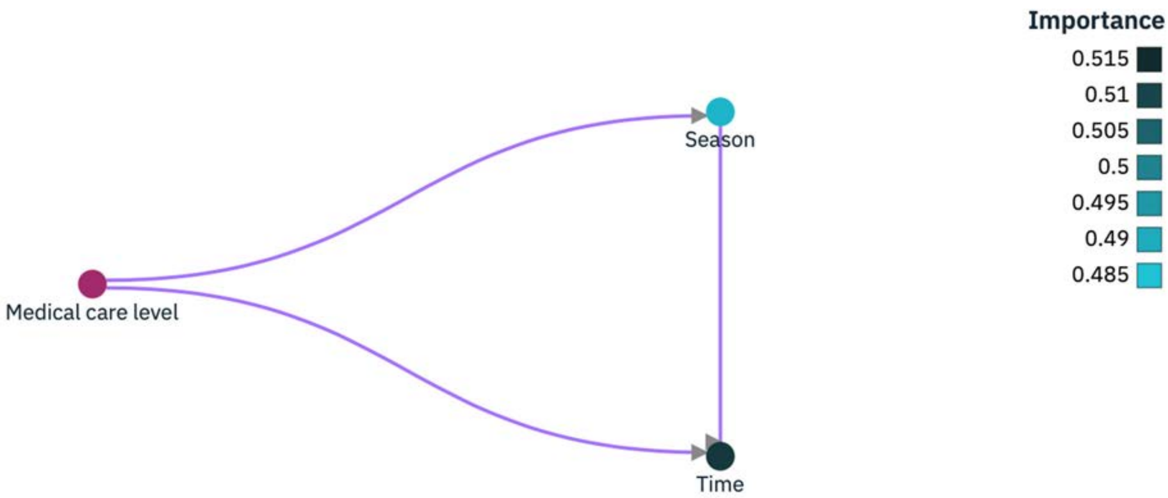

Figure 1: Tree Augmented Naïve Bayes structure.

Table 2 and table 3 are both displaying the estimated conditional probabilities based on the applied Tree Augmented Naïve Bayes for season and time, respectively. For the season, summer has a higher conditional probability compared to all other seasons of the year, followed by autumn, winter, and lastly, the spring season. For the time variable, the working hours category has the highest conditional probabilities during all seasons for all medical care categories that are provided for the slightly injured person except spring season when a person got a slight injury, but this injured person rejected medical assistance.

Parents		Season Probability			
Medical care level	Autumn	Winter	Spring	Summer	Total
With medical assistance	0.245	0.233	0.180	0.341	2,263
Rejected health care	0.243	0.231	0.188	0.338	420
Hospitalization up to 24 hours	0.255	0.235	0.164	0.346	5,428

Table 2: Season conditional probability.

Parents		Time Probability		
Season	Medical care level	Working hours	Rest of the day	Total
Autumn	With medical assistance	0.514	0.486	555
Autumn	Rejected health care	0.520	0.480	102
Autumn	Hospitalization up to 24 hours	0.525	0.475	1,384
Spring	With medical assistance	0.576	0.424	408
Spring	Rejected health care	0.468	0.532	79
Spring	Hospitalization up to 24 hours	0.552	0.448	888
Winter	With medical assistance	0.547	0.453	528
Winter	Rejected health care	0.619	0.381	97
Winter	Hospitalization up to 24 hours	0.558	0.442	1,277
Summer	With medical assistance	0.585	0.415	772
Summer	Rejected health care	0.549	0.451	142
Summer	Hospitalization up to 24 hours	0.559	0.441	1,879

Table 3: Time conditional probability.

3. CONCLUSIONS

The fact that there are enormous factors that influence traffic accident occurrences and severities is leading to conducting several studies to examine these potential risk factors. Temporal factors are part of these factors that can impact traffic accidents. Working hours and the season of the year are part of these temporal factors that may lead to traffic accidents. Therefore, this study has exploited traffic accident injuries by focusing on the level of medical care that is provided for the slightly injured person in Barcelona in the year 2019.

Tree Augmented Naïve Bayes based on Bayesian network is employed to classify the correlations between the two predictors and the dependent variable.

Four seasons are included to understand its temporal impact on the three levels of medical care. Two timings are included the working hours which starts at 9 a.m. and ends at 7 p.m. with having 2 hours break that is not included in this category which is from 2 p.m. to 4 p.m. period. The results show that the summer season has higher conditional probabilities of having slight injuries with including different medical care assistance compared to other seasons. For the timing, the working hours period, similar to the summer season, has the highest conditional probabilities for traffic accidents with being involved in slight injuries with different medical care assistance. For the future work and based on the concluded results, data from delivery operating firms is needed to grasp the impact of these different timings on traffic accidents occurring while the operation is maintained. Then, similar data analysis can be carried out to detect the impact of working hours on this category of employees as they may have a higher risk of being involved in traffic accidents compared to other categories during these timings. Other levels of injury resulted from traffic accidents may also be considered in the future work.

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TRANSPORTE PÚBLICO
PUBLIC TRANSPORT

ANÁLISIS ESTRUCTURAL DE REDES DE TRANSPORTE PÚBLICO USANDO TEORÍA DE REDES. CASO DE GUADALAJARA MÉXICO.

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RESUMEN

Dentro del contexto de planeación de transporte público el análisis estructural es clave para entender la eficiencia del sistema. En este trabajo se propone una metodología de análisis estructural aplicada a una red alternativa de transporte público en Guadalajara México. El análisis se deriva de teoría de redes y se enfoca en 3 propiedades: accesibilidad, resiliencia y fricción espacial.

En el caso de la accesibilidad, esta se vincula con el Shimbel index que mide el promedio de tiempos de viajes de cada nodo al resto de los nodos. Por ende, el grado de accesibilidad brindará un parámetro de la efectividad en términos de tiempo de traslado que brinda cada red. Por otra parte, la resiliencia integra 3 propiedades de red los cuales son: betwenness centrality, central point dominance y average path length. El betwenness centrality mide la frecuencia en la que un área de la ciudad es usada como el camino más corto entre 2 destinos.Con esto se identifica las zonas con mayor polarización de uso. Mayores polarizaciones corresponderían a problemáticas de vulnerabilidades.

Por otro lado, el central point dominance mide la variabilidad de la media del betwnneess centrality y el mayor betwness centrality. Una mayor variación se traduce en una mayor vulnerabilidad. Finalmente, el average path length mide el grado de conectividad de la red. Este se mide en un escenario base y se mide nuevamente cuando los principales nodos de la red fallan, esto con objeto de verificar el impacto que tiene la conectividad de la red cuando ciertos nodos fallan. Finalmente, se aborda la fricción espacial donde se toma el parámetro del índice deuter el cual compara la distancia euclidiana entre todos los posibles viajes y su distancia sobre la red de transporte. Esto otorgará un indicador de la eficiencia espacial.

1. INTRODUCCIÓN

Dentro de los procesos de planeación de sistemas de transporte público existen temas claves de integración como lo son análisis de patrones de movilidad, uso de suelo, modelación, análisis económico y ambiental entre otros. Sin embargo, existen propiedades de los sistemas de transporte público que son claves para la evaluación de su eficiencia y por ende para la toma de decisiones los cuales son los análisis del rendimiento en términos estructurales. Para medir dichos aspectos estructurales los planeadores de transporte han recurrido al uso de teoría de redes. Teoría de redes es raramente aplicado a planeación de sistemas de transporte a pesar de la gran importancia en los resultados de los análisis.

La Teoría de Redes (TR) es un campo de la ciencia que usa matemáticas discretas para comprender las propiedades estructurales de una red. Para realizar dichos análisis es necesario tener una representación de red de un sistema lo cual se sintetiza generación de nodos y links que representan las vinculaciones que existen entre objetos, entes o individuos. En el caso de las redes de transporte público la representación puede generarse por dos vías. La primera en donde cada parada funge como nodos y la conectividad de las paradas son los links. La segunda en la que cada zona de la ciudad (previamente generadas) es un nodo y la conectividad entre cada zona vía la red de transporte funge como links. Esta concepción se puede visualizar en la siguiente imagen:

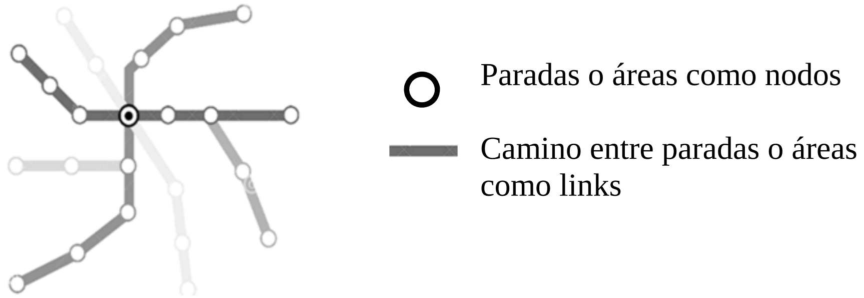

Figura 1: Ejemplo de la representación de sistemas de transporte público a redes

Dentro del campo de teoría de redes existe una gran cantidad de propiedades redes (atributos de redes) las cuales están sujetas a medición. En el contexto de redes de transporte publico las principales son: Diámetro de la red, Índice Deuter, Densidad de red, Índice Pi, Índice Eta, Índice Theta, Índice Beta, Índice Alpha, Índice Gamma, Índice Shimbel, dependencia central entre otras Rodrigue (2020).

Sin embargo, en este trabajo nos enfocaremos a 3 propiedades de red principales las cuales son: Grado de accesibilidad (vinculado a el índice de Shimbel), fricción espacia (vinculado al índice deuter) y la resiliencia de la red (vinculado a betweness centrality, central point dominance, average path length and spectral gap.)

El índice Shimbel está vinculado al concepto llamado grado de accesibilidad el cual es una medida de eficiencia en términos de tiempo de desplazamiento que una red de transporte ofrece. Una red de transporte dada sus características estructurales como el trazado geométrico de sus líneas, las velocidades comerciales, la frecuencia de paso, la conectividad entre líneas entre otros aspectos determinará en gran medida los tiempos de desplazamiento que esa red ofrece a los usuarios. Esta propiedad de eficiencia en términos de tiempos de desplazamiento es la que mide el grado de accesibilidad.

Por otro lado, la fricción espacial vinculado al índice deuter mide la eficiencia en términos espaciales de los viajes realizados en la red. Es decir, que tan directos espacialmente son los viajes. Finalmente, la resiliencia de la red lo vincularemos a las siguientes propiedades de red: betweenness centrality, central point dominance, average path length and spectral gap. Estas propiedades se explicarán cada una de ellas a detalle. Sin embargo, en conjunto forman una batería de propiedades que reflejaran el grado de resiliencia que tiene la red de transporte.

La importancia de la medición de estas propiedades de red recae en que la medición de las propiedades estructurales de una red de transporte es otro de los grandes campos de análisis que deberían de estar integrados a la evaluación del desempeño general del sistema de transporte. Dado que la estructura de la red y la tecnología de propulsión determinará en gran medida la eficiencia de la red en los principales ámbitos de rendimiento. Esta vinculación se puede observar en la siguiente figura:

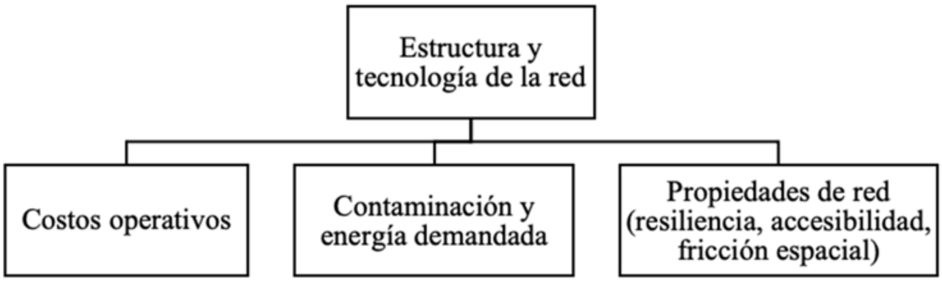

Figura 2: Vinculación entre los principales aspectos a evaluar de una red de transporte con su estructura y tecnología de propulsión

Para la evaluación estructural se tomará como sistema de transporte público la red superficial propuesta por Barraza (2018). Con esta red base se generaron los archivos GTFS (General Transit Feed Spesification) que fungirán como la representación de red del sistema de transporte. Los GTFS son una excelente opción para la representación del sistema de transporte dado los grandes detalles estructurales que otorgan de la red (las paradas, la secuenciación de paradas, el tiempo de traslado entre paradas, la frecuencia, la geometría de las líneas entre otros).

Para realizar una profunda explotación de los GTFS se usaran 2 principales herramientas. La primera es R el cual es un lenguaje de programación de código libre. La segunda es OTP (Open Trip Planner) el cual es una herramienta de motor de búsqueda multimodal. Esta ponencia está dividida en 5 secciones. La sección 1 es la parte de introducción donde se expone de manera general el contenido del trabajo. La sección 2 contempla el objetivo general del trabajo, la sección 3 expone la metodología seguida, sección 4 expone resultados y discusiones y finalmente sección 5 es de conclusiones.

2. OBJETIVOS

El objetivo principal de este trabajo es analizar las propiedades de red del sistema de transporte propuesto para Guadalajara México en lo relativo al grado de accesibilidad, resiliencia y fricción espacial; con la finalidad de tener una evaluación puntual de la eficiencia estructural de dicha red.

3. MATERIALES Y METODOLOGÍA

3.1 Materiales

Para lograr hacer el análisis de redes propuesto es necesario contar con 3 datos fundamentales los cuales son la representación de la red de transporte público en formato GTFS, una zonificación del área de estudio y la red vial de la zona. La siguiente figura muestra la zonificación propuesta para el área de servicio:

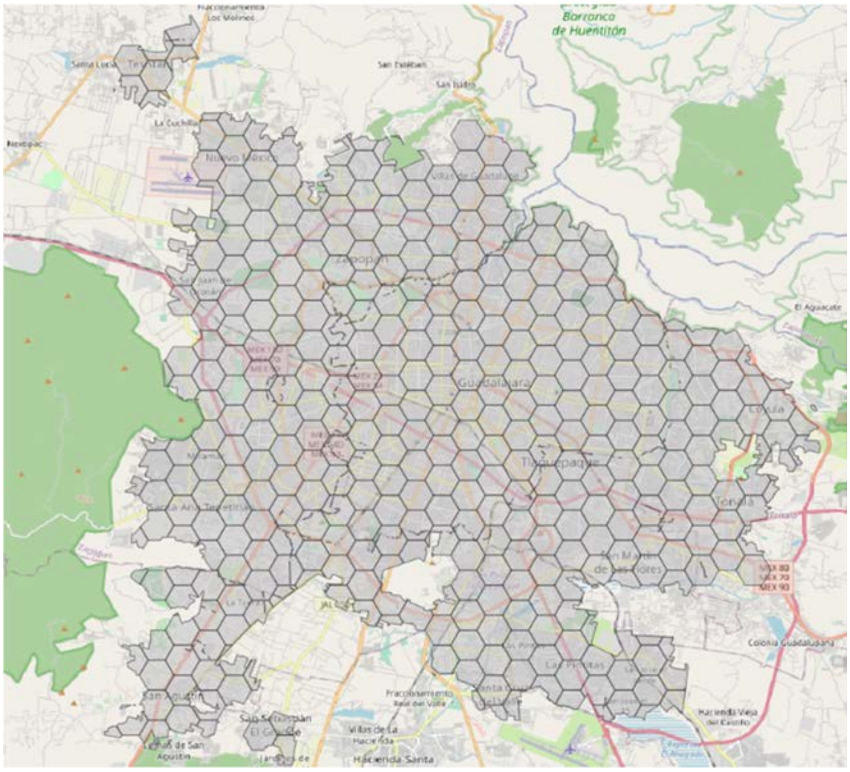

Figura 3: Zonificación propuesta para el área de servicio

La figura 3 muestra la zonificación propuesta para el área de estudio, consta de 398 hexágonos con un diámetro de 670 metros. Adicionalmente, se obtuvo la red vial del área de estudio por medio de OSM. Finalmente, la generación del los GTFS se resumen en los siguientes elementos:

Concepto	**Magnitud**
Stops	1,970
Agency	1
Routes	39
Trips	78
Stop times	4,666
Shapes	4,666
Frecuencies	78

Tabla 1: Resumen de los GTFS

3.2 Descripción conceptual y matemática

En este trabajo se aborda el análisis estructural de tres principales aspectos: accesibilidad, fricción espacial y finalmente resiliencia de la red. Cada una de estas propiedades de red serán descritas en los siguientes puntos:

3.2.1 Grado de accesibilidad

El grado de accesibilidad es una propiedad de red que representa la eficiencia en términos de tiempos de desplazamientos que una red de transporte ofrece. Para generar este indicador se toma como nodo a cada centroide de la zonificación propuesta para posteriormente sacar la suma de los tiempos de traslado de ese nodo hacia el resto de los nodos esto generara una media de tiempo de desplazamiento de dicho nodo (zona del área de servicio al resto de los nodos (el resto de las áreas de servicio). Esto se puede replicar para toda la red y queda expresado en la siguiente ecuación:

$$C(x) = \Sigma_y d(a \dots z)/(N-1) \tag{1}$$

donde:

- C(x): Es el indicador shimbel para el nodo x
- d(x,y): Es el tiempo de viaje entre los nodos a….z
- N: Número total de nodos

3.2.2 Índice Deuter

El índice deuter se vincula con la eficiencia en términos espaciales. Es decir, es una propiedad de red que hace referencia a que tan directos son los viajes en términos espaciales (fricción espacial), para lograr esto se obtienen la distancia euclidiana (distancia en línea recta) de un origen y un destino así como la distancia que sobre la red en tomando la ruta optima. Los orígenes y destinos en este caso son los nodos (centroides de cada área de la zonificación) y la vinculación vía red de transporte público actúan como links. La siguiente ecuación expresa dicho índice:

$$DI = D(S)/D(T) \tag{2}$$

donde:

- DI: Índice deuter
- D(S): Distancia euclidiana entre dos puntos
- D(T): Distancia sobre la red de transporte público

3.2.3 Resiliencia

A diferencia de las propiedades de red presentadas anteriormente la resiliencia (en la literatura vinculado al concepto de hub dependence) puede integrar distanasias propiedades de red descritas en la literatura de teoría de redes. En este trabajo se tomará en consideración 4 propiedades de red que vincularemos a la resiliencia del sistema de transporte. Estas propiedades son: centralidad de intermediación (betweenness centrality), domino del punto central (central point dominance), longitud media del camino (average path length) y brecha espectral (spectral gap).

En el caso de la centralidad de intermediación esta propiedad mide la frecuencia en que un nodo es usado como parte del camino más corto entre otros 2 nodos. En este caso los nodos representarán zonas de la ciudad (creadas como un conjunto de paradas) y las vías de comunicación vía la red de transporte público como nodos. En este sentido esta propiedad puede identificar áreas concretas de la ciudad con altos flujos de viajes óptimos dentro de la red. En caso de que un nodo (un área de la ciudad) tenga una alta frecuencia de uso como puente entre 2 nodos esto significa que cualquier perturbación en esta zona (como puede ser tráfico, manifestaciones, accidentes viales entre otros) afectará en gran medida el rendimiento de una gran cantidad de viajes. La centralidad de intermediación se representa matemáticamente en la siguiente ecuación:

$$C_i = \Sigma_{(j,k)}(b_{ijk}/b_{jk}) \quad (3)$$

donde:

- Ci: Centralidad de intermediación para el nodo i
- bjik: Indica la frecuencia del total de caminos más cortos entre el nodo j y k que va usando el nodo i
- bjk: Representa el número total de rutas más cortas entre el nodo j y k

En el caso del domino del punto central este representa un indicador de la diferencia media entre el nodo con mayor centralidad de intermediación con el resto de los nodos, Yazdani (2011). En este sentido, el domino del punto central es una especial de desviación estándar de centralidad. En caso de que el valor sea alto significa que hay una polarización de centralidad a ciertos nodos lo cual a su vez refleja una red propensa a tener una baja resiliencia. Este indicador se expresa matemáticamente en la siguiente expresión:

$$C_B = 1/(n-1) \cdot \sum_1 (B_{max} - B_i) \qquad (4)$$

donde:

- n: número de nodos
- Bmax: centralidad máxima
- Bi: Centralidad del nodo i

Por otra parte, la longitud media del camino es un indicador de conectividad. Su valor representa la cantidad media de steps (secuencia de paradas) de un nodo al resto de los nodos. Generalmente este valor se expresa integrados todos los nodos de la red por lo que expresa la conectividad de la red completa. Menores valores de la longitud media de camino significan una mayor conectividad pues esto expresa que la red requiere pocas secuencias de nodos (paradas) para realizar los viajes. Este valor será evaluado en 2 escenarios. El primero en un escenario base con todos los nodos funcionando y el segundo escenario se removerán el 10 % de los nodos con mayor centralidad para ver la afectación a la conectividad que esta remoción tuvo. Esta propiedad puede observase en la siguiente expresión:

$$l_g = 1/(n \cdot (n-1)) \cdot \sum_{i \neq j} d(v_i, v_j) \qquad (5)$$

donde:

- lg: Longitud media de camino
- n: Número de nodos
- vi , vj: Caminos cortos entre vi y vj

Finalmente, la brecha espectral $\Delta\lambda$ es la diferencia entre el primer y el segundo autovalor de la matriz adyacente del grafo, Gutiérrez (2011). Esta propiedad proporciona información sobre la robustez de la red. La brecha espectral se usa con el propósito de detectar redes con propiedades de "buena expansión" (aquellas que poseen diseños de conectividad óptimos) y dicho valor debe ser suficientemente grande. Una pequeña brecha espectral probablemente indicaría la presencia de nodos o links que pueden causar serias interrupciones en el flujo de la red cuando remoto, Estrada (2006).

3.3 Metodología y procesos

Los puntos anteriores describieron los conceptos y las matemáticas que describen cada uno de las propiedades de red a evaluar en este trabajo. Sin embargo, el proceso de transformación y uso de GTFS como input de datos para su evaluación será descritos en los siguientes puntos.

3.3.1 Generación de row data y OTP

Los procesos de generación de datos base usados para evaluar las propiedades de accesibilidad y de fricción espacial se generaron a partir del uso de OTP y su integración en R. Ambas herramientas se utilizaron para generar una matriz de viajes N*N en el área de servicio (en transporte público y usando la zonificación presentada anteriormente). Este proceso puede ser resumido en los siguientes puntos:

- Selección del área de estudio
- Creación de la zonificación y generación de centroides
- Vinculación de OTP y R así como el input de datos requeridos (GTFS y vialidades)
- Generación de una matriz de viajes N*N
- Limpieza y procesado de datos
- Generación del grado de accesibilidad y fricción espacial

Los puntos anteriores resumen las etapas para la generación del grado de accesibilidad y la fricción espacial. En la figura 4 se observa el interfaz visual de OTP. OTP es un motor de búsqueda multimodal el cual se puede vincular a R, esta vinculación permite el procesamiento masivo de viajes dentro del área de estudio. Dicho procesamiento masivo de viajes genera una gran cantidad de datos vinculados a estos mismo los cuales fungen como los datos base para análisis más complejos vinculados a la red de transporte. La tabla 1 muestra un extracto de este cuadro de datos generado con el procesamiento masivo de viajes.

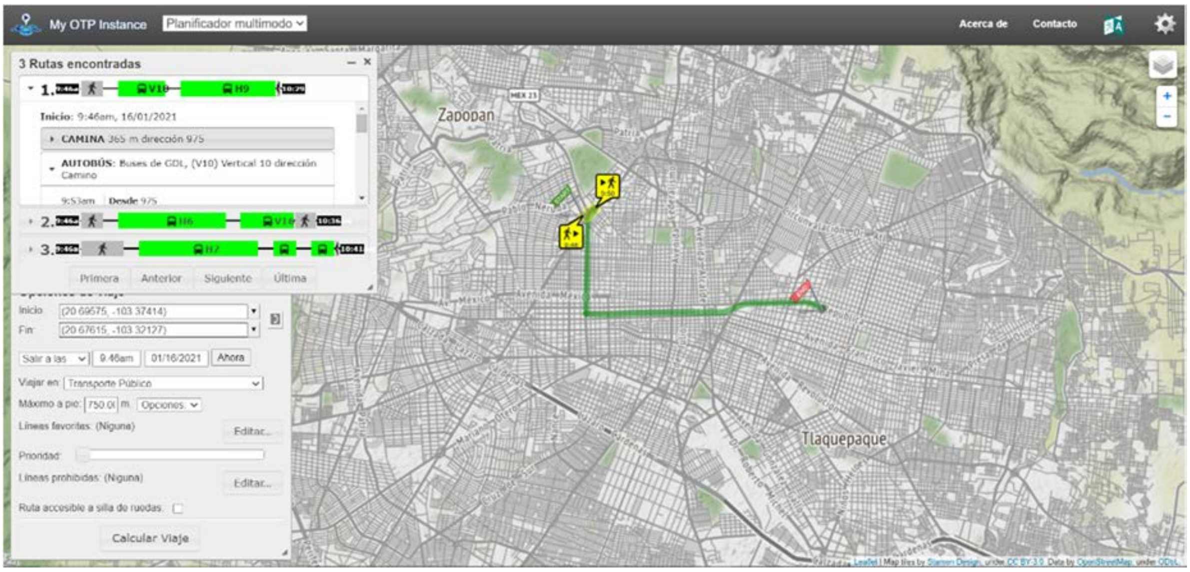

Figura 4: Visualización de OTP

Duration	**Start time**	**End time**	**Walk time**	**Transit time**	**Waiting time**	**Walk distance**
2680 s	14/01/2021 8:24	14/01/2021 9:08	368 s	2132 s	180 s	400 m
Transit distance	**Euclidian distance**	**Transfers**	**Route**	**From place**	**To place**	
12,436 m	9,142 m	0	H4	651	987	

Tabla 2: Datos generados por requerimientos de viajes en OTP

En la tabla 2 se puede observar una muestra del tipo de cuadro de datos que genera OTP vinculándolo con R. Cada requerimiento de información de viaje genera este tipo de datos en los que se puede destacar: distancia del recorrido, tiempo del recorrido, tiempo de espera, distancia caminando entre otros datos importantes vinculados al viaje. Este cuadro de datos será procesado para genera el grado de accesibilidad y la fricción espacial.

Por otra parte, se siguió otro procedimiento para generar las propiedades vinculadas a la resiliencia de la red. Este procedimiento se baso en el trabajo hecho por Pereira (2019). Dicho procedimiento contiene las siguientes etapas:

- Lectura de GTFS
- Unión de archivos
- Unión de paradas cercanas dentro un radio determinado de distancia }
- Actualización de coordenadas dado los clusters de paradas
- Identificación de modalidades de transporte y rutas de cada viaje
- Identificación y generación de links entre paradas
- Cálculo de tiempos de viaje entre paradas
- Remoción de paradas sin conexión de links
- Creación de objeto igraph
- Medición de propiedades de red

El procedimiento descrito anteriormente convierte a los GTFS en un objeto formato igraph el cual ya es sujeto de análisis de propiedades de redes clásica en la literatura de teoría de redes Pereira (2019).

4. RESULTADOS Y DISCUSIÓN

4.1 Grado de accesibilidad

Como se mencionó anteriormente el grado de accesibilidad está vinculado a la propiedad de red del índice Shimbel. Con el procesamiento de los datos obtenidos via OTP y R se generó la siguiente figura donde se muestra la media de tiempo de traslados de cada zonificación en el área de estudio:

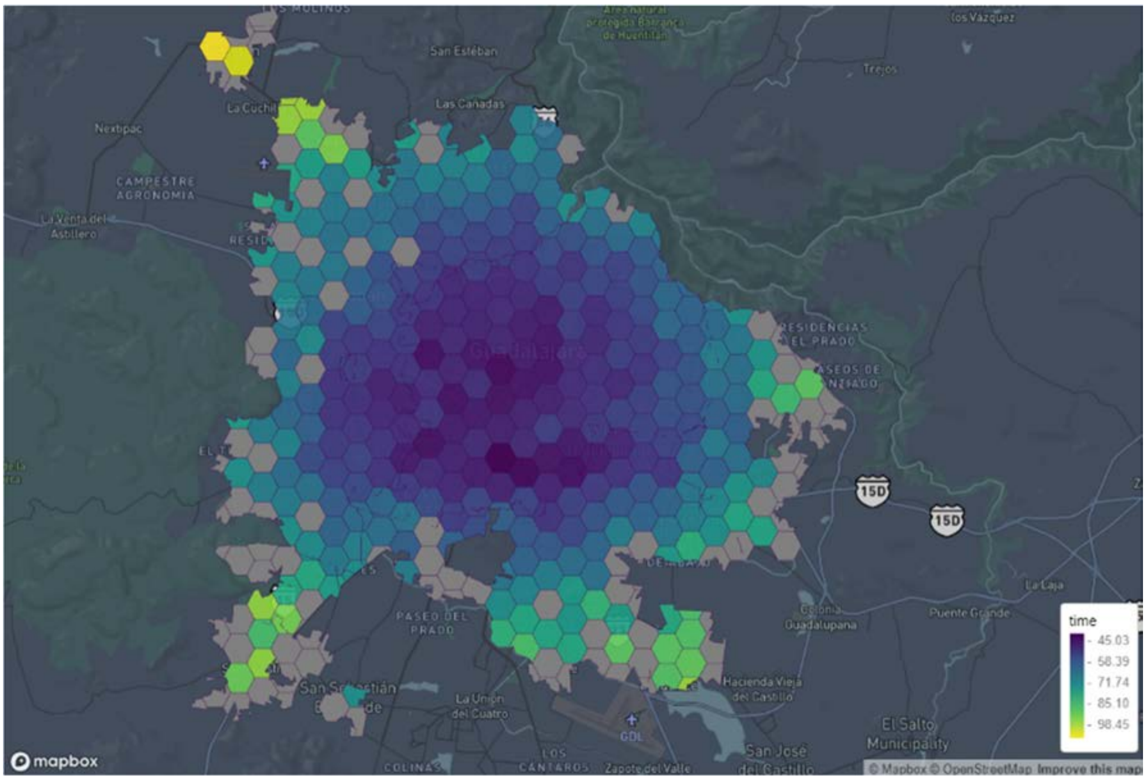

Figura 5: Grado de accesibilidad, red alternativa

La figura 5 muestra el grado de accesibilidad para cada uno de las zonas para el área de servicio. El rango de tiempos medio de traslado varía entre 45 – 98 minutos. Como se puede observar en la figura el centro de la ciudad por su posición geográfica en donde se encuentran menores tiempos de traslado medios en comparación con las periferias que tienen mayores tiempos de traslado. Estos tiempos de traslado no solo están sujetos a la ubicación de cada centroide, sino que en gran medida son afectados por las características geometrías, de frecuencia, de velocidad medias de las unidades, entre otras características estructurales de la red de transporte público. Variaciones en de estas características tendrán un impacto también en los tiempos de traslados de cada zona. Por esta razón el grado de accesibilidad es un indicador muy importante de evaluar de una red a otra. Finalmente, el indicador Shimbel para esta red sería de 66 minutos, esto realmente representaría los tiempos medios de viaje de toda la red.

4.2 Índice Deuter

La fricción espacial está vinculada a la propiedad llamada índice deuter. Con el procesado masivo de los datos obtenidos en la matriz N*N se elaboró la siguiente tabla:

Parámetro	Red alternativa	Unidades
Distancia media sobre la red	18.3	km
Distancia media euclidiana	11.68	km
Índice Deuter	0.63	Adimensional

Tabla 3: Resultados de la fricción espacial

En la tabla 3 se muestra los resultados del análisis sobre la distancia de los viajes generados en el área de servicio. Se puede observar que la distancia media de todos los viajes es de alrededor de 18.3 km, mientras que la distancia euclidiana media de todos los viajes es de 11.68. Esto genera un índice deuter con valor de 0.63. Este es otro indicador de eficiencia en la red de transporte. Redes de transporte con un mayor índice deuter significa que su trazo geométrico permite realizar los viajes más directos en términos espaciales.

4.3 Resiliencia

Como se mencionó anteriormente la resiliencia será abordara por una serie de propiedades las cuales serán indicadores del nivel de vulnerabilidad que tiene la red. Estos indicadores son: betweenness centrality, central point dominance, average path length y spectral gap. La siguiente tabla muestra los resultados vinculados a dichas propiedades:

Parámetros	**Red alternativa**	**Unidades**
Valor más alto de betweenness centrality	566,562	adimensional
Valor medio de betweenness centrality	65,153	adimensional
Valor más bajo del betweenness centrality	0	adimensional
Central point dominance	501,714	adimensional
Valor del Average path length en condiciones normales	40,65	Stops
Valor del Average path length removiendo el 10 % de los nodos más críticos	43,02	Stops
Spectral gap	0,1264	adimensional

Tabla 4: Resultados de propiedades de red vinculados a resiliencia

La table 4 muestra los principales resultados de las propiedades vinculadas a la resiliencia y vulnerabilidad de la red de transporte. En el caso del betweenness centrality la tabla 4 muestra 3 valores los cuales son el valor más alto, valor medio y valor más bajo. Esta propiedad genera una contabilización de la frecuencia en que ese nodo (conjunto de paradas) es utilizado como parte del camino más optimo entre 2 destinos. La contabilización y visualización del betweenness centrality puede generar una apreciación de las zonas más vulnerables de la red dado que perturbaciones de cualquier tipo de estas zonas provocarían afectaciones a una gran cantidad de viajes. En la siguiente figura se observa los valores del betweenness centrality espacialmente:

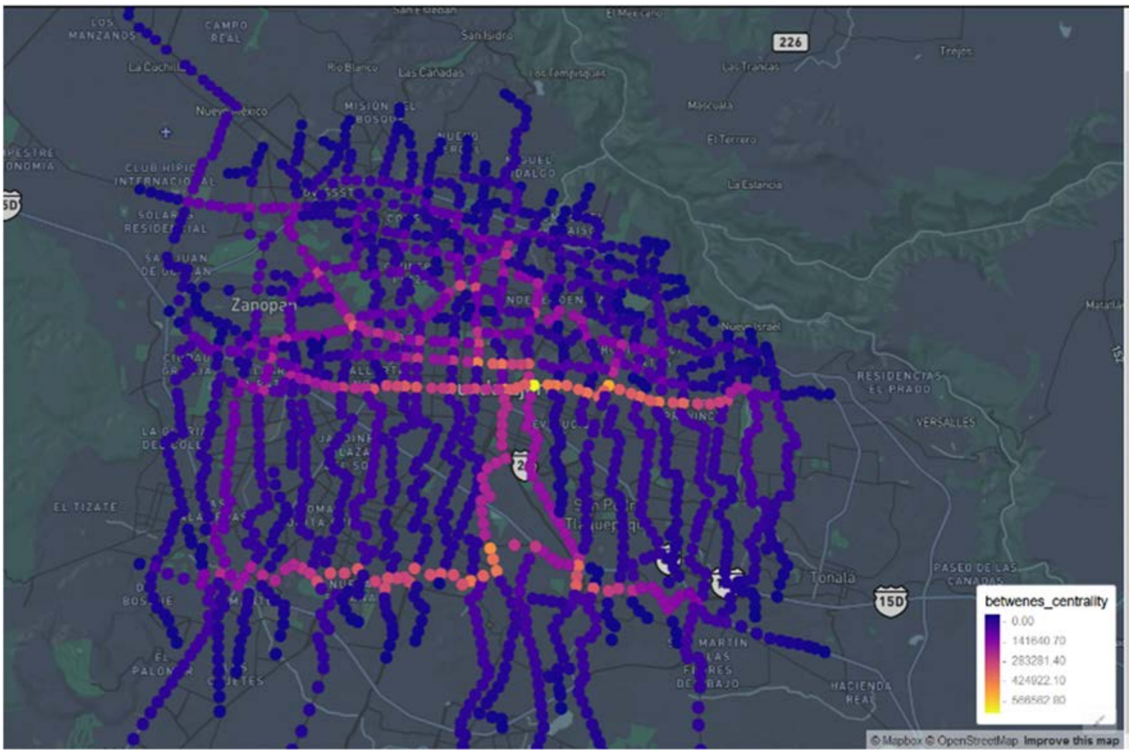

Figura 6: Visualización de los valores de betweenness centrality

Como se muestra en la figura 6 el valor del betweenness centrality en cada nodo varía considerablemente. Existen líneas de transporte con una mayor relevancia en este indicador. Se observa que la parte del centro de la ciudad tiene una especial relevancia. En este sentido los valores del betweenness centrality dan una guía de cuales son las áreas específicas de la ciudad donde se debe de cuidar el funcionamiento optimo de la red para evitar comprometer el rendimiento de gran parte de la red de transporte.

Por otra parte, otro de las propiedades evaluadas es el central point dominance. Como se expresó anteriormente el central point dominance indicar la diferencia media entre el nodo con mayor centralidad y el resto de los nodos por lo que es un indicador del grado de polarización de los valores de centralidad. En este caso el valor obtenido para la red alternativa fue de 501,714 unidades.

En cuanto al average path length, recordemos que este indicador esta vinculado a la conectividad de la red. En el caso del primer escenario el average path length fue de 40.6 stops. Esto quiere decir que la media de paradas efectuadas en todos los viajes posibles en la red es de 40.6 pardas. A medida que disminuye este valor indica una mayor conectividad de la red puesto que se requieren menos paradas para desplazarse a otros nodos (paradas) de la red. En el caso del segundo escenario se eliminó el 10% de los nodos con mayor centralidad o mayor relevancia dentro de la red para ver las afectaciones a la conectividad. En este caso se obtuvo un average path length de 43 paradas lo que representa un decrecimiento en la conectividad del 6.6%.

Finalmente, el valor del spectral gap obtenido es de 0.126. Dentro de la literatura expuesta en Estrada (2006) esto corresponde a un valor bajo que correspondería a una red con bajos grados de robustez. Para tener un mejor panorama este valor tendrá que ser comparado con el de la red operativa actual.

Los resultados de las propiedades presentados anteriormente obedecen a la red alternativa tomada del trabajo de Barraza (2018). Sin embargo, estos resultados tienen limitantes importantes al no estar comparados con la red operativa u otra red propuesta en el area de servicio. Para que los análisis de propiedades de red tengan sentido en el campo de planeación de la movilidad es necesario tener puntos de referencia como las condiciones de la red actualmente operativa u alguna otra propuesta de red de transporte. Desafortunadamente, para este trabajo no se logró tener acceso a los GTFS de la red actual. Este análisis comparativo quedará postergado y se espera que dentro de un par de meses se tenga acceso a los GTFS de la red actual.

5. CONCLUSIONES

El presente trabajo presenta una metodología para la medición de propiedades de red vinculados al rendimiento en términos de tiempo, espaciales y de resiliencia de los sistemas de transporte público. El análisis de las propiedades de red se realizó para la red alternativa superficial propuesta en Barraza 2018. Los resultados presentados fueron generados a partir de un proceso robusta que asegura la veracidad de los resultados. Sin embargo, dentro del trabajo no se cuenta con puntos de referencia es decir con redes de transporte distintas a esta (que puede ser la actual o alguna otra propuesta) por lo que no es posible de dimensionar si el rendimiento en términos de accesibilidad, fricción especial o resiliencia de la red analizada son positivos o negativos.

Este trabajo se plantea extender para poner en contexto esta comparativa entre la red alternativa ya analizada y la red de transporte actual para tener una mejor comprensión de las mejoras o perdidas de rendimiento entre ambas redes. Finalmente, este trabajo sirve como base metodológica para la evaluación de las propiedades de red de sistemas de transporte público.

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MEJORA DE LA CARACTERIZACIÓN DE LOS SERVICIOS DE UN SISTEMA DE TRANSPORTE PÚBLICO COMBINANDO DATOS DE LOS SUBSISTEMAS DE LOCALIZACIÓN, BILLETAJE Y PLANIFICACIÓN

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RESUMEN

Este trabajo propone una metodología flexible para mejorar la caracterización de cada uno de los servicios ofrecidos por un sistema de transporte público, utilizando eventos de llegada de autobuses a nivel de parada y de embarque de pasajeros procedentes de sus sistemas automatizados de localización de vehículos y de cobro de billetes, así como la información del subsistema de planificación si está disponible. Se aplican diferentes técnicas para estructurar, corregir y completar los datos disponibles, con el objetivo de minimizar las distorsiones que aparecen debido a la naturaleza de estas fuentes.

El procedimiento descrito en este trabajo pretende ser adecuado en situaciones con diferente disponibilidad, integridad y fiabilidad de la información. En particular, los inicios de los servicios programados pueden ser conocidos o no, incluyendo opcionalmente qué vehículo había sido asignado inicialmente a la tarea. La información procedente de los diferentes subsistemas que integran un sistema de ayuda a la explotación se combina para crear una caracterización mejor y más útil de los servicios que han tenido lugar en un sistema de transporte.

Los datos del ejemplo de aplicación provienen de los eventos del sistema de ayuda a la explotación en la ciudad de Santander (España) durante un año. Los resultados se discuten con capturas de una herramienta de visualización web interactiva que se ha desarrollado para este trabajo.

1. ESTADO DEL ARTE

Los sistemas de transporte público inteligentes (*IPTS*) están construidos sobre varios subsistemas que se encargan de diferentes tareas, como proporcionar información a los viajeros o trabajadores, gestionar incidencias y eventos especiales, localizar los vehículos, programar, emitir billetes, contar pasajeros, información geográfica, nóminas, mantenimiento, meteorología, satisfacción del cliente o comunicaciones. Si se implantan con éxito, aumentan la calidad del servicio, disminuyen los costes de explotación, mejoran el proceso de toma de decisiones y facilitan la gestión de la flota [de Pablos Heredero et al., 2012].

Dejando a un lado los casos en los que no se dispone de horarios fijos (por ejemplo, las rutas de autobús en Jinan (China), con una gran incertidumbre en los tiempos de viaje, múltiples agencias y un horario de salida que cambia según la demanda observada in situ, donde un estudio empleó redes neuronales artificiales para mejorar la estimación de la llegada de los autobuses en tiempo real basándose en la información del sistema de billetaje automático (AFC) y de la ubicación histórica de los vehículos [Lin et al., 2013]), los datos que describen los servicios de tránsito (es decir, las rutas, sus horarios y la ubicación de las paradas) se publican con antelación. La herramienta más extendida para hacerlo es el componente estático de la especificación general de datos de tránsito (GTFS) [Google]. Sin embargo, aunque se ha propuesto una extensión [MobilityData], este formato aún no puede representar algunos cambios en tiempo real, como la definición de viajes adicionales. Además, es posible que las agencias de transporte no mantengan una recopilación de estos archivos a lo largo del tiempo, aunque en algunos casos pueden obtenerse de terceros (por ejemplo, OVapi [OVapi B.V], Transitland [Mapzen Foundation e Interline Technologies LLC], u OpenMobilityData [MobilityData IO,]).

Además de otras aplicaciones como la identificación de irregularidades en las cabeceras [Gokasar y Cetinel, 2019], la implementación de estrategias de prioridad vehicular más inteligentes [Hounsell y Shrestha, 2012], y la gestión de flotas y operaciones [Saghaei, 2016]; el satélite de navegación global por satélite (GNSS) se utiliza para estimar inicialmente y finalmente identificar la llegada del vehículo a cada punto de interés. Normalmente, ofrece una precisión de 5 m a cielo abierto, aunque hay varios factores que pueden empeorar su precisión [van Diggelen, Frank, Enge, 2015].

Por otro lado, los sistemas AFC tienen como principal objetivo mejorar el proceso de recaudación, pero también proporcionan datos valiosos, especialmente cuando se enriquecen con las posibilidades de seguimiento y caracterización de usuarios de la tecnología de tarjetas inteligentes (SC).

Cuatro aspectos clave caracterizan la información de los IPTS [Furth et al., 2003]: detalle espacial y temporal, cobertura (todos los eventos o sólo los excepcionales), representatividad (penetración de la flota y tasa de recuperación de datos) y calidad.

Los registros a nivel de parada, que pueden almacenarse en el IPTS con un coste incremental bastante bajo, han permitido estimar mejor los indicadores de rendimiento y las métricas de uso anteriormente utilizados (por ejemplo, los tiempos de viaje) [Trépanier et al., 2009], y también evaluar atributos antes casi imposibles de cuantificar debido a la escasez de datos, como los relacionados con la fiabilidad del servicio [Wilson et al., 2009]. Sin embargo, pueden requerir un esfuerzo importante para obtener conclusiones significativas [Ma et al., 2014]. Además, se necesitan herramientas de visualización adecuadas para poder comprender la gran cantidad de resultados que se pueden generar. Bertini y El-Geneidy, 2003].

En la literatura existente se proponen varias distribuciones de probabilidad para caracterizar la variabilidad de los tiempos de viaje de los enlaces [Dai et al., 2019], como la log-normal desplazada, la log-normal, la normal [Qu et al., 2014], la gamma, la de Weibull, la de Burr tipo XII [Taylor y Susilawati, 2012], la de valor extremo generalizado [Chepuri et al., 2018], etc. Numerosos estudios [Harsha et al., 2020, Dai et al., 2019, Li et al., 2017, Srinivasan et al., 2014] eligen la primera, que muestra una densidad de probabilidad de cero cuando el valor de la variable aleatoria cae por debajo de un umbral (que sería el tiempo de viaje del enlace de flujo libre) y puede ajustarse adecuadamente a los datos asimétricos y con sesgo positivo; y que para muchos enlaces es la función que más probablemente describe cómo se distribuyen los tiempos de viaje. Un estudio de 2017 realizado con datos del sistema de posicionamiento global (GPS) de los taxis durante las horas punta de la mañana de 5 días laborables en Wuhan (China) [Chen et al., 2017] descubrió que los tiempos de viaje de los enlaces pueden estar mejor representados por distribuciones logarítmicas normales, gamma o normales (en el 50 %, el 30 % y el 20 % de los enlaces analizados, respectivamente) y optó, para evitar cálculos intrincados desde el punto de vista informático, por asumir que los tiempos de viaje a lo largo de un trayecto pueden aproximarse mediante distribuciones normales.

En cuanto a los tiempos de permanencia, la mayoría de los trabajos sugieren que, debido a su naturaleza no negativa y a su posible asimetría, es probable que la distribución logarítmica normal sea la mejor alternativa (por ejemplo, un estudio de 18 meses de datos de una ruta de autobús en Nueva Jersey, Estados Unidos [Rajbhandari et al., 2003]; 6000 registros de un estudio de un día en Changzhou, China; o un análisis de datos de un mes de autobuses públicos en Jinan, China [Zhang et al., 2019]). Otras distribuciones posibles son la normal, utilizada por el software comercial de microsimulación de tráfico como AIMSUN [Aimsun, 2020] o VISSIM [PTV Group, 2020], y también elegida en algunos trabajos científicos (por ejemplo para caracterizar los datos de 1 día de una parada de autobús en la ciudad de Chennai, India [Koshy y Arasan, 2005]); Wakeby, que superó a la distribución log-normal en un estudio con 3 meses de datos de 4 paradas en Auckland,Nueva Zelanda [RASHIDI y RANJITKAR, 2013]; o Erlang, propuesta en un estudio que analizó 435 registros de 12 paradas de autobús en Shanghái, China [Jiang y Yang, 2014].

Los subsistemas que contribuyen a un IPTS a menudo no captan adecuadamente información que sería útil para un análisis posterior, porque suelen tener otros objetivos: apoyar la planificación táctica y la respuesta de emergencia en el caso del AFC, y gestionar las concesiones para el AFC. En consecuencia, suelen surgir una serie de cuestiones relacionadas con problemas internos de cada conjunto de datos o con incoherencias entre ellos. Los que entran en el ámbito de este trabajo son [Luo et al., 2018]:

- Registros AFC erróneos, que pueden ser causados por fallos de funcionamiento, comportamiento atípico de los viajeros, desvíos de rutas de emergencia o mal manejo de los equipos por parte de los conductores y operadores [Trépanier et al., 2007].
- Entradas erróneas en el sistema de localización automática de los vehículos (*AVL*) debido a fallos del del mismo, operaciones incorrectas del controlador o problemas específicos en las terminales.
- Múltiples registros para el mismo evento AVL, posiblemente con diferentes atributos (marca de tiempo, identificación del vehículo o de la ruta).
- Eventos perdidos.
- Falta de información que vincule los viajes reales con el programa de servicios vigente en ese momento.
- Ausencia de información o información errónea para relacionar los viajes con los desplazamientos de los vehículos.

En algunos casos, estos problemas pueden ser tan graves que los investigadores han desarrollado metodologías que modelan las características del transporte público de forma indirecta, en lugar de utilizar una alternativa más inmediata, pero propensa a errores (por ejemplo, utilizando AVL en lugar de AFC o registros de contadores de pasajeros automatizados para estimar la demanda de transporte público [Moreira-Matías, 2016]).

Hay muchos ejemplos publicados de la aplicación combinada de múltiples sistemas de datos de recogida automatizada en los diferentes aspectos de la gestión y planificación del tránsito urbano. Entre los que utilizan datos de AVL y AFC, algunos ejemplos destacables son:

- Perfiles de carga espaciotemporales de los vehículos de tránsito urbano durante un mes en La Haya (Países Bajos), integrando completamente los registros GTFS como tercera fuente de datos con la información AVL y AFC [Luo et al., 2018].
- Procesamiento fuera de línea de los sistemas de seguimiento automatizado de trenes y de cobro de billetes basados en tarjetas magnéticas de viaje en el área de la bahía de San Francisco (EE.UU.) [Buneman, 1984].

- Estimación de matrices origen-destino (OD) y modelos de elección de ruta para pasajeros de ferrocarril de la Autoridad de Tránsito de Chicago [Wilson et al., 2009].
- Modelización multimodal del propósito del viaje y estimación mejorada de la DO en Queensland (Australia) [Alsger y Eng, 2016].Matrices de OD de metro y autobús, perfiles de velocidad de los vehículos y calidad, indicadores de servicio, etc. para el sistema de transporte público Transantiago en Santiago de Chile [Gschwender et al., 2016]. "Entrevistas de autobús asistidas por el conductor": si los registros de SC están correctamente vinculados con la información de AVL, pueden funcionar como encuestas de preferencias reveladas [Chu et al., 2009].
- Seguimiento de los SC a lo largo del metro y el autobús para identificar el comportamiento de los transbordos en Shenzhen (China), haciendo uso de los registros del AFC del autobús que solo muestran la identificación de la tarjeta y el tiempo de barrido [Huang et al., 2019].

Sin embargo, no hemos encontrado en la literatura existente una metodología que se centre en mejorar la caracterización de los servicios que tienen lugar en un sistema de transporte público de autobuses combinando AFC, AVL, y arranques programados; con el objetivo de trabajar en torno a los problemas comunes de datos de IPTS y, lo suficientemente flexible como para ser aplicado en diferentes situaciones. Esperamos que sea útil para otros investigadores e ingenieros de transporte durante sus actividades; como la auditoría, el modelado del comportamiento de los usuarios o la estimación de los perfiles de carga de los vehículos.

2. METODOLOGÍA

Esta sección comienza especificando las fuentes y la estructura prevista de los datos de entrada. A continuación, se detallan los pasos de preprocesamiento que se aplican a la información AVL, AFC y de planificación; representando cada visita de un autobús a una parada como un único evento de cada fuente. A esto le sigue el análisis de los datos AVL como secuencias que se descomponen en fragmentos de sus respectivas líneas; y la implementación de modelos de distribución de tiempos de viaje de los enlaces y de tiempos de permanencia. A continuación, se lleva a cabo la caracterización inicial de los servicios realizados, que puede mejorarse si es necesario detectando cambios de id de los vehículos a mitad de servicio. A continuación, se vinculan los inicios programados para identificar los servicios planificados y los adicionales, distinguiendo en el primer caso si se utilizó el vehículo previsto o no; y también para mejorar la fidelidad de la recreación. A continuación, se asignan los eventos AFC a las visitas del autobús. Por último, se aceptarán aquellos servicios respaldados por suficiente información del IPTS. La figura 1 muestra un resumen general de todo el proceso.

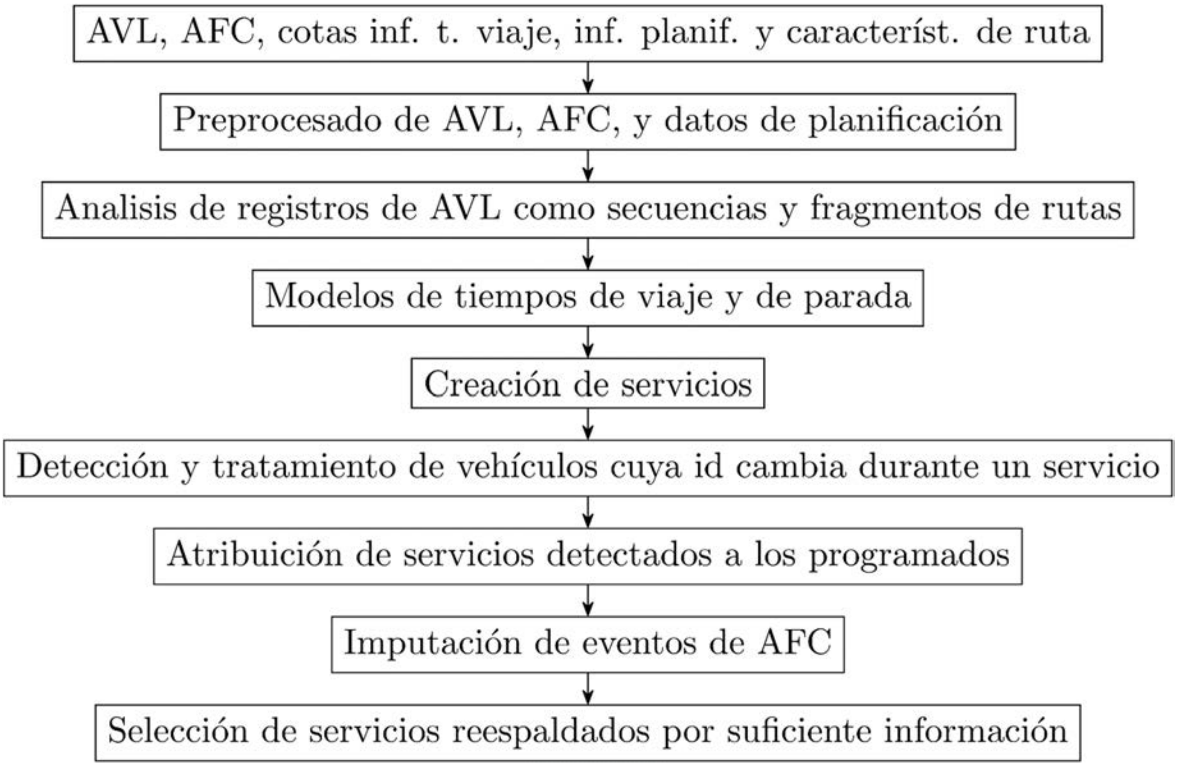


Figura 1: Esquema de la metodología

2.1 Datos de entrada

La Tabla 1 contiene un resumen de la información necesaria sobre las paradas de autobús, AFC, AVL, límites inferiores de los tiempos de viaje y el horario de inicio del servicio. Cabe señalar que los identificadores de las paradas de autobús, las rutas y los vehículos deben ser coherentes en todos los subsistemas. Las columnas llamadas “grupo” en AFC y AVL deben contener un identificador único para cada conjunto de valores presentes en su subsistema particular, que puede ayudar a diferenciar entre los recorridos de un vehículo.

En cuanto al horario, la metodología está diseñada para funcionar incluso cuando está incompleto, o para detectar recorridos de servicios no planificados. En esta sección se asumirá que las tres columnas con información temporal pueden estar disponibles en al menos parte del conjunto de datos.

Columna	*Tipo*	*Descripción*
id	entero	Id del bus en el IPTS.
localización	(real, real)	Coordenadas geográficas.
nombre	texto	Cómo es llamada por los usuarios.

(a) *paradas*

Columna	*Tipo*	*Descripción*
parada_0	entero	Id de la parada inicial.
parada_1	entero	Id de la parada final.
t_fluj_libr	tiempo	Cota inferior del t. necesario para este viaje.

(b) *cotas inferiores de los tiempos de viaje*

Columna	*Tipo*	*Descripción*
parada	entero	Id de la parada.
línea	entero	Id de la línea.
vehículo	entero	Id del vehículo.
t_validac	instante	Momento de validación.
grupo	entero	UID para cada conjunto de valores de otras cols. que varían en diferentes visitas del bus.

(c) *AFC en bruto*

Columna	*Tipo*	*Descripción*
parada	entero	Id de la parada.
línea	entero	Id de la línea.
vehículo	entero	Id de vehículo.
durac_parad	tiempo	Cuánto t. estuvo el bus en la parada.
llegada	instante	Momento de llegada a la parada.
grupo	entero	UID para cada conjunto de valores de otras cols. que diferencien distintas visitas de un bus.

(d) *AVL en bruto*

Columna	*Tipo*	*Descripción*
línea	entero	Id de línea.
vehículo	entero	Id de vehículo.
parada	entero	Id de parada.
comienzo_pl	instante	Instante planificado de inicio.
llegada_reg	instante	Detecc. llegada vehículo a parada inicial.
comienzo_reg	instante	Detecc. comienzo servicio.

(e) *planificación en bruto*

Columna	*Tipo*	*Descripción*
línea	entero	Id de línea.
term_dudos	lógico	Verdadero si AFC y AVL en cabec. poco fiables.
ini_srv_crrct	tiempo	T. medio entre 1^{er} evento AVL y detecc. inicio serv.
sep_max	tiempo	Cota superior entre el paso de dos servicios.
t_prds_max	tiempo	T. viaje máx. entre paradas consecutivas.
t_vuelt_min	tiempo	T. min. para dar una vuelta completa.

(f) *información de las líneas*

Tabla 1: Datos de partida de la metodología

2.2 Preprocesamiento

En esta sección se crean nuevas tablas para los conjuntos de datos AFC y AVL, sintetizando en una sola entrada la información que cada fuente bruta proporciona sobre una visita de autobús. Además, se utilizan límites inferiores de tiempos de viaje para filtrar los datos AVL poco fiables.

2.2.1 AFC

Se supone que no hay filas duplicadas en la información bruta de AFC, ya que debido a las repercusiones monetarias de los datos, la información de los billetes se gestiona de forma muy cuidadosa. Las operaciones de pago con tarjeta inteligente o manuales son atómicas: o se completan con éxito o no se producen.

Como se explicará en detalle en la sección 2.5, la información del AFC (que proporciona un dato por validación) se utiliza para hacer frente a las carencias de los datos del AVL (idealmente, un dato por visita al autobús). Así, el objetivo es clasificar como un único evento de embarque todas las validaciones que se producen cada vez que un autobús hace escala en una parada. El primer y último eventos de emisión de billetes de estos "grupos de embarque" pueden utilizarse como una aproximación de cuándo llegó y salió el autobús de la parada. Para crearlos, se lleva a cabo un proceso de tres partes:

2.2.1.1 Crear grupos de parada

Se analizan los registros en bruto de AFC correspondientes a cada autobús, buscando distinguir grupos de eventos consecutivos referidos a la misma visita a una parada.

id parada	*rango en conj.* -	*rango en subconj.* =	*variable clasiff.*	*grp. parad.*	*instante validación*	*sep. temp.*	*cumple lím. sup.*	*∄ AVL intermedio*	*cambio. grupo embarq.*	*grupo de embarq.*
					...					
A	1	1	0	A	03-24 12:31:23	<null>			1	987
B	2	1	1	B	03-24 12:33:56	<null>			1	988
C	3	1	2	C	03-24 12:36:14	<null>			1	989
C	4	2	2		03-24 12:36:16	00:00:02	✓	✓*	0	
D	5	1	4	D	03-24 12:37:24	<null>			1	990
E	6	1	5	E	03-24 12:39:44	<null>			1	991
E	7	2	5		03-24 12:45:22	00:05:38	✓	✓*	0	
F	8	1	7	F	03-24 12:47:37	<null>			1	992
G	9	1	8	G	03-24 13:48:51	<null>			1	993
G	10	2	8		03-24 13:50:59	00:02:08	✓	✓*	0	
G	11	3	8		03-24 13:53:04	00:02:05	✓	✓*	0	
G	12	4	8		03-24 14:11:11	00:18:07	✓	✗**	1	994
G	13	5	8		03-24 14:11:13	00:00:02	✓	✓*	0	
					...					
B	45	2	43	B	03-24 15:49:28	<null>			1	1004
C	46	3	43	C	03-24 15:51:33	<null>			1	1005
D	47	2	45	D	03-24 15:54:02	<null>			1	1006
D	47	2	45		03-24 15:54:02	00:00:00	✓	✓*	0	
D	48	3	45		03-24 23:05:49	08:11:47	✗		1	1007
E	49	2	47	E	03-24 23:09:09	<null>			1	1008
					...					

*: No se encontró una visita intermedia a otra parada en la información AVL
**: Los registros AVL revelan que este vehículo visitó la parada K a las 14:01:51

Tabla 2: Preprocesado de AFC en bruto. Vehículo, línea y UID de grupo permanecen constantes durante este ejemplo.

Este procedimiento se basa en el hecho de que, tal y como se representa en la tabla 2, para un conjunto (en este caso, las entradas del AFC en bruto vinculadas a un único vehículo) en el que se puede utilizar una relación ("ocurrió antes") para establecer una jerarquía sobre todo éste (columna "rango sobre el conjunto") y también sobre los diferentes subconjuntos definidos por una partición (entradas con los mismos valores de *vehículo*, *línea*, *grupo*, e *id de parada*) la diferencia entre el rango sobre el conjunto y sobre un subconjunto particular (la columna "variable de clasificación") proporciona un valor que diferencia los miembros de ese subconjunto que aparecen consecutivamente al ordenar todos los elementos del conjunto (el grupo de paradas, mostrado en la columna "grp. parad."). El significado del resto de las columnas de la tabla 2 y la coloración de las celdas se explicará a medida que se mencione a lo largo del resto de esta descripción del preprocesamiento del AFC. El proceso se explica como tres tareas consecutivas:

2.2.1.1.1 Clasificación por vehículo

Las entradas del AFC se agrupan por vehículo, y luego se obtiene su rango según una ordenación cronológica.

2.2.1.1.2 Clasificación por vehículo, ruta, grupo y parada de autobús

Las entradas AFC se clasifican por vehículo, línea, grupo y parada de autobús; y de nuevo se almacena su rango tras una ordenación cronológica. Estas cuatro columnas de la tabla de datos brutos de AFC permanecen constantes durante todas las validaciones de un evento de embarque concreto.

2.2.1.1.3 Crear grupos de parada

La diferencia de los dos rangos descritos anteriormente, la ‘*variable de clasificación*’, es constante y única para cada grupo de filas que reportan los mismos valores de *vehículo, línea, grupo* y *parada*, y aparecen consecutivamente.

La columna ‘*grupo parada*’ de la tabla 2 muestra el resultado de esta primera aproximación al objetivo de identificar los grupos de embarque; mostrando una sola letra para todas las entradas de avl en bruto consecutivas que forman parte del mismo grupo de parada. La coloración de las columnas ‘*id. de parada*’, ‘*variable clasificación*’ y ‘*grupo de parada*’ ilustra el proceso de clasificación y su resultado. Por ejemplo, las filas correspondientes a las visitas a la parada D se reúnen en dos ‘*grupos de paradas*’, diferenciados por los valores de la ‘variable de clasificación’ de 2 y 5.

Una forma de comprobar cómo ha funcionado esta primera tarea es estudiar la ‘*separación temporal*’ (tabla 2) entre las entradas consecutivas del mismo ‘grupo de paradas’. A medida que este desfase aumenta, es más probable que esta última entrada haya tenido lugar durante una visita diferente del autobús (sin filas intermedias debido a que no se registraron validaciones hasta que el autobús regresó). En la siguiente sección se estudia esta situación.

2.2.1.2 Dividir grupos de parada en grupos de embarque

La cuestión relativa a los desfases temporales excesivos entre algunas de las entradas que forman parte del mismo grupo de paradas se aborda con los siguientes supuestos:

- En algunas ciudades, no es raro que el conductor permita a los pasajeros esperar el inicio de un servicio dentro del autobús, especialmente si hace mal tiempo. Sin embargo, si la separación entre dos entradas consecutivas del mismo grupo de paradas es mayor que el recorrido máximo de la ruta, su grupo se dividirá entre ellas. Esto ocurre en la penúltima fila de la tabla 2: el tiempo transcurrido desde la validación anterior es extremadamente largo (representado con el símbolo '✓' en la columna '*cumple límite superior*'), por lo que se puede estar seguro de que está describiendo un evento de embarque diferente y el grupo se divide, como se ha representado con el cambio de color de naranja a rojo. Un valor adecuado para este parámetro dependerá de las particularidades del caso analizado.
- Para todos los demás pares de entradas consecutivas del mismo grupo de paradas, si la tabla *avl_sintetizado* (definida más adelante durante la descripción del preprocesamiento de los datos AVL) muestra que el autobús visitó otra parada entremedias, pertenecen a grupos de embarque diferentes. Un ejemplo de esta situación se encuentra en la fila con '*rango en conjunto*' = 12 de la tabla 2, donde el grupo de paradas de 5 entradas (G,8) del que forma parte está dividido en dos grupos de embarque (993 y 994); porque, como denota el símbolo '✗' de la columna '*∄ registro AVL intermedio*', entre su marca de tiempo (14:11:11) y la de la entrada anterior (13:53:04) una búsqueda a través de los datos AVL brutos (no representados) ha concluido que el autobús pasó por la parada K a las 14:01:51.

Estas premisas se utilizan para definir la columna '*cambio de grupo de embarque*' de la tabla 2), un valor que será igual a 1 si una fila es la primera de un grupo de embarque, y 0 en los demás casos. Si las filas se ordenan por vehículo, rango cronológico, parada de autobús y cambio de grupo de embarque (de forma descendente), aparecerán consecutivamente si forman parte del mismo grupo de embarque, con un valor de cambio de grupo de 1 para la primera entrada y de 0 para las demás hasta su final. El identificador de grupo de embarque de cada fila es la suma total de todos los cambios de grupo hasta llegar a ella.

Volviendo a la Tabla 2, el contenido y los colores de las celdas de las columnas '*separación temporal*', 'cumple límite superior', '*∄ registro AVL intermedio*', '*cambio de grupo de embarque*' y '*grupo de embarque*', se han elegido para describir cómo se dividen los grupos de parada en grupos de embarque:

- Si una entrada es la primera de su grupo de parada ('*separación temporal*' = <nulo>), también debe comenzar un nuevo grupo de embarque (filas con '*rango sobre el conjunto*' ∈ {1,2,3,5, 6,8,9,45,46,47,49}). '*Cambio de grupo*' es igual a 1, y no es necesario comprobar las columnas '*cumple límite superior*' o '*∄ registro AVL intermedio*'. Para cada una de estas filas, las columnas que intervienen en la identificación de su grupo de parada y grupo de embarque se rellenan con el mismo color, diferente de sus respectivas predecesoras.

- Si el lapso entre dos validaciones sucesivas del mismo '*grupo de parada'* es demasiado largo, son el final y el principio de dos '*grupos de embarque'* diferentes. La última fila muestra el símbolo ✗ en '*cumple límite superior*', mientras que su columna '*∄ registro AVL intermedio*' no es necesaria, y "*cambio de grupo*" es 1. También representa todo su proceso de decisión, utilizando un color para 'id parada', 'parámetro de agrupación' y 'grupo de paradas'; y otro para '*cumple límite superior*' e '*identificación del grupo de embarque*', mostrando cómo se divide cada '*grupo de paradas*' en grupos de embarque.
- Para el resto de pares de filas consecutivas que comparten el mismo '*grupo de parada'*, el símbolo de la columna '*∄ registro AVL intermedio*' indicará si pertenecen al mismo grupo de embarque:

  ✗: El vehículo relacionado con ambas entradas se ha movido a otra parada (y eventualmente ha vuelto) entre ambas lecturas de tiempo, por lo que pertenecen a diferentes grupos de embarque. De nuevo, '*cambio de grupo*'=1, y los colores ilustran el razonamiento de esta decisión: un color para '*grupo de parada*' y el primer '*grupo de embarque'*, y otro diferente para el segundo '*grupo de embarque*' creado por la división.

  ✓: No hay evidencia de que el vehículo se haya movido entre los instantes de ambas entradas, por lo que se concluye que pertenecen al mismo '*grupo de embarque*': '*cambio de grupo*' = 0. Las columnas de la última fila que deciden su '*grupo de parada*' y su '*grupo de embarque*' muestran los mismos colores que en la primera.

Se considerará que los grupos de embarque que duren más que el recorrido máximo para su ruta provienen de datos no fiables, y no se utilizarán para deducir las visitas perdidas a paradas no registradas por el IPTS.

2.2.1.3 Resultado

Los resultados del preprocesamiento del AFC se recogen en grupos_de_embarque, estructurada como se muestra en la tabla 3, mientras que la fig. 2 representa la transición de 15 eventos individuales de emisión de billetes a 4 grupos de embarque que engloban diferentes paradas.

Columna	*Tipo*	*Descripción*
id	entero	Id del grupo de accesos.
parada	entero	Id de la parada.
vehículo	entero	Vehicle id.
línea	entero	Route id.
grupo	entero	AFC group UID.
rang_embarq	rango temp.	[1ª validac., última validac.]

Tabla 3: Resultado del preprocesado de AFC: grupos_de_embarque

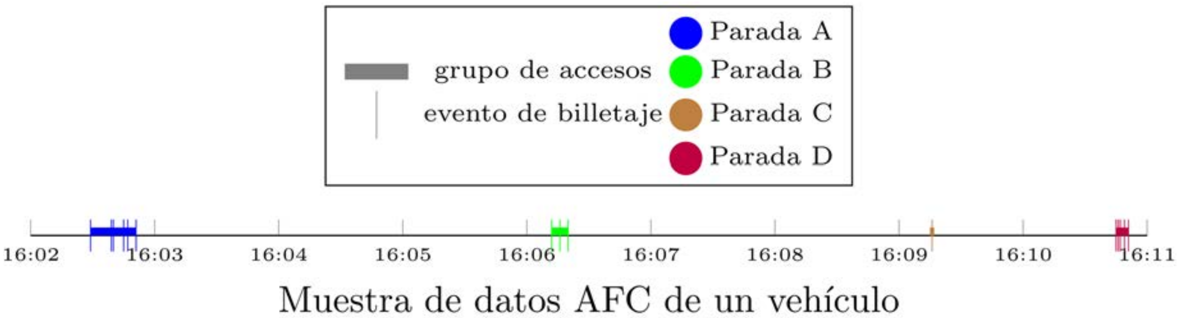


Figura 2: Recolección de eventos de billetaje individuales en grupos de embarque

2.2.2 AVL

Los procedimientos detallados en esta sección tienen como objetivo caracterizar el movimiento de los vehículos con un único registro para cada parada de cada servicio.

2.2.2.1 Eliminar filas duplicadas e inválidas

En primer lugar, se identifican y filtran las entradas duplicadas. Además, se supone que las entradas con un identificador de parada que no se corresponda con uno de los definidos en los datos de entrada (tabla 1-a), están causadas por eventos excepcionales que no corresponden a una llegada a una parada del sistema.

2.2.2.2 Identificar trayectorias

El siguiente paso es utilizar las columnas de los datos AVL para diferenciar las trayectorias que constituyen la oferta de transporte público. Para ello, en este trabajo se define una '*trayectoria*' como una serie de registros AVL consecutivos que comparten los mismos valores de *vehículo, línea* y *grupo*.(tabla 6a)

2.2.2.3 Determinar grupos de visitas

La tabla 4 muestra cómo se examina cada trayectoria para distinguir las ocasiones en las que se añade más de una fila al conjunto de datos para la misma escala en una parada (por ejemplo, cuando se vuelven a abrir las puertas para dejar entrar a un pasajero retrasado en el autobús). El procedimiento para identificar estos '*grupos de visitas'* (calcular los rangos de cada entrada sobre su trayectoria, y entre aquellos registros con los mismos valores de trayectoria y parada; y luego evaluar la variable de clasificación de cada elemento como su resta) es similar al que ya se ha descrito e implementado en 2.2.1.1 para encontrar *grupos de paradas* en los datos AFC.

Parada	*Rango cronológico en trajectoria*	-	*Rango cronológico en (traject., parada)*	=	*Número del grupo de visita*	*Parada*
A	1	-	1	=	0	A
B	2	-	1	=	1	B
C	3	-	1	=	2	C
C	4	-	2	=	2	
D	5	-	1	=	4	D
E	6	-	1	=	5	E
C	7	-	3	=	4	C
F	8	-	1	=	7	F
...						

Tabla 4: Cómo se identifican los eventos de AVL vinculados a una única visita

2.2.2.4 Combinar los eventos de cada grupo de visitas

La información correspondiente a cada grupo de visita se resume en la tabla avl sintetizado (tabla 5), que incluye el instante más temprano y más tardío en el que según el AVL el bus estuvo en la parada.

instante	*duración*	*parada*
...		
12:50:29	0	151
12:51:11	19	135
12:51:18	198	135
12:51:47	<null>	135
12:55:07	14	134
...		

(a) *avl*

llegada	*salida*	*parada*
...		
12:50:29	12:50:29	151
12:51:11	12:54:36	135
12:55:07	12:55:21	134
...		

(b) *avl_sintetizado*

Tabla 5: Combinación de múltiples eventos AVL en una visita a la parada

2.2.2.5 Identificar y descartar desplazamientos entre paradas no plausibles

Considerando cada trayectoria como una serie de tramos de viaje entre sus grupos de visitas, no son posibles aquellos más cortos que el tiempo de viaje en flujo libre entre las paradas implicadas. Se dan dos situaciones posibles:

- Al retrasar la hora de salida en la parada anterior, aumentando así la longitud del tramo, se resuelve el problema. Esto equivale a suponer que la información sobre el tiempo que el autobús permaneció en la parada inicial del tramo no es fiable.
- Ni siquiera poniendo a cero el tiempo de permanencia en la primera parada hay tiempo suficiente para viajar a la segunda. En este caso, ambos grupos de visitas se considerarán poco fiables y se eliminarán.

Además, los tramos de viaje más largos que el límite superior establecido para su ruta (tabla 1f) se utilizarán para dividir sus trayectorias. Así, las entradas de AVL que presenten el mismo vehículo, ruta y grupo, pero separadas por un tramo de viaje demasiado largo para haber ocurrido durante un único servicio, se considerarán por separado.

2.2.2.6 Resultado

La tabla 6 muestra cómo se almacena el resultado del preprocesamiento AVL en las tablas *trayectorias* y *avl_sintetizado*.

Columna	*Tipo*	*Descripción*
id	entero	Id de la visita.
línea	entero	Id de línea.
vehículo	entero	Id vehículo.
group	entero	UID del grupo (AVL).
sec_paradas	entero	Id sec. paradas (descrita más adel.).
rang_trayect	rango de t.	[inicio tray., fin trayect.]

(a) *trayectorias*

Columna	*Tipo*	*Descripción*
id	entero	Id de la visita.
parada	entero	Id parada
ord_en_trj	entero	Orden cronológ. dentro de trayect.
trayectoria	entero	Id de trayectoria.
rango_avl	rango t.	[llegada, salida]

(b) *avl_sintetizado*

Tabla 6: Resultado del preprocesado de AVL

2.2.3 Planificación

En primer lugar, los eventos registrados en el subsistema de programación deben ser corregidos por el valor apropiado de ini_srv_crrct (tabla 1f, representado por *s* en la formulación de esta sección), si está definido para la ruta correspondiente.

A continuación, se crea un intervalo de tiempo *n* para cada servicio planificado, que engloba las horas de llegada y salida que pueden deducirse de las columnas más específicas disponibles, siempre que proporcionen una información coherente (por ejemplo: las salidas no pueden producirse antes que las llegadas). También se crea otro buffer de tiempo *q* en torno a su hora de inicio prevista t_p, con un semi-ancho igual al a la separación máxima entre servicios (tabla 1f, *s* en esta sección). Este intervalo se utilizará en la sección 3.7 para vincular cada entrada del horario con el servicio que lo materializa. Las ecuaciones (1) y (2) enuncian respectivamente el parámetro y las variables, y detallan las condiciones que se acaban de describir; mientras que la tabla 7 muestra la estructura de la información de planificación tras el preprocesamiento.

$$n = \left[[t_a, t_d]\ if\ t_a \leq t_d\right], \left[[t_p, t_d]\ if\ (t_a > t_d \vee \nexists t_a) \wedge t_p \leq t_d\right], \left[[t_d, t_d]\ if\ (t_a > t_d \vee \nexists t_a) \wedge t_p > t_d\right], [< null > en\ otro\ caso]] \quad (1)$$

$$q = [t_d - s, t_d + s] \quad (2)$$

donde:

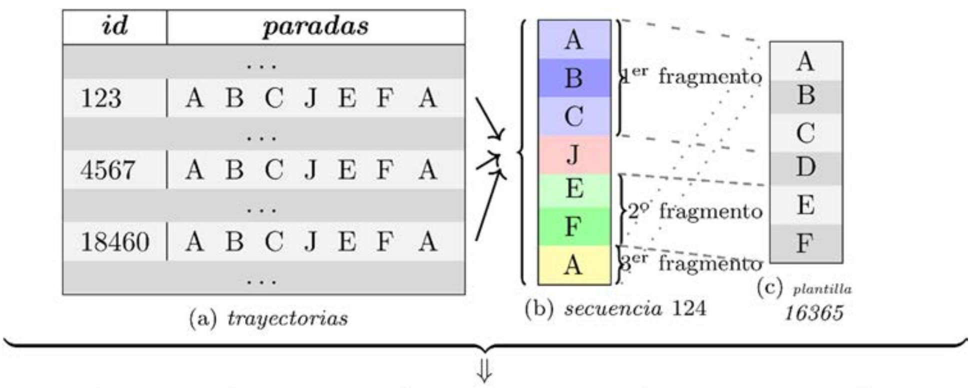
- tp: t. salida programado instante
- td: t. salida registrado instante
- ta: t. llegada bus registrado instante
- n: rango t. del subsist. De planif. [t. llegada, t. salida]
- q: búfer de búsqueda [cota t. inf., cota t. sup.]

Columna	*Tipo*	*Descripción*
id	entero	Id inicio serv.
parada	entero	Id parada.
vehicle	entero	Vehicle id.
buff_busq_serv	rango t.	[t. min, t. max] para búsqueda serv.
rango_planif	rango t.	[llegada, salida] de subs. planif.

Tabla 7: Resultado del preproceso de la planificación en bruto´

2.3 Analizar las trayectorias de la AVL como secuencias y fragmentos de rutas

Las trayectorias de AVL se analizan como secuencias ordenadas de paradas, que serán los bloques de construcción para ensamblar los servicios completos que se han producido, definidos por aquellas secuencias elegidas como ‘plantillas’.



Ordin. en sec.	*Ordin. en plantilla (núm. parada)*	*Longitud*	*Id sub-secuenc.*	*Id secuenc.*	*Plantilla*
...					
1	1	3	1	124	16365
5	4	2	2	124	16365
7	1	1	3	124	16365
...					

(d) *fragmentos*

Tabla 8: Análisis de las trayectorias de una línea, para una de sus plantillas

Columna	*Tipo*	*Descripción*
id	entero	Id de la secuencia.
línea	entero	Id de la ruta.
secuenc_parads	tupla de ent.	Secuenc. de ids de paradas

(a) *secuencias_paradas*

Columna	*Tipo*	*Descripción*
id	entero	Id de la secuencia.
n_stops	entero	Número de paradas.
name	texto	Nombre utilizado por los usuarios.

(b) *secuencias_plantillas*

Columna	*Tipo*	*Descripción*
ord_en_seq	entero	Ordinal del evento en su secuencia
núm_parada	entero	Ordinal del evneto en la plantilla.
fragmento	entero	Id del fragm. en su secuenc.
secuencia	entero	Id secuenc.
plantilla	entero	Id plantilla.

(c) *fragmentos*

Tabla 9: Resultado del análisis de las secuencias de AVL

La tabla 8 ilustra este proceso, y la 9 recoge los resultados de sus tres pasos.

2.3.1 Identificar distintas secuencias de trayectorias de la AVL

Se asigna un identificador a cada secuencia de paradas única extraída de las trayectorias de cada ruta, como se muestra en las tablas 8a, 8b y 9a. Esta relación se almacena en campo ‘*secuencia de paradas*’ de la tabla de trayectorias.

2.3.2 Encontrar las secuencias a utilizar como plantillas

Esta metodología parte de la base de que cada línea puede dividirse en una serie de ‘sublíneas’ que representan los servicios que la componen (por ejemplo, los viajes de ida y vuelta entre los terminales; o un único viaje de ida y vuelta en el caso de las rutas circulares). Cada sublínea se caracteriza por su ‘plantilla’ de secuencia de paradas (tabla 8c) que debe seguir un recorrido típico, completo y perfectamente registrado de esa sublínea. Estas plantillas pueden conocerse de antemano, o averiguarse mediante el examen de las secuencias de paradas encontradas durante su paso anterior, y sus frecuencias relativas, ya que las plantillas estarán muy probablemente entre las que se encuentran más a menudo. Se almacenan como se ilustra en la tabla 9b.

2.3.3 Descomponer las secuencias en fragmentos de plantilla

Como se muestra en las tablas 8b a 8d, las secuencias seguidas por las trayectorias pueden dividirse en:

- Fragmentos continuos de las plantillas de su ruta (es decir, no faltan elementos entre sus extremos), que representan partes de servicios que el sistema AVL logró registrar correctamente. Permiten ver cada trayectoria encontrada en los datos AVL como una serie de segmentos que se ajustan a su plantilla. El cuadro 9c muestra cómo se almacenan.

- Porciones incompatibles (causadas por entradas erróneas en el subsistema AVL; el vehículo que realiza otra ruta secundaria; u operaciones incorrectas, por ejemplo, no actualizar el ordenador de a bordo para reflejar que el autobús sigue una ruta diferente).

2.4 Elegir los modelos de distribución de los tiempos de recorrido y de parada

Estos modelos se utilizan como parte de los criterios para identificar los fragmentos de AVL o los grupos de embarque que forman parte del mismo servicio; para inferir la información de las paradas que faltan; y para filtrar los tiempos de inicio de servicio registrados erróneamente. Para cada ruta, se necesitarán los tiempos de viaje de los enlaces entre las paradas consecutivas y los tiempos de permanencia de todas ellas menos la última.

Deben tener en cuenta los factores conocidos que modifican los tiempos de desplazamiento y permanencia en la zona de estudio, como la hora, si es un día laborable o no, o los cambios de movilidad estacionales.

2.5 Ensamblar los servicios

Los servicios se construyen partiendo de una 'semilla' que se completa hacia atrás y hacia delante en el tiempo, buscando segmentos de AVL y eventos de grupos de embarque que formen parte de la misma sublínea y con el mismo identificador de vehículo que la semilla que, según el instante del punto de datos conocido más lejano en la dirección de crecimiento actual y las distribuciones de probabilidad de la duración de los tramos intermedios desconocidos del viaje y las llamadas en las paradas, caen dentro del intervalo de predicción de amplitud mínima de probabilidad $\boldsymbol{g}$.

'$\boldsymbol{g}$' es un parámetro de esta metodología (ecuación 3). Cuanto más se acerque a uno, más exhaustiva será la búsqueda, y aumenta el riesgo de considerar eventos no válidos o no relacionados como parte de los servicios actuales. Sin embargo, si se fija demasiado bajo, pueden ignorarse eventos que realmente formaban parte del servicio que se está caracterizando.

$$g: probabilidad\ del\ intervalo\ de\ predicción \quad g \in [0,1] \tag{3}$$

Para cada sublínea y dirección (hacia atrás o hacia delante en el tiempo), las semillas se seleccionan siguiendo dos procesos iterativos consecutivos. En primer lugar, haciendo un bucle sobre los fragmentos de AVL con una longitud mínima $\boldsymbol{c}$, de mayor a menor. '$\boldsymbol{c}$' es el parámetro "**longitud mínima de las semillas AVL**" (ecuación 4). Esta decisión parte de la hipótesis de que los fragmentos de trayectoria AVL más largos tienen más probabilidades de ser fiables, mientras que los más cortos pueden deberse a errores de reloj, GPS o de funcionamiento. A continuación, los grupos de embarque no filtrados se utilizarán también como semillas. El algoritmo omitirá aquellas semillas contenidas en la tabla de eventos a ignorar (explicada en el último párrafo de esta sección).

$$c: Long.\,mín.\,de\ la\ semilla\ AVL \quad c \in \mathbb{N} - \{0\} \tag{4}$$

Una vez que se ha establecido una semilla, ésta "crece" tanto hacia atrás como hacia adelante, siguiendo un procedimiento que se asemeja al de la navegación por estima: partiendo del punto más lejano conocido en una dirección (el punto fijo inicial), se calculan intervalos de predicción de amplitud mínima de probabilidad ***g*** para las salidas o llegadas (si se recorre hacia atrás o hacia adelante, respectivamente) de las escalas en paradas consecutivamente más lejanas, como la suma de los tiempos de viaje y de parada de las paradas intermedias implicadas, hasta que se alcanza una de las siguientes condiciones (comprobadas en este orden) y se selecciona un nuevo punto fijo:

- El intervalo de predicción interseca el *rango_avl* de al menos un registro de la tabla *avl_sintetizado*. En este caso, se escoge el rango de horas de llegada y salida más cercano al más probable, y se identifica una porción del fragmento que lo engloba, para añadirlo al nuevo servicio en crecimiento, desde este registro hasta lo que se encuentre primero entre:

    - La penúltima o segunda parada de la ruta, mientras crece hacia adelante o hacia atrás, respectivamente.
    - El final de su fragmento en la dirección de crecimiento actual.

  Esta distinción tiene como objetivo, por un lado, ahorrar tiempo de computación, al sumar en un solo paso varias escalas del vehículo; y por otro, asegurar que siempre se calcule un rango de viabilidad en los terminales. Estos rangos, además de utilizarse como parte del proceso actual, para filtrar las entradas irreales del IPTS en esas paradas, se emplearán para decidir la mejor manera de incluir la información disponible de planificación.
- El intervalo de predicción se solapa con el rango de embarque de al menos un grupo de embarque compatible. Se elige el intervalo más cercano a las horas de llegada y salida más probables.
- Si la parada analizada es una terminal, se elige la llegada (o la salida, si se hace crecer el servicio hacia atrás) y el tiempo de permanencia más probables.

En la primera o en la segunda condición, "compatible" significa que se refiere a la misma ruta y al mismo vehículo que la semilla; y que no está en la tabla de eventos a ignorar (explicada en el último párrafo de esta sección). Si aparece más de una posibilidad, se selecciona la más probable según las distribuciones de tiempo de viaje y tiempo de parada.

En los tres casos, una vez seleccionado el nuevo punto fijo, el conjunto de valores más probables para los tiempos de viaje y los tiempos de permanencia del enlace se utilizará para inferir los tiempos de llegada y salida en las paradas intermedias que falten.

Después de llegar a una terminal, el crecimiento en la dirección actual termina. Para aquellas rutas en las que los datos en éstas se han considerado especialmente poco fiables (*term_dudos* = verdadero en la tabla 1f), si la llamada en la parada más cercana está respaldada por los datos de AVL o AFC, siempre se inferirán las horas de llegada y salida.

Una vez que una semilla ha crecido hasta abarcar un servicio completo, tal y como se describe en su plantilla; se crea un buffer que la engloba, extendiéndose hacia atrás y hacia delante en el tiempo desde la respectiva llegada y salida de cada llamada, añadiendo el límite inferior de tiempo de ida y vuelta para la ruta correspondiente (*t_vuelt_min*, tabla 1f). Los segmentos de AVL y los grupos de embarque con los que se superponga se añaden a las tablas de elementos a ignorar durante el resto del proceso de ensamblaje del servicio. Esto sirve para dos propósitos: hacer que ningún evento sea utilizado como parte de más de un servicio; y que los vehículos sigan itinerarios factibles (que pase suficiente tiempo antes de que vuelvan a la misma parada, como parte de otro servicio).

La figura 4 muestra un diagrama de flujo de la primera parte de este proceso, que utiliza segmentos de datos AVL como semillas. La segunda parte es completamente análoga, pero sólo se utiliza la información restante del AFC. La figura 3 ilustra un ejemplo completo, en el que los principales pasos son:

- (1): La semilla inicial es un segmento AVL que va desde la llegada a las :20:13 a AB, hasta la salida a las :22:41 de AE.
- (2): Ésta crece hacia atrás, utilizando el intervalo de búsqueda [:18:51, :19:53] en el punto final AA. Se ha definido fijando la llegada a AB como punto fijo, y calculando el intervalo de predicción con probabilidad ***g*** para la presencia del vehículo en AA.
- (3): Se encuentra un único evento AVL compatible y superpuesto (3a), con horas de llegada y salida :18:31 y :18:55, respectivamente:

    - Si las lecturas en los terminales de esta ruta se han considerado tan fiables como en otras paradas (y = falso), se aceptará (3a) como la llamada del autobús en el terminal inicial.
    - En caso contrario, dado que el punto fijo del que parte la búsqueda se encuentra en la parada próxima al terminal (3c), se preferirá la visita inferida 3b, de :19:15 a :19:46.

Al ser uno de los extremos de la ruta, el crecimiento hacia atrás termina.

- (4): A medida que se avanza, se calcula el intervalo de búsqueda que se utilizará en AF, utilizando como referencia fija la hora de salida de AE (:22:41). El resultado es el intervalo de predicción de probabilidad g de la presencia del autobús en AF: [:23:04, :24:05], que no cruza ninguna entrada compatible de los subsistemas AVL o AFC.
- (5): Se sigue buscando hacia adelante. En AG, se crea otro intervalo de predicción con probabilidad ***g*** para la llegada del autobús. Esta vez, se necesitará la suma de las distribuciones individuales de los tiempos de viaje de AE a AF, y de AF a AG; y del tiempo de parada en AF. El rango resultante ([:23:17, :24:57]) se solapa con un grupo de embarque ([:23:55, :23:59]). Sus eventos de embarque más tempranos y más tardíos se utilizarán como aproximación a la llegada y salida en AG.
- (6): Considerando ahora el intervalo de 1m14s entre la salida del autobús de AE a las :22:41, y la llegada a AG a las :23:55; la combinación más probable de los tiempos de viaje de AE a AF y de AF a AG; y del tiempo de parada en AF es, según sus respectivas distribuciones probabilísticas, 45s, 26s y 3s; respectivamente. Así, los tiempos de llegada y salida en AF se fijan en [:23:26, :23:29].
- (7): De nuevo, la búsqueda se realiza en la parada H. Esta vez, se encuentra una entrada AVL compatible. Ésta y otras tres del mismo fragmento se añaden al servicio.
- (8): Hubo que deducir varias paradas intermedias entre la salida de AK y la llegada y AR. Las horas de llegada y salida que faltan se fijarán en sus valores más probables, de acuerdo con las 7 distribuciones de tiempo de viaje y 6 de tiempo de permanencia implicadas.
- (9): Por último, se llega al otro extremo de la ruta. Dado que no se encuentra ningún AVL o AFC compatible, la llegada a esta parada; así como las llegadas y salidas a otras posteriores a la última salida conocida, si la hay; se fijan en sus valores medios.

El resultado después de utilizar todos los datos de AVL y AFC (tabla 10) es el resultado de esta metodología, y consiste en tres tablas:

- *servicios*, que sintetiza cada uno de los servicios que han sido detectados por esta metodología.
- *visitas_a_paradas*, que caracteriza a cada servicio.
- *rangos_búsqueda*, donde se guardan los intervalos de predicción utilizados durante la creación de los servicios.

Columna	*Tipo*	*Descripción*
vehículo	entero	Id vehículo.
id	entero	Id servicio.
serv_comb	entero	Id del serv. que lo engloba (si es aplic.).
plantilla	entero	Id. plantilla
comienz_prog	entero	Id del inicio planeado (si es aplic.).
rang_serv	rango t.	[Salida 1ª parada, llegada a últ. parada]
servs_comb	tupla de ent.	Ids de servicios englobados (si es aplic.)

(a) *servicios*

Columna	*Tipo*	*Descripción*
núm_parada	entero	Ordinal of stop in template.
id	entero	Id de la visita.
servicio	entero	Id del servic. del que forma parte.
avl_sint_id	entero	Fuente en *avl_sintetizado* (si es aplic.).
gr_acc	entero	Fuente en *grupos_de_accesos* (si es aplic.).
rango_visita	rango t.	[llegada, salida]

(b) *visitas*_a_paradas

Columna	*Tipo*	*Descripción*
origen	entero	Ordinal de la última parada con información del IPTS.
num_parada	entero	Ordinal de la parada analizada.
servicio	entero	Servicio del que forma parte la visita.
rang_búsq	rango t.	Extremos del intervalo de predicción.

(c) *rangos_búsqueda*

Tabla 10: Resultado de la caracterización de servicios

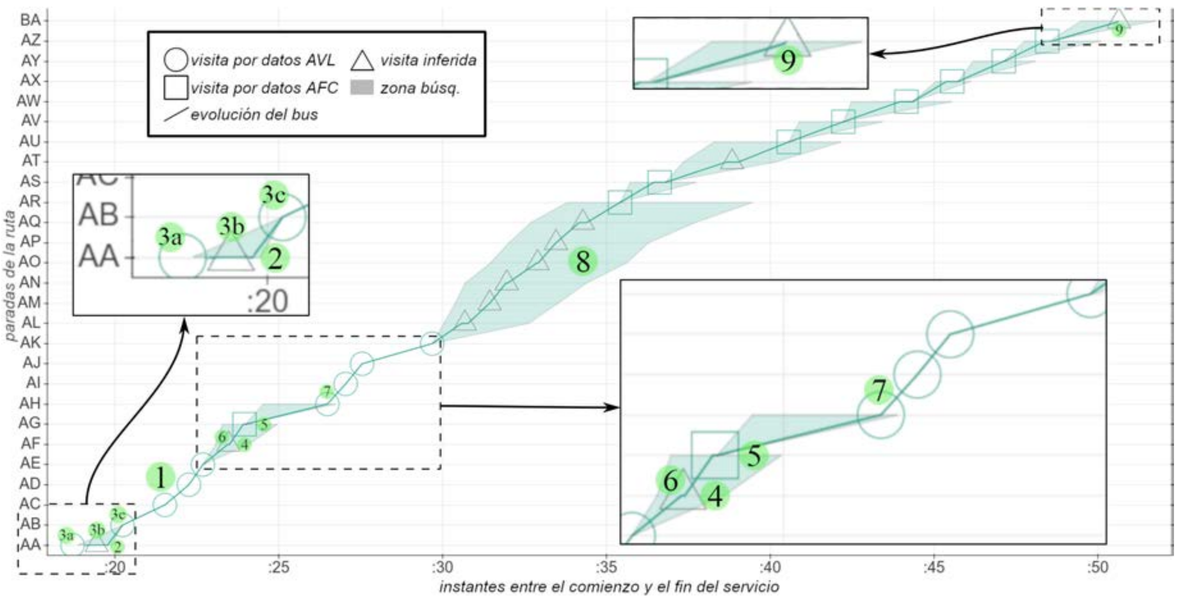


Figura 3: Proceso de inferencia de un servicio

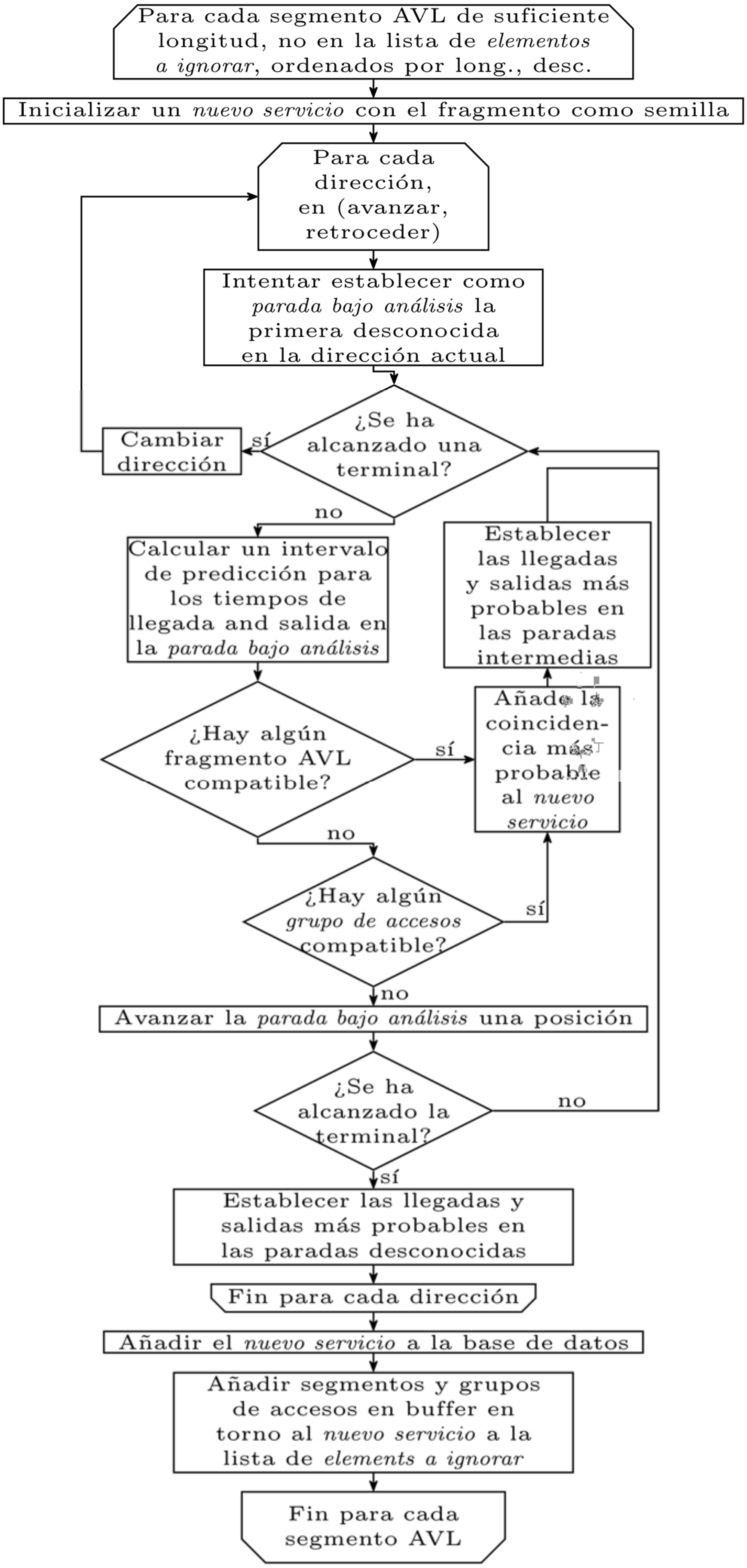


Figura 4: Proceso de inferencia de un servicio a partir de una semilla AVL

2.6 (Opcional) detectar y fusionar los casos en los que un vehículo ha cambiado su id a mitad de servicio

Algunos de los servicios del caso presentado en la siguiente sección de este trabajo varían su identificación de vehículo a mitad de servicio una vez. Pueden detectarse en esta metodología como dos servicios, uno 'anterior' y otro 'posterior', extremadamente cercanos en el tiempo; en los que un único vehículo podría haber proporcionado todas las visitas no inferidas a las paradas. Esta sección sigue la nomenclatura descrita en (5).

[$\emptyset, \lambda$:ids de servs. ant. y post. con $\emptyset, \lambda \in \mathbb{Z}$], [$C$:relación deben combinarse con $C = \{(\emptyset, \lambda) / \emptyset, \lambda$ son el mismo serv.$\}$], [T:instantes. son los posibles instantes],
[R:rangos t. con $R = \{(\rho[0], \rho[1]) \in T^2, \rho[0] \leq \rho[1]\}$],
[&&:relación "se superponen" con $\&\& = \{\rho_i, \rho_j\}, \rho_j[0] \leq \rho_i[1] \leq \rho_j[1] \vee \rho_j[0] \leq \rho_i[0] \leq \rho_j[1] \vee \rho_i[0] < \rho_j[0] \wedge \rho_i[1] > \rho_j[1]$], [$\sigma_i$:rango del serv. i-ésimo con $\sigma =$ (comienzo, fin) $\in R$], [$\upsilon_{i,j}$: visit range for service i at stop j con $\upsilon =$ (llegada, salida) $\in R$], [$\in_{i,j}$: rango de búsqueda del servicio i en parada j con $\in =$ (cota inf., cota sup.) $\in R$], [τ: núm. parada con $\tau \in \mathbb{N}$], [$\sigma\mu_i$:cota inf. del t. viaje entre paradas i e $i+1$] (5)

Para corregir este problema, los autores proponen el siguiente procedimiento que se debe llevar a cabo para cada secuencia utilizada como plantilla de servicios

2.6.1 Identificar los pares de servicios que deben combinarse

- Para ahorrar tiempo de cálculo, sólo se considerarán aquellos servicios que presenten solapamiento entre sus correspondientes rangos de servicio:

$$\emptyset C \lambda \Longrightarrow \sigma_{\emptyset} \&\& \sigma_{\lambda} \quad (6)$$

- Además, para cada escala de cada servicio en una parada, se crea un buffer de tiempo, como el más pequeño que incluye su rango de visita y, si existe, su rango de búsqueda. Se considera que dos servicios se suceden lo suficientemente cerca como para ser candidatos viables cuando sus buffers de tiempo se solapan.

$$\emptyset C \lambda \Longrightarrow \exists \tau, \upsilon_{\emptyset,\tau} \&\& \upsilon_{\lambda,\tau} \vee \in_{\emptyset,\tau} \&\& \in_{\lambda,\tau} \vee \upsilon_{\emptyset,\tau} \&\& \in_{\lambda,\tau} \vee \in_{\emptyset,\tau} \&\& \in_{\lambda,\tau} \quad (7)$$

- Por último, debe ser posible, teniendo en cuenta los límites inferiores de los tiempos de viaje entre paradas, que un solo autobús realice todas las entradas de visitas a paradas de ambos servicios que se desprenden de los datos del IPTS. El cumplimiento de esta condición depende del número de parada más alto para el que el servicio 'anterior' presenta una entrada de visitas a paradas no inferida (τ_{φ}); y, correspondientemente, del más bajo del 'posterior' (τ_{λ}):

- Si $\tau_\varphi = \tau_\lambda = \tau$, ambos representan la misma parada, en la que el IPTS tiene registros con los identificadores de los vehículos antiguos y nuevos. En dicha parada se calculan los siguientes rangos de tiempo:

  - Un "intervalo de viabilidad" $\zeta_{\varphi,\lambda}$ que delimita el lapso de tiempo en el que es posible que el autobús haya llegado tras salir de la $(\tau\text{-}1)^{\text{ésima}}$ parada, como se describe en el servicio ‘anterior’ φ, y aun así llegue a la $(\tau +1)^{\text{ésima}}$ del ‘posterior’ λ, teniendo en cuenta los límites mínimos de las duraciones de los tramos de viaje implicados:

$$\xi_{\emptyset,\lambda} \in R;\ \xi_{\emptyset,\lambda} = (\upsilon_{\emptyset,(\tau-1)}[1] + \mu_{(\tau-1)}, \upsilon_{\lambda,(\tau+1)}[0] - \mu_\tau) \tag{8}$$

  - Un "rango de presencia de bus" $\eta_{\varphi,\lambda}$, que es el rango de mínimo-ancho que engloba a los de los servicios ‘anterior’ y ‘posterior’:

$$\eta_{\emptyset,\lambda} \in R;\ \eta_{\emptyset,\lambda} = (min(\upsilon_{\emptyset,\tau}[0], \upsilon_{\lambda,\tau}[0]), max(\upsilon_{\emptyset,\tau}[01], \upsilon_{\lambda,\tau}[1]) \tag{9}$$

  La condición se cumple si estos dos rangos se superponen:

$$\emptyset C\lambda \wedge \tau_\emptyset = \tau_\lambda \Longrightarrow \xi_{\emptyset,\lambda} \&\& \eta_{\emptyset,\lambda} \tag{10}$$

- Si $\tau_\varphi < \tau_\lambda$, el lapso entre la salida registrada del primer servicio desde la parada τ_φ y la llegada registrada del segundo a τ_λ debe ser mayor o igual que el límite inferior del tiempo total de viaje entre ellos.
- Si $\tau_\varphi > \tau_\lambda$, los dos servicios candidatos no proceden de uno solo que haya cambiado su id.

La ecuación (11) resume estos criterios:

$$\emptyset C\lambda \Leftrightarrow \{[\xi_{\emptyset,\lambda} \&\& \eta_{\emptyset,\lambda}\ if\ \tau_\emptyset = \tau_\lambda], [\upsilon_{\lambda,\tau_\lambda}[0] - \upsilon_{\emptyset,\tau_\emptyset}[1] \leq \sum_{\tau=\tau_\lambda}^{\tau_\emptyset - 1} \mu_i\ \ if\ \tau_\emptyset < \tau_\lambda\} \tag{11}$$

2.6.2 Actualizar las tablas de caracterización de los servicios

Los servicios que cumplen las ecuaciones. (6), (7) y (11) se fusionan en uno nuevo. Las horas de llegada y salida de cualquier parada entre τ_φ y τ_λ se elegirán como las más probables, según las distribuciones de tiempo de permanencia y de viaje; y la información para relacionarlos se almacena en las columnas serv_comb y servs_comb. de la tabla 10a.

La figura 5 ilustra un ejemplo, en el que la metodología detecta que las entradas que en una primera aproximación se utilizaron para afirmar que dos servicios diferentes de una ruta entre las paradas AR y BJ tuvieron lugar (azul y naranja) son en realidad parte de uno solo, y entonces reevaluar las llamadas desconocidas en las que este hecho puede ser utilizado para mejorar las estimaciones de llegada y salida:

- El estado de los dos servicios propuestos por el apartado 2.5 de esta metodología cumple con las condiciones que los identifican como uno solo, con un cambio de id de vehículo intermedio:

    - Sus buffers temporales se solapan en al menos una parada, como puede verse observando las partes coloreadas en azul y naranja.
    - Considerando sólo las escalas respaldadas por datos del IPTS, la más tardía de uno de los servicios (visita del servicio anterior en AY, 17:11:50, marcado 1a) ocurre en una parada anterior a la más temprana del posterior (visita a BE, 17:22:05, marcada 1b). El intervalo entre la salida del primero y la llegada al segundo es de 10m15s, mientras que la suma de los límites inferiores de los tramos de viaje implicados es de 2m23s, lo que significa que un solo vehículo podría ser responsable de ambos.

- Se recalculan los tiempos intermedios de llegada y salida entre AY y BE. En lugar de sus valores medios según sus respectivas distribuciones y la salida de AY o la llegada a BE; adoptarán la combinación más probable de valores que satisfagan ambas condiciones al mismo tiempo.

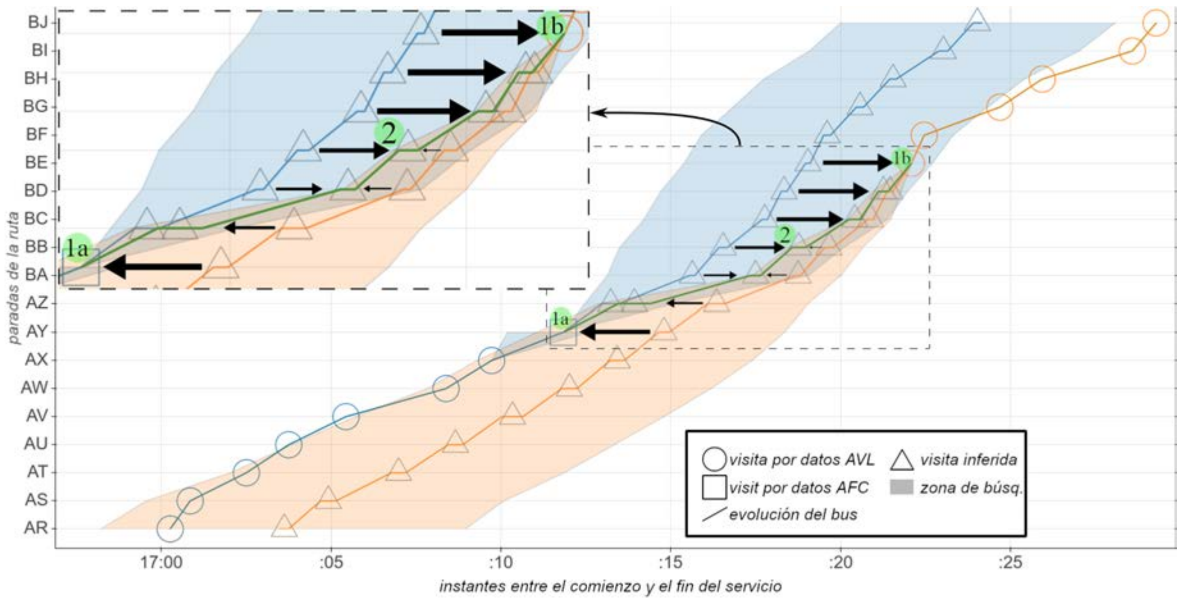


Figura 5: Fusión de 2 servicios (‘anterior’ azul, ‘posterior’ naranja, visitas modificadas: línea verde)

2.7 Asignación de servicios a los recorridos programados y actualización de los intervalos de tiempo de las visitas

Esta parte de la metodología tiene varios objetivos: en primer lugar, diferenciar entre los servicios previstos que se materializaron o no; identificar los recorridos extra no programados; y eliminar las visitas inferidas a paradas que no se produjeron realmente, para aquellos servicios que se identifican con éxito como que comienzan ‘aguas abajo’ de la terminal inicial.

Una vez que se ha vinculado un servicio con su inicio programado, la información adicional de la tabla de horarios puede utilizarse para afinar aún más las horas de llegada y salida. Estos son los pasos propuestos, que también se muestran en forma de diagrama de flujo en la fig. 6:

- Se realiza un bucle sobre todos los pares (inicio programado, servicio) en los que la salida de este último de la parada prevista cae dentro del buffer *q* (eq. 2) del primero, dando prioridad a los pares que que comparten la mismo *id de vehículo*, y luego ordenados por el valor absoluto del lapso entre la salida del servicio y el inicio programado, de forma ascendente. A menos que alguno de ellos ya haya sido vinculado, pasan a serlo entre sí.
- Si se encuentra un emparejamiento, a partir del terminal inicial de toda la ruta, se eliminan consecutivamente las visitas inferidas a las paradas, hasta llegar a una que esté respaldada por registros AFC o AVL.
- Si el subsistema de planificación registró el inicio del servicio, se evaluará la verosimilitud de su correspondiente rango de tiempo *n* (eq. 2), utilizando el rango de viabilidad apropiado almacenado en la tabla de rangos de búsqueda (tabla 10c, si no está disponible, se crea uno utilizando la llamada más cercana del servicio con soporte de datos). Si *n* se considera creíble, pueden darse dos situaciones:

    - Si la escala del servicio se había deducido previamente (sección 2.5) a partir de otros datos del IPTS, la información disponible se combinará para obtener las presencias más temprana y más tardía del autobús en esa parada.
    - En caso contrario, se utilizará n como rango [llegada, salida] al inicio del servicio.

- Las visitas inferidas aguas abajo, hasta la primera sustentada por datos del IPTS, se mejoran hasta sus nuevos valores más probables, considerando el tiempo total de viaje entre el inicio del servicio programado y ese primer punto de datos conocido, y las distribuciones de tiempo de viaje y de parada.

La figura 7 muestra las primeras paradas de un servicio de ejemplo:

- Su estimación inicial se ha vinculado a una salida prevista en la parada AF, con una diferencia entre sus tiempos de salida inferidos y los previstos de 51s.
- Las paradas anteriores al inicio previsto no están respaldadas por ningún registro IPTS, y se borran.
- En este caso, la llegada y la salida fueron registradas por el subsistema de planificación a las 07:25:39 y 07:26:01, respectivamente. Como estas horas están dentro del rango de búsqueda de ese servicio en la parada AF ([07:23:39, 07:26:13]), se aceptan como lo que realmente ocurrió.
- Las visitas a AG, AH, AI y AJ también se recalculan teniendo en cuenta la nueva información.

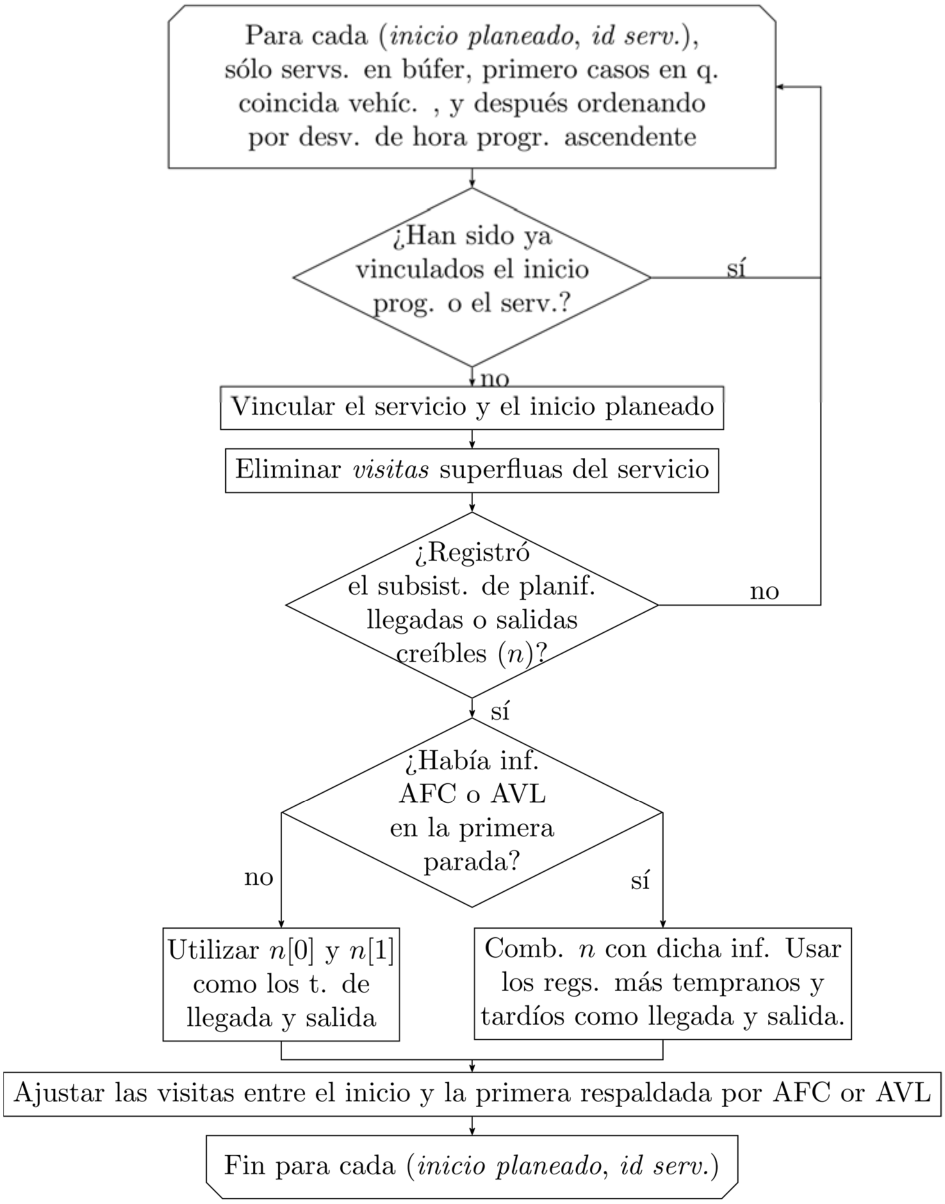


Figura 6: Asociación de servicios programados e inferidos

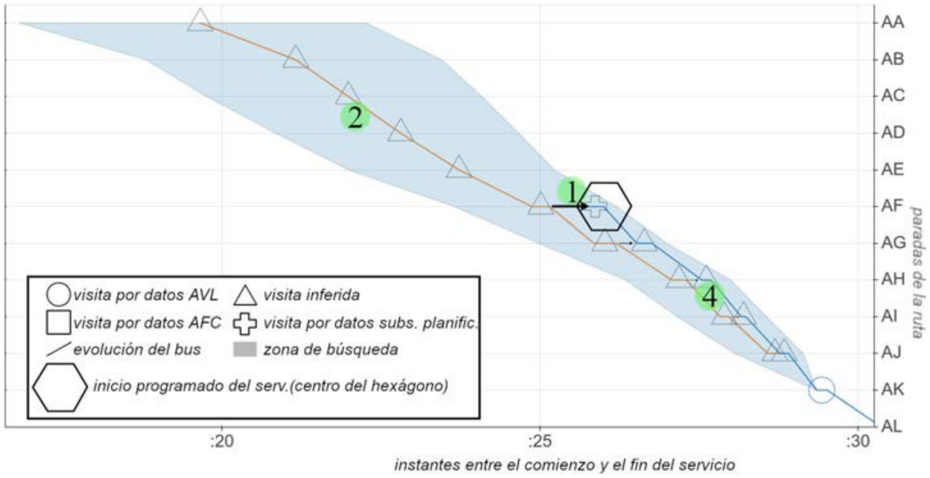


Figura 7: Mejora de la llegada y salida de un servicio una vez identificado su probable inicio programado. Caracterización final en azul, entradas modificadas en naranja

2.8 Imputación de grupos de embarque

Una vez definidas y refinadas las escalas de todos los servicios posibles, los grupos de embarque se asignarán primero a un servicio y luego a la parada en la que se produjeron.

Para la primera tarea, un rango de imputación (ligeramente resaltado con un patrón diagonal para el segundo caso de la fig. 8) se crea para cada servicio desde el momento en que el vehículo llegó a su parada inicial, menos el límite superior del tiempo entre servicios (‘*s*’ *en la fig. 7*, *sep_max* en la tabla 1f) para asegurarse de que se identifican todos los eventos AFC pertinentes en el terminal inicial, marcado como 6a); hasta el momento en que dejó su penúltima parada (ya que no se deben asignar eventos AFC a la última parada de un servicio), más el parámetro ‘***o***’ (), que permite cierto margen entre los eventos AVL y AFC, para cubrir casos como validaciones después de que el vehículo abandone la parada o desincronizaciones menores del reloj, marcado como 6b.

$$\boldsymbol{o}: \text{holgura AFC} \quad \text{tiempo} \qquad (12)$$

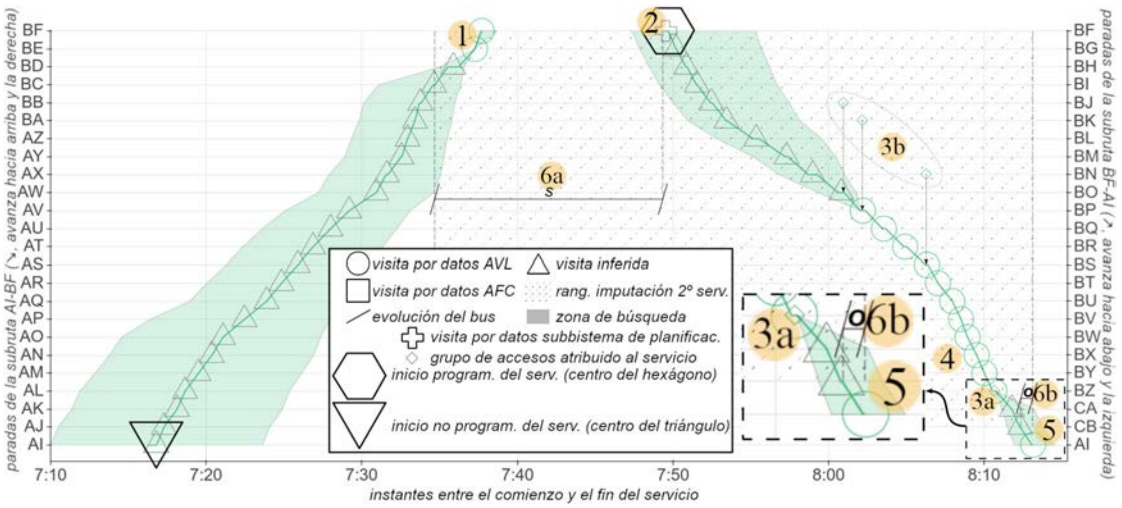


Figura 8: **Imputación de los grupos de embarque y análisis de los datos del IPTS**

Cada *grupo de embarque* se trata en un proceso de dos pasos:

- En primer lugar, se asigna al servicio cuya franja horaria solapa, y que se refiere al mismo vehículo y ruta. Si no se encuentra ningún servicio, se ignora el requisito de coincidencia de ruta, para tratar aquellos casos en los que el estado del subsistema de expedición de billetes no reflejaba la ruta que seguía realmente el vehículo. Cualquier grupo de embarque que quede no estará vinculado a un servicio.
- A continuación, se identifica la parada adecuada dentro del servicio, considerando todas sus escalas menos la última:
    - Si la diferencia entre el *rango_embarque* (tabla 3) y el *rango de visita* (tabla 10a) en la parada especificada por el grupo de embarque es menor o igual a la holgura ***o***, esa parada será aceptada como aquella en la que los viajeros subieron al autobús (por ejemplo, 3a en la fig. 8).
    - En caso contrario, se asumirá que el AFC no identificó correctamente la identificación de la parada. En su lugar, se elegirá el de la llamada más cercana del vehículo (por ejemplo, 3b en la fig. 8, donde los 3 grupos de embarque que se registraron como ocurridos en las paradas BJ, BK y BN se asignan respectivamente a BO, BP y BS).

2.9 Seleccionar servicios respaldados por suficiente información

El último paso es establecer y aplicar un criterio para aceptar o rechazar cada uno de los posibles servicios que han sido identificados por esta metodología. Se sugiere establecer límites que consideren estas características (ecuación 13):

- Si se asignó o no una salida planificada al servicio (*w*). En este último caso, también hay que tener en cuenta si la identificación del vehículo es la misma en ambas bases de datos (*p*), y si el subsistema de programación registró una hora de salida compatible (*v*).
- El número total *h* de grupos de embarque atribuidos al servicio, como se ha descrito en la sección 2.8.
- Cuántas visitas de ese servicio provienen de la información de AVL (*f*).
- El número de paradas entre la primera y la última visita apoyada por los datos del IPTS (*l*).

$[w$: el servicio esta planeado (lógico)$]$, $[p$: se empleó el vehículo previsto (lógico)$]$,
$[v$: Subs. de planif. resgistró un t. salida válido (lógico)$]$,
$[h$: Núm. de grupos de acceso $(h \in \mathbb{N})]$, $[f$: Visitas respaldadas por AVL $(f \in \mathbb{N})]$,
[l: separación máx. entre visitas respaldadas por IPTS $(l \in \mathbb{N})]$ (13)

La figura 8 ofrece un ejemplo, analizando dos posibles servicios consecutivos de un vehículo, que cubren sub-líneas complementarias entre los terminales AI y BF, ambos compuestos por 23 tramos de viaje. Sólo 2 entradas consecutivas de la tabla *avl_sintetizado* apuntan a la existencia del primero (1); mientras que el segundo se apoya en un servicio planificado de ese vehículo para el que el subsistema de programación registró la primera escala (2), 4 grupos de embarque (mostrados en 3a y 3b), 12 filas de *avl_sintetizado* (4), y por el hecho de que el intervalo entre la primera (2) y la última (5) escala, obtenidas a partir de observaciones registradas en el IPTS cubre toda la ruta. Es casi seguro que el primer servicio no ocurrió, mientras que el segundo es muy probable que sí.

3. APLICACIÓN A UN CASO REAL

Los resultados de esta metodología se ilustran utilizando los eventos AVL y AFC, y los inicios de servicio programados de los vehículos que, durante 1 año, recorren la línea 1 en Santander, una ciudad de la costa norte de España (fig. 9).

Figura 9: Ciudad de Santander [mapa, Wikimedia] [foto, SPIEGEL]

Funciona aproximadamente desde las 07:00 hasta las 23:00, con intervalos entre servicios de como máximo s = 20min. En aproximadamente la mitad de las ocasiones, el subsistema de programación registra, con una desviación de alrededor de z = 20s, la llegada y salida del vehículo de la primera parada del servicio. Un viaje completo de ida y vuelta requiere al menos d = 1h, mientras que un tramo de viaje único, incluso en las circunstancias más desfavorables, no debería durar más de e = 15min. Aunque el IPTS es extremadamente útil durante las operaciones diarias, la explotación de sus datos tiene que superar varios problemas:

- Baja fiabilidad de AVL y AFC en la mayoría de los extremos de los servicios (y = verdadero), debido a la forma en que a veces se manejan los ordenadores de abordo y al hecho de que cuando un autobús está vacío al acercarse al final de la ruta, los conductores a menudo encuentran más conveniente esperar hasta su próximo recorrido en una parada anterior a la final.
- Diariamente, cada viaje que cubre una de las 2 sub-líneas a veces no puede ser identificado de forma fiable con un *id* dentro de los conjuntos de datos AVL y AFC: este campo puede mostrar varios valores dentro de un mismo viaje, o el mismo valor puede ser utilizado para recorridos consecutivos que cubren ambas sub-líneas.

Además, este identificador no es coherente entre las informaciones de AVL, AFC y planificación.

- Falta de entradas AVL.
- Eventos AVL y AFC erróneos que se derivan de las limitaciones del IPTS, como la pérdida de la señal GPS, los fallos de comunicación o los errores del ordenador de a bordo; o de operaciones atípicas o incorrectas (por ejemplo, el establecimiento de parámetros de estado del vehículo que identifican erróneamente la tarea que se está realizando).
- La información relativa a si un viaje planificado finalmente ocurrió y cuándo comenzó es la mayoría de las veces precisa, pero a veces el inicio de un servicio normalmente realizado no se registra, o lo hace con marcas de tiempo muy inexactas.
- En ocasiones, al cambiar el conductor de un bus en mitad de un servicio, el identificador del vehículo cambia, por lo que presentarán 2 valores diferentes.

Esta implementación utiliza el lenguaje procedimental PL/pgSQL dentro de una base de datos PostgresSQL 13.2 para sus tareas principales; y Python 3.8 y Bokeh 2.2 para mostrar una representación interactiva de los resultados.

3.1 Aplicación de la metodología

3.1.1 Datos de entrada

3.1.1.1 Paradas y sub-líneas

Santander cuenta con aproximadamente 460 paradas de autobús. La ubicación de las 75 que conforman la ruta 1, que se divide en dos sub-lineas con una parada intermedia ("Consuelo Berges 16") y ambas terminales en común, se muestra en la fig. 10. Estas sub-líneas proporcionan las plantillas que se utilizarán para desglosar las secuencias de paradas encontradas durante el tratamiento de los datos de la AVL.

Figura 10: Paradas de la línea 1

Este itinerario comienza en el parque científico PCTCAN, en el oeste, y atraviesa la ciudad hacia el este a través de las principales arterias, pasando por muchos de sus centros comerciales, residenciales, turísticos y administrativos hasta llegar al Parque de la Península de La Magdalena (uno de sus principales lugares de ocio). A continuación, gira hacia el noroeste y sigue el litoral, dando acceso a las playas más populares de Santander. Finalmente desemboca en Valdenoja, un barrio que aunque presenta algún uso comercial limitado se puede caracterizar como un suburbio dormitorio.

Durante los días no laborables la actividad en el PCTCAN disminuye considerablemente, por lo que los autobuses no visitan las 3 paradas más orientales. Además, especialmente durante los días laborables, varios servicios de refuerzo planificados pero no anunciados comienzan “aguas abajo” por la primera parada, para aprovechar espacios libres breves que tengan los conductores entre otras asignaciones.

3.1.1.2 AFC

El conjunto de datos incluye 2586600 eventos AFC en bruto. Casi todos (99,99%) corresponden a paradas reales dentro de la ciudad, mientras que el resto tiene ids que no se refieren a una parada física.

3.1.1.3 AVL

Hay 1569417 eventos AVL en bruto. Todos representan llamadas en paradas reales de la ciudad.

3.1.1.4 Información del subsistema de planificación

Mientras que el horario diario que los viajeros tienen en cuenta a la hora de planificar sus viajes en la ruta 1 especifica, dependiendo de si es un día laborable o no, alrededor de 100 u 80 lugares y horas en los que comienza un servicio, la autoridad de transporte planifica algunos recorridos extra de vehículos reales, ofreciendo servicios adicionales menos conocidos de la ruta, como varios que comienzan en el hospital Valdecilla para el personal que acaba de terminar sus turnos, o reforzando la oferta durante los períodos conocidos de máxima demanda cuando la distribución de los recursos disponibles lo permite. Los recorridos adicionales de los vehículos que no están presentes en la información de programación pueden producirse debido a decisiones tácticas durante las operaciones diarias.

3.1.2 Preprocesamiento

3.1.2.1 AFC

Siguiendo la metodología expuesta en el apartado 2.2.1, se han encontrado 719971 grupos de paradas., divididos en 724550 grupos de embarque (un 0,6% más de eventos). De ellos, 108 (0,01%) duran más de *s* y no se tendrán en cuenta.

Hay, en promedio, 1 grupo de embarque por cada 4 eventos de billetaje en bruto. Estos grupos de embarque proporcionan además una primera estimación de reserva de las horas de llegada y salida en las paradas, que se utilizará si no se dispone otros registros.

3.1.2.2 AVL

Como se explica en el apartado 2.2.2, los eventos AVL consecutivos que representan la misma visita a una parada se fusionan, dejando 1532299 entradas (un 2% menos). De ellas, 78520 (5%) se consideran poco fiables porque forman parte de tramos de viaje imposiblemente cortos. Las 1453779 entradas restantes, reunidas en la tabla *avl_sintetizado*, se clasifican en 45840 trayectorias.

3.1.3 Analizar las trayectorias de la AVL como secuencias

Las 45840 trayectorias presentan 5800 secuencias de paradas diferentes. Las dos más frecuentes coinciden con los itinerarios ya conocidos de las sub-líneas estudiadas (fig. 10), y representan alrededor del 30% de los trayectos. Las demás contienen en la mayoría de los casos uno o varios fragmentos compatibles con una de las sub-líneas (como se describe en la tabla 8d), aunque a veces (2% de las trayectorias) el estado de un vehículo no cambió entre las sub-líneas, por lo que una misma trayectoria contiene información relativa a más de un servicio.

3.1.4 Especificar los modelos de distribución de tiempos de viaje y de parada

Debido a sus ventajas computacionales, se han elegido dos familias de distribuciones normales (ecuación 14) para modelar los tiempos de viaje y de parada. Teniendo en cuenta los ciclos de movilidad de la ciudad, cada una de estas familias proporciona una función diferente para cada línea, parada, tipo de día (laborable, sábados, o domingos y festivos), periodo del año (verano o no), y clase temporal (con un lapso de 30min, y aproximadamente 16 horas diarias de servicio, hay 32 clases posibles: De 07:00 a 07:30, de 07:30 a 08:30, etc.).

$[p_{a,\tau,\gamma,\delta,\xi,\eta}$: t. viaje entre paradas con $p \in T; p \sim \mathcal{N}((\mu_p)_{a,\tau,\gamma,\delta,\xi}, (\sigma_p)_{a,\tau,\gamma,\delta,\xi}{}^2)]$,
$[u_{a,\tau,\gamma,\delta,\xi,\eta}$: t. parada con $u \in T;\ u \sim \mathcal{N}((\mu_u)_{a,\tau,\gamma,\delta,\xi}, (\sigma_u)_{a,\tau,\gamma,\delta,\xi}{}^2)]$, [$a$: id de la línea],
[τ: núm. de parada (para t. viaje, el de la parada inic.)], [γ: época del año, $\gamma \in$
{verano, resto del año}], [δ: tipo de día, $\delta \in$
{laboral, sábado, domingo o festivo}], [ξ: clase de h. del día, $\xi \in$
$\{1 \ldots \eta\}$], [η: núm. de clases de h. $\eta \in \mathbb{N}$ (14)

Los tiempos de viaje y los tiempos de permanencia de los tramos de la ruta 1 se han caracterizado en cada parada por 192 distribuciones cada uno, según el periodo del año, el tipo de día, y la franja horaria aplicables. Sus medias y desviaciones estándar se han calculado utilizando las entradas pertinentes de la tabla avl_sintetizado.

3.1.5 Ensamblar los servicios

Tras aplicar el proceso descrito en el apartado 3.5, se encontraron 42319 posibles servicios.

3.1.6 Fusionar los casos en los que un vehículo ha cambiado su id a mitad de servicio

Este refinamiento permite detectar alrededor de 2 incidencias diarias de este problema, reduciendo el número de servicios candidatos a 41641.

3.1.7 Asignación de servicios a los viajes programados y actualización de los intervalos de tiempo de las visitas

40352 servicios han sido asignados a un inicio de servicio programado (111 utilizando un vehículo diferente al previsto); mientras que los otros 1289 no lo fueron.

3.1.8 Imputación de grupos de embarque

La aplicación de los criterios descritos en el apartado 2.8 proporciona los siguientes resultados:

- Se ha considerado que el 94,7% de los grupos de embarque informan correctamente de su ruta y parada de autobús.
- El 5% han sido asignados a otra parada que la registrada automáticamente.
- El 0,3% no estaba vinculado a ningún servicio. Es probable que representen casos en los que el estado del vehículo erróneamente reflejaba que viajaba por la línea 1.

3.1.9 Seleccionar los servicios respaldados por suficiente información

Tras considerar los resultados de los apartados 3.1.7 y 3.1.8, se han elegido los siguientes criterios de aceptación, utilizando la nomenclatura de la ecuación (13):

- Para los servicios asignados a un inicio programado (w = True):
    - Aceptar siempre si se ha utilizado el vehículo previsto (p = True).
    - Si se ha utilizado un autobús distinto al programado (p = Falso), exigir al menos 3 grupos de embarque vinculados al servicio ($h \geq 3$).
- Los servicios no programados requerirán más pruebas: al menos tres grupos de embarque y no menos de 12 entradas totales (un tercio del número de paradas de una sub-línea) que avalen su existencia ($h \geq 3 \land h + f \geq 12$).

Aplicando estos umbrales, la metodología reporta una media de 120 y 97 servicios diarios, según se analice un día laborable o no. En el primer caso, el 96,5% de los servicios habían sido previamente planificados, y se materializaron con el vehículo previsto; mientras que el 3% fueron planificados, pero ejecutados con un vehículo diferente; y el 0,5% fueron servicios no planificados. Durante los días no laborables, las ratios correspondientes son del 99,2%, 0,5% y 0,3%; lo que es coherente con el hecho de que los fines de semana y los días festivos suelen ser menos exigentes para el transporte público de la ciudad, lo que se traduce en menos desviaciones del horario para reaccionar a la evolución del sistema de tráfico.

3.2 Análisis de los resultados

3.2.1 Caracterización de los servicios

Esta sección recoge varios ejemplos para ilustrar cómo esta metodología ha mejorado con éxito la caracterización de los servicios que estaban registrados en el IPTS de una manera que dificultaba su consideración.

3.2.1.1 Reconstrucción de un servicio a partir de información fragmentada y errónea

La figura 11 muestra el caso elegido para este análisis. El eje horizontal temporal se ha dividido en tres regiones con un desplazamiento entre ellas para facilitar su visualización:

- El central, donde se representa el servicio real detectado por la metodología y la salida prevista (5). Su eje temporal se ha colocado en la parte inferior del gráfico.
- La zona más a la izquierda, con su eje temporal situado en la parte superior de la figura. Incluye los datos brutos pertinentes de AVL y AFC, con un desplazamiento de -20min:
    - 4 identificadores de viaje AVL
        - (1): Desde “Arsenio Odriozola 16” hasta “San Fernando 66”, con un espacio de casi 1h entre “Plaza de Italia” y “Luis Martínez”.
        - (2): Desde “San Martín” hasta “Pctcan”, solapando con (1) a lo largo de sus primeras 9 paradas, faltando datos en “Avenida de Valdecilla” y “Torres Quevedo 22”.
        - (3): Un único evento, en la “Plaza de Italia”.
        - (4): Un único evento, en 'Pctcan', la última parada del servicio. Ocurre alrededor de medio minuto antes de que termine (2).
    - 19 eventos de AFC, que se producen entre la “Plaza de Italia” y “José Mª Cossío 24”.
- La zona de la derecha sólo contiene las horas de llegada y salida claramente no relacionadas registradas por el subsistema de planificación (6), con un desplazamiento de -40min.

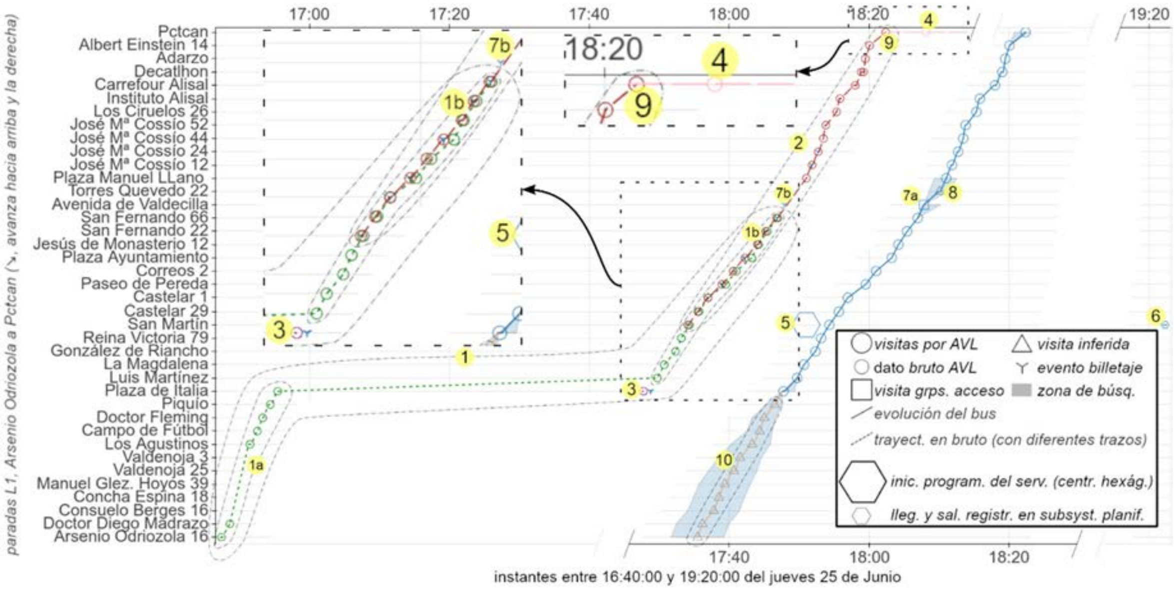


Figura 11: Caracterización de un servicio con información fragmentada y errónea

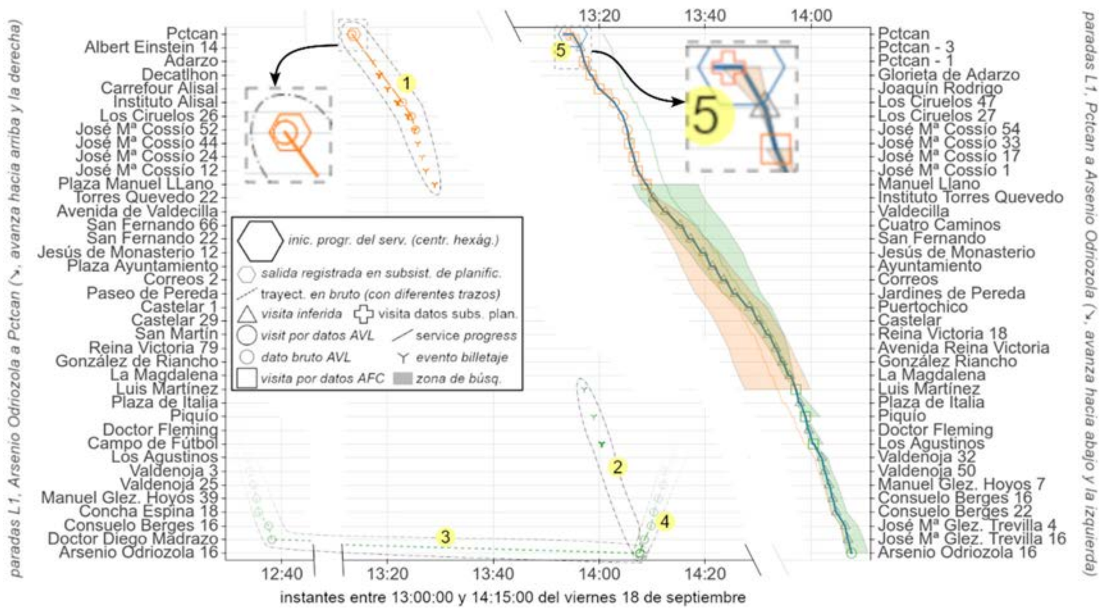


Figura 12: Caracterización de un servicio cuya id de vehículo cambia mientras sucede

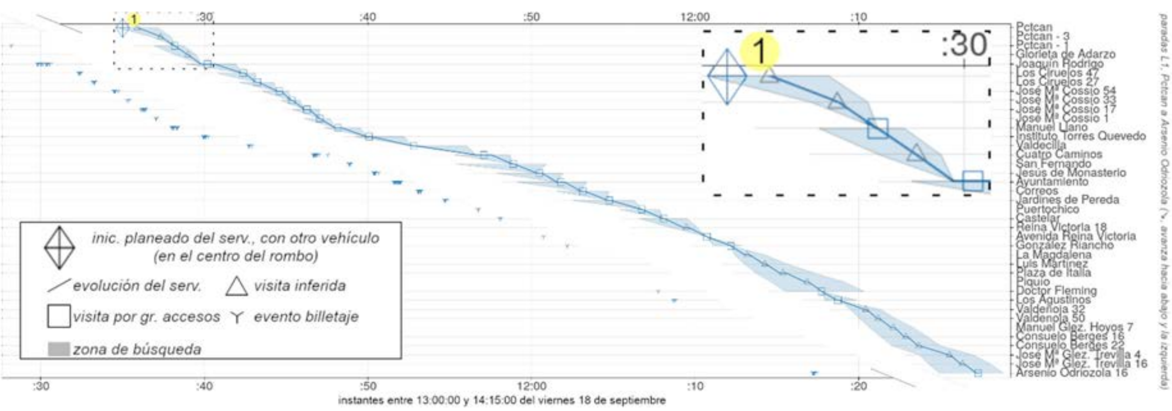


Figura 13: Servicio con sólo datos AFC. El vehículo utilizado no fue el previsto

El servicio propuesto se ha construido haciendo uso de la información disponible. La primera parte del viaje 1 se ha considerado como 2 fragmentos diferentes, descartando el primero (1a, que probablemente se debe a un estado incorrecto del vehículo) y utilizando el segundo (1b). Después de la última entrada de 1, la escala en “Avenida Valdecilla” (7a) se aproxima a partir de un evento de billetaje (7b); y la de “Torres Quevedo 22” (8) se infiere considerando las horas de salida y llegada de la parada anterior y siguiente, respectivamente. De las dos posibles llegadas a la terminal final (9), la del viaje 4, que ocurre 30s antes, es más probable según la hora de salida de “Albert Einstein 14” y la distribución de tiempos de viaje entre estas paradas durante el periodo de tiempo [17:30-18:00] en un día laboral.

Cabe destacar que, aunque el servicio estaba programado para comenzar en “San Martín”, la metodología ha detectado con éxito que en realidad comenzaba unas paradas más arriba (en “Plaza de Italia”, a partir del viaje 3). La búsqueda de eventos anteriores (10) no devolvió ninguna coincidencia.

3.2.1.2 Cambio de id de vehículo a mitad de servicio

La figura 12 muestra cómo aparece la información relativa a un servicio de la sub-línea de Pctcan a Arsenio Odriozola en el IPTS, y su caracterización por esta metodología. De nuevo, el eje temporal horizontal se ha dividido en tres zonas:

- La zona de la derecha, que contiene, con el eje temporal en la parte superior, los dos servicios detectados inicialmente, cómo se han combinado y el inicio previsto vinculado a ellos.
- Las regiones del centro y de la izquierda muestran, con desplazamientos de -40min y -20min y sus ejes temporales en la parte inferior, los registros brutos pertinentes.

Inicialmente, el paso 2.5 de la metodología había encontrado dos servicios:

- Uno para el vehículo 14 (naranja), respaldado por una trayectoria de 4 paradas, y varios eventos de billetaje (1), siendo el último en "Manuel Llano".
- Otro para el vehículo 224 (verde), deducido de 4 eventos de billetaje en 3 paradas (2 , el más temprano en “Luis Martínez”), y cualquiera de los dos eventos en bruto de AVL con la misma marca temporal en la terminal “Arsenio Odriozola 16”, que forman parte de trayectorias opuestas que terminan (3) o comienzan (4) en ese lugar.

Se ha detectado, como se describe en el apartado 2.6, que estos servicios están formados con información parcial de uno que los engloba (se muestra con una línea azul más gruesa). Su correspondiente entrada en el subsistema de programación (5) sólo ha detectado la salida del vehículo, un poco más tarde que los datos de AVL disponibles en esa parada. Como está dentro del rango de viabilidad de “Pctcan – 1”, se acepta y se utiliza para actualizar la hora de salida en “Pctcan”, y para mejorar la llamada inferida en la parada intermedia “Pctcan – 3”.

3.2.1.3 No hay datos de AVL y la identificación del vehículo es incorrecta

La figura 13 muestra un caso que ilustra dos situaciones que se dan en el caso de uso: que el subsistema AVL no registre ninguna entrada y que un vehículo diferente al previsto realice el servicio.

Hay un desplazamiento de 10 minutos entre el lugar donde se dibuja el servicio y la salida programada (parte derecha, eje temporal en la parte superior), y donde se encuentran los datos brutos del AFC (a la izquierda, eje temporal en la parte inferior). Se puede observar (1) que, como el subsistema de planificación no registró el inicio del servicio, las escalas en "Pctcan" y "Pctcan - 3" tuvieron que inferirse utilizando la llegada a "Pctcan - 1" como punto fijo.

3.2.2 Tratamiento de las terminales donde se inician los servicios

El objetivo de esta sección es estudiar el beneficio de la forma en que esta metodología maneja los datos disponibles en los terminales especialmente problemáticos, como ocurre en esta ruta. Para ello, los 25466 servicios que presentan tiempos de salida registrados del subsistema de planificación que, como se describe en el apartado 2.7, han sido aceptados para su caracterización, se utilizarán como verdad de base para compararlos con los resultados obtenidos en tres escenarios en los que no se tendrá en cuenta esa información:

(A): Sigue el comportamiento de la metodología por defecto para una ruta cuando el subsistema de programación no registró el inicio de un servicio.

(B): Si los datos de la primera parada se consideran creíbles, utilícelos de la misma manera que en cualquier otra parada.

(C): Si el inicio planificado de un servicio cae dentro de su rango de búsqueda (tabla 10c) correspondiente (ya almacenado, o calculado utilizando la escala más cercana del servicio sustentada en datos reales), se utilizará como salida, si ocurre más tarde que cualquier entrada AFC o AVL disponible. Esto equivale a suponer que el cumplimiento del horario es lo suficientemente estricto como para confiar en las horas de salida previstas, a menos que sean imposibles o muy improbables.

La figura 14 muestra las distribuciones del error absoluto de la hora de salida del servicio comunicada en los escenarios A y C. Los servicios se han clasificado en función de su “espacio vacante”: a qué distancia (medida en tramos de viaje) se encuentran sus primeras visitas basadas en los datos de AVL o AFC respecto a sus inicios programados. Como puede observarse, la decisión de basarse en la hora de inicio inferida en lugar de la prevista proporciona aproximaciones con menor dispersión (desviaciones estándar de 13s y 17s, respectivamente) y un menor error medio absoluto (MAE), aunque a medida que aumenta la incertidumbre (más llamadas desconocidas entre el inicio del servicio y el primer punto de datos) esta ventaja disminuye.

Los escenarios A y B sólo difieren para aquellos servicios en los que se pueden encontrar datos AVL o AFC compatibles en la primera parada programada (espacio vacante cero). La figura 15 muestra sus distribuciones de errores absolutos en este caso. De nuevo, el escenario A infiere los datos que faltan con menos dispersión (desvíos estándar de 15s y 17s, respectivamente) y MAE (11s frente a 13s).

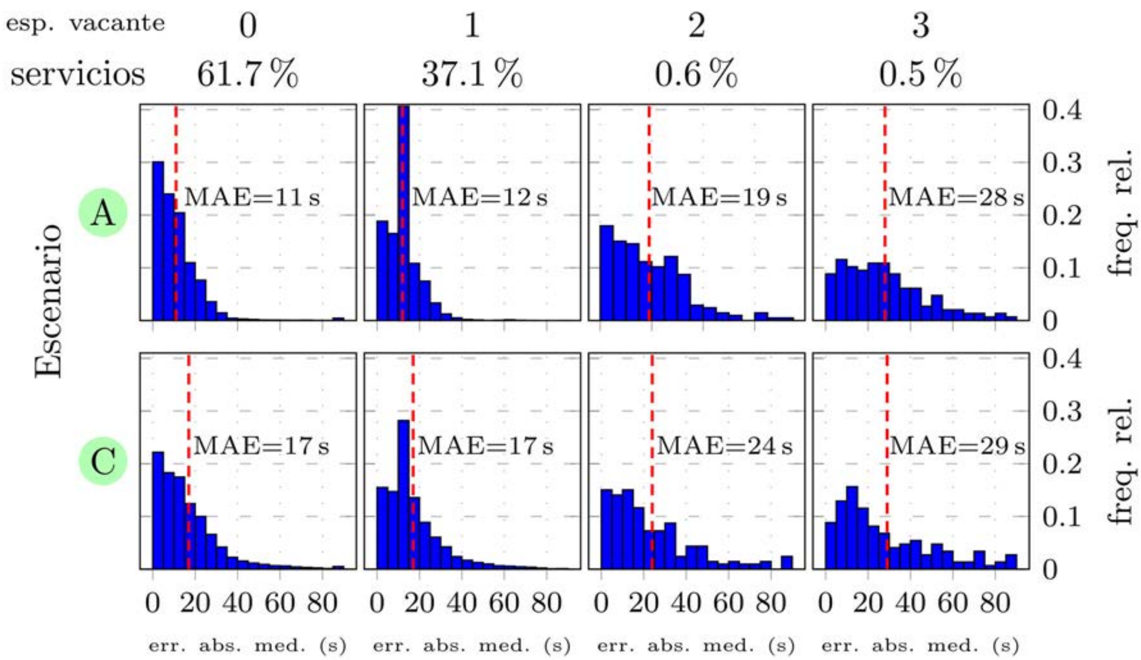


Figura 14: Distr. de errores abs. de hora de salida para los escenarios A y C

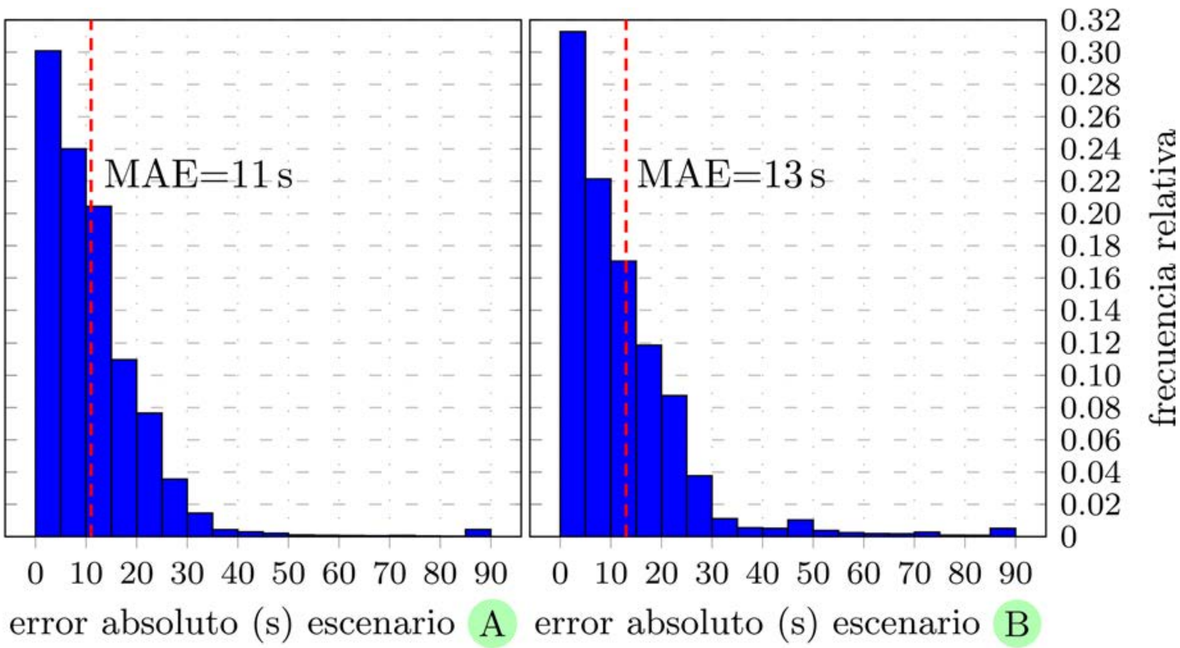


Figura 15: Distr. de los errores abs. de la hora de salida en los escenarios A y B

3.2.3 Solidez frente a los datos ausentes y erróneos

En esta sección se analiza cómo afecta a la metodología información de AVL y de detección del inicio del servicio incompleta y errónea (los eventos de emisión de billetes están totalmente disponibles en todos los escenarios). Los 16863 servicios en los que los subsistemas de planificación y AVL registraron todas las escalas (el 49% del total) se utilizarán como datos reales; y se compararán con los resultados de ejecutar esta metodología utilizando sólo una parte de los datos AVL brutos registrados y de las detecciones del subsistema de planificación, elegidos mediante un muestreo Bernoulli; añadiendo también diferentes cantidades de lecturas erróneas AVL sintéticas, que se han generado aleatoriamente siguiendo estas reglas:

- La *parada*, el *vehículo* y la *UID de grupo* se eligen entre todos sus valores presentes.
- *Instante* ocurre entre las 07:00 y las 23:00 de cualquier día del año.
- El muestreo de la distribución de duraciones se simula utilizando sus percentiles y la Distribución Uniforme.

En la fig. 16, los porcentajes son relativos a las lecturas de AVL en bruto y a los servicios planificados disponibles en el conjunto de datos. Por ejemplo, un escenario con un 25% de datos reales y un 75% de errores simulados sólo lee la llegada y la salida de los vehículos en la parada inicial registrada por el subsistema de programación en el 25% de los servicios programados; mientras que sus registros de AVL en bruto se crea combinando un muestreo de Bernoulli de la información real con una probabilidad del 25% y una cantidad tres veces superior de entradas falsas.

A medida que se dispone de más datos reales en un escenario, los servicios se caracterizan con mayor precisión. Por ejemplo, con una muestra relativamente pequeña (25%), si bien el percentil 99 no difiere significativamente de no utilizar AVL o de detectar el inicio del servicio en absoluto (algo menos de 7min), ya se puede apreciar que el MAE es bastante más probable que sea menor: el cuartil inferior, la mediana y el cuartil superior se reducen de 4s, 9s y 24s a 0s, 4s y 13s, respectivamente (A y B).

También es notable la resistencia de la metodología contra las entradas incorrectas artificiales, que crece a medida que se dispone de más lecturas verdaderas en el escenario. Dos ejemplos son:

- Con sólo el 25% de los datos reales, añadir cuatro veces más entradas erróneas sólo aumenta el cuartil superior de 6m50s a 7m7s (B y C).
- Si toda la información real está disponible, la metodología identifica con éxito los valores correctos como semillas, y es capaz de ignorar por completo muchos eventos falsos (D y E).

4. CONCLUSIÓN

La metodología descrita en este trabajo es capaz de combinar la información del AFC, del AVL y del subsistema de programación para proporcionar una mejor caracterización de los servicios de las rutas ofrecidas en un Sistema de Transporte Público; mejorando los problemas que comúnmente ocurren cuando se trabaja con datos del IPTS. Los eventos cuyos atributos los clasifican erróneamente como parte de diferentes servicios son identificados y tratados adecuadamente, así como aquellos que probablemente no hayan ocurrido realmente. Las escalas en cada parada de cada servicio se delimitan combinando las múltiples fuentes de datos disponibles en ese caso concreto, proporcionando las horas de llegada y salida más probables si no las hay. Asimismo, se formula una forma de detectar y tratar aquellos casos en los que un vehículo cambia su identificación a mitad de servicio, lo que llevaría a una tergiversación de su perfil de carga.

Se ha presentado un estudio de caso, en el que varios ejemplos ilustran algunos de los problemas que resuelve esta metodología (información fragmentada y errónea, cambio de identificación del vehículo a mitad de servicio y caracterización de un servicio no planificado utilizando únicamente datos AFC). También se utiliza para analizar la repercusión de la forma en que se tratan los datos de los terminales y cómo se comporta la metodología con diferentes proporciones de información buena y errónea.

Como próximo objetivo, los autores están trabajando actualmente en la aplicación de la metodología de cadenas de viaje con los eventos de billetaje y los servicios caracterizados por esta metodología, para proporcionar perfiles de carga de vehículos y matrices OD más precisos. Otras posibles líneas de investigación son la utilización de otras distribuciones para modelar los tiempos de permanencia y de viaje, o la aplicación de modelos más detallados para estimar a partir de los eventos de billetaje la llegada y la salida en una parada cuando no se dispone de registros AVL.

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ANÁLISIS DE LA INFLUENCIA DE LA RESERVA DE PLATAFORMA EN LAS OPERACIONES DE UN SISTEMA DE AUTOBÚS

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RESUMEN

La reducción del tiempo de viaje en transporte público y la mejora de su fiabilidad constituyen elementos fundamentales para la captación de usuarios no cautivos. Para alcanzar estos objetivos en sistemas de transporte público en superficie, especialmente en situaciones de frecuente congestión, una estrategia adecuada es la reserva de plataforma. Sin embargo, estas reservas se encuentran en ocasiones con una fuerte contestación por parte de la opinión pública, especialmente por los perjuicios inmediatos que se provocan a algunos ciudadanos, debido fundamentalmente a la reducción de espacio para la circulación y estacionamiento del vehículo privado. Por ello, los técnicos deben aportar cuantificaciones lo más precisas posible de los beneficios de la plataforma reservada para el sistema de transporte público y sus usuarios.

El objetivo del trabajo que se expondrá en esta ponencia es avanzar en la cuantificación de la influencia de la existencia de un carril bus en algunas variables de operación del sistema. Se analizan las variaciones en los tiempos de viaje o en la propia variabilidad del tiempo de recorrido entre situaciones con carril bus y situaciones de referencia en plataforma compartida.

Como caso de estudio se presenta el carril bus en la ciudad de A Coruña, que se implantó en el año 2008 y se retiró finalizando el año 2011, siendo sustituido por una vía prioritaria vigilada con priorización semafórica y control del aparcamiento indebido. A partir del análisis estadístico de la información recogida en la base de datos del Sistema de Ayuda a la Explotación, se analizan los tiempos de viaje y su variabilidad en tres años de comparación. Se realiza un estudio desde una perspectiva temporal, durante y después del periodo en el que funcionó la reserva de plataforma, y desde una perspectiva transversal, comparando con la situación en otras líneas o tramos que no empleaban el carril bus. Se ha obtenido que el tiempo medio de recorrido tras retirar el carril bus aumentó en un 14% y el coeficiente de variación aumentó en un 46%. Para el caso de estudio, los viajes con una duración mayor de 6 minutos pasaron del 3,57% al 18,67%. La influencia de la reserva se cuantifica tanto para días hábiles como no hábiles. Los tramos de contraste no han mostrado variaciones relevantes en las variables analizadas en el mismo periodo.

1. INTRODUCCIÓN

Uno de los pilares para alcanzar una movilidad sostenible en las áreas urbanas y metropolitanas es el fomento de la utilización del transporte público. En conjunción con otras medidas, esta utilización es uno de los instrumentos relevantes para alcanzar los objetivos establecidos en el acuerdo de París. Dentro del transporte público, el autobús convencional juega un papel fundamental en la movilidad de las ciudades pequeñas y medianas, así como en ciertas relaciones de baja demanda en grandes áreas metropolitanas. Los sistemas BRT y BHLS pueden prestar servicios de capacidad alta o media en estos contextos mediante la implantación de medidas específicas de reserva de plataforma y explotación. Aumentar el atractivo del autobús, especialmente para captar a los viajeros no cautivos, constituye por tanto una medida deseable dentro de la política de transporte.

Los sistemas de autobuses en plataforma compartida tienen el inconveniente de que sufren los efectos de la congestión del tráfico, lo que repercute en los tiempos de viaje en esas situaciones y en la fiabilidad del cumplimiento de horarios. Esta incertidumbre supone un inconveniente añadido para el viajero, especialmente en los viajes pendulares al trabajo o estudios, dado que tiene que adelantar su salida para aumentar la probabilidad de llegar puntualmente a su destino.

Con el fin de promover el uso de los sistemas de autobuses, mejorando sus tiempos de viaje, comodidad de uso, visibilidad y fiabilidad, la reserva de plataforma es una de las medidas fundamentales. Estas reservas abarcan desde simples carriles de uso reservado señalizados con pintura, con potenciales problemas de respeto, hasta separaciones físicas de una parte de la calzada reservada al transporte público, en ocasiones compartida con otros usuarios como taxis o bicicletas.

Estas reservas de plataforma suponen en general la disminución de espacios para el aparcamiento y para la circulación del tráfico general. Por este motivo, es frecuente que sufran una contestación importante por parte de algunos colectivos. Se considera relevante disponer de medidas empíricas que permitan cuantificar los beneficios para la operación de los autobuses que supone una reserva de plataforma. Una herramienta adecuada para este fin es el empleo de datos de funcionamiento de las operaciones en presencia y en ausencia de una reserva de plataforma.

En la presente ponencia se analiza la influencia en los tiempos de viaje del autobús y en su variabilidad de un caso de estudio singular, dado que se refiere a la retirada de una plataforma reservada existente en la ciudad de A Coruña. En el segundo apartado se revisa el estado del conocimiento, en el apartado 3 se presenta el caso de estudio, en el apartado 4 se expone la metodología empleada y se analizan los resultados obtenidos. Se finaliza con unas conclusiones y unas líneas abiertas de trabajo.

2. EFECTOS DE LAS PLATAFORMAS RESERVADAS EN LAS OPERACIONES

Diversos estudios han puesto de manifiesto que la fiabilidad del servicio, el tiempo de viaje en el vehículo y el tiempo de espera (condicionado por la frecuencia del servicio y también por el cumplimiento de los horarios programados) están entre los factores que los usuarios valoran en el momento de elegir un sistema de transporte público frente al vehículo privado. Para una revisión de la literatura acerca de los atributos de calidad que atraen a los usuarios del coche puede consultarse Redman et al. (2013).

En lo relativo a la influencia de la plataforma reservada en el tiempo de recorrido y en la fiabilidad, existen diversos análisis estadísticos de esta influencia. Tanaboriboon y Toonim (1983) analizaron el impacto de diferentes carriles para autobús en Bangkok, con longitudes entre 1,2 y 6,3 km y tiempos de recorrido entre 5 y 15 minutos. Los análisis se llevaron a cabo con medidas manuales en las horas punta de mañana y tarde. Sus resultados muestran un rango de variación amplio, con reducciones del tiempo medio de viaje entre 0,7% y 23% según corredor, sentido y horario.

Arasan y Vedagiri (2010) analizaron mediante microsimulación un carril reservado de 10 km, sin interferencia del tráfico general en las intersecciones ni prioridad semafórica. Obtuvieron como resultado una reducción del tiempo de recorrido de los autobuses de alrededor de un 15% en condiciones de nivel de servicio C, lo que es equivalente en ese caso a un aumento del 17,8% sin plataforma reservada. Para el nivel de tráfico correspondiente a la capacidad de la infraestructura, la reducción obtenida fue del entorno del 70%. Es evidente que la plataforma reservada no va a tener efecto en ausencia de tráfico.

Surprenant-Legault y El-Geneidy (2011) estudiaron el impacto de añadir un carril reservado para autobuses en dos rutas paralelas en Montreal. Analizando un tramo de 6,82 km con carril bus obtuvieron que la inclusión de la reserva de plataforma supuso un ahorro entre el 1,3% y el 2,2% en el tiempo de recorrido total según la dirección. Llamativamente, los coeficientes de variación del tiempo de recorrido total aumentaron en una de las direcciones de viaje para las dos rutas tras la implementación de la reserva de plataforma, mientras que disminuyeron en dirección contraria, lo que atribuyen a las circunstancias del caso. Como señalan estos autores, un coeficiente de variación bajo facilita la programación de horarios e incrementa la fiabilidad y el cumplimiento de horarios. El estudio posterior de Diab y El-Geneidy (2013) incide en modelizar la influencia de los diferentes factores y medidas tanto en los tiempos de viaje como en su variabilidad. Este nuevo estudio obtiene que el carril exclusivo supone un 2,7% de ahorro en el tiempo de viaje y una reducción del 4,3% en la desviación respecto a la programación, pero un 0,5% más de varianza del tiempo de viaje, que atribuyen a las colas de vehículos delante del autobús en los giros.

3. CASO DE ESTUDIO

El caso de estudio corresponde a la red de autobuses de la ciudad de A Coruña. La red está explotada por la Compañía de Tranvías de La Coruña (CTC), operador privado histórico constituido en 1901 que opera el transporte urbano de la ciudad desde 1903 (Martínez y Piñeiro, 1997). La red está constituida por 23 líneas diurnas y una nocturna. En el año 2019 transportó 23.003.516 viajeros, con un incremento de 5,08% respecto a 2018 (Compañía de Tranvías de La Coruña, 2020). En 2020, como consecuencia de la pandemia, la cifra de viajeros descendió un 40,8% hasta los 13.623.457 (Compañía de Tranvías de La Coruña, 2021). Puede encontrarse un análisis del efecto de la pandemia en esta red en Orro et al. (2020).

Es habitual que la implantación de una reserva de plataforma venga acompañada de cierta reordenación de las líneas, así como de medidas complementarias de apoyo a la circulación de los autobuses. El objeto de este análisis es el carril bus que se implantó en la ciudad en el año 2008. Tras decidirse su eliminación, los separadores físicos se retiraron a mediados de diciembre del año 2011, lo que constituye una circunstancia poco frecuente en los últimos años. Esta retirada permite estudiar el funcionamiento de las líneas durante la existencia de la reserva de plataforma y en el periodo posterior a su retirada, en el que durante cierto tiempo se mantuvo la misma configuración de las líneas.

Debe señalarse que una vez retirado el carril bus se estableció en el tramo afectado lo que se denominó una “Vía prioritaria vigilada” (VPV), en la que se estableció un especial control de los estacionamientos indebidos, así como un sistema de priorización semafórica del transporte público (Villas, 2012). Este sistema de priorización semafórica se activaba para aquellos autobuses que estuviesen retrasados. Sin embargo, la reducida distancia entre intersecciones y el número de paradas no permiten esperar una gran eficiencia de este sistema, especialmente en situaciones de tráfico congestionado. El proceso de implantación se realiza desde diciembre de 2011 hasta mediados de marzo de 2012 en que entran en funcionamiento las cámaras de vigilancia.

La comparación se va a establecer por tanto entre una reserva de plataforma y una situación posterior de calle con especial atención a la fluidez del tráfico. Se van a tomar como referencias temporales tres años. El primero es el año 2010, con el carril bus en pleno funcionamiento, como valor correspondiente a la reserva de plataforma. El segundo es el año 2012, una vez culminada la retirada del carril bus y año en el que se implanta la VPV. Como tercera referencia temporal se incluirán datos del año 2014, donde es previsible una cierta relajación en la supervisión de la VPV.

El carril bus constaba de varios tramos. Se ha seleccionado como tramo objeto de estudio el comprendido entre las paradas 194 y 197 de la red, correspondiente al trayecto por la calle Federico Tapia y posteriores, en el centro de la ciudad, en el que posteriormente se implantó la VPV incluyendo la priorización semafórica. Las líneas que transcurrieron por el tramo en algún momento del periodo de estudio fueron 4, 6, 6A, 11, 21, 23, 24 y UDC (línea especial a la Universidad de elevada frecuencia y utilización en periodo lectivo). La longitud del tramo es de 945 m con distancias entre paradas de 351 m, 300 m y 294 m. Existen 6 intersecciones semaforizadas en el tramo.

La calle es de dirección única, el carril bus estaba ubicado a la derecha de la sección y separado del carril de circulación mediante un separador físico de tipo “aletas de tiburón”. En la mayor parte del tramo la sección con carril bus incluía un carril de circulación y una línea de aparcamiento en la margen izquierda de la calzada. El carril bus podía ser empleado por los taxis, las motocicletas y las bicicletas. En la situación con VPV se disponía de dos carriles de circulación y aparcamiento a ambos lados de la calzada. Ambas situaciones pueden observarse en la Figura 1, en la que se pueden observar las marcas viales de color naranja que denotan la VPV.

Figura 1: Sección de la calle Federico Tapia con carril bus (2010) y con la VPV (2012)

Con el fin de aislar en lo posible la influencia de la eliminación de la reserva de plataforma de otros efectos provocados por las variaciones de demanda a lo largo del tiempo, se han seleccionado dos tramos de contraste en otras ubicaciones de la ciudad. Los criterios de selección para estos tramos de contraste fueron que tuviesen una configuración viaria, una longitud, una demanda de los servicios de autobús y una distancia entre paradas similar al tramo de Federico Tapia. El primero de los tramos de contraste corresponde a la Avenida Salvador de Madariaga (paradas 380 a 383) y el segundo a la Avenida de Oza (paradas 29 a 32). En la Figura 2 se puede observar la ubicación de los tramos dentro de la ciudad, así como las paradas y la distancia entre ellas en el tramo de Federico Tapia.

Figura 2: Ubicación de los tramos de estudio y detalle del tramo de Federico Tapia

4. METODOLOGÍA Y RESULTADOS

4.1 Metodología

La fuente fundamental de información para el desarrollo del análisis es la base de datos del Sistema de Ayuda a la Explotación de la CTC. Se han realizado las consultas correspondientes para obtener los instantes de paso por cada una de las paradas de los tramos objeto de estudio de todas las expediciones que realizaron esos trayectos en los periodos estudiados. Se ha recopilado también la información del número de viajeros que subieron en cada parada, que serán empleados en desarrollos posteriores. Se ha realizado el proceso de curación de los datos para eliminar registros erróneos y un preproceso de la información para estructurarla adecuadamente poder realizar los análisis de tiempo de recorrido.

Tras los análisis de consistencia de los datos se ha decidido eliminar el periodo comprendido entre octubre y diciembre de 2012 en todos los tramos, debido a que en la Avenida Salvador de Madariaga se realizaron obras que mantuvieron las paradas sin servicio.

Una vez depurados los datos se dispone de una muestra total para el tramo de estudio de 47.863 expediciones en 2010, 46.591 expediciones en 2012 y 45.611 expediciones en 2014. A efectos de análisis se emplearán tanto los datos generales como separados por días hábiles y no hábiles.

4.2 Tiempo de recorrido en el tramo con plataforma reservada

En la Tabla 1 se muestra la estadística descriptiva de la distribución de los tiempos de recorrido en el tramo en el que estuvo funcionando el carril bus. Los datos de 2010 corresponden a la situación con plataforma reservada, mientras que los datos de 2012 y 2014 corresponden a la situación sin reserva de plataforma y con VPV.

Como se ha señalado, la finalidad habitual de establecer una reserva de plataforma es evitar el efecto de la congestión en el transporte público. A lo largo de la semana, lo habitual es que las horas con congestión significativa se concentren en determinados horarios, generalmente en días hábiles. Por este motivo, la presencia de una reserva de plataforma va a reducir principalmente los viajes con tiempos de recorrido elevados. Es fundamental para el análisis representar la distribución de los tiempos de viaje. Para ello, en la Figura 3 se muestran los histogramas de los tiempos de recorrido y las estimaciones de densidad *kernel*, además de la media y la mediana en cada uno de los años.

	General			**Días hábiles**			**Días no hábiles**		
Año	**2010**	**2012**	**2014**	**2010**	**2012**	**2014**	**2010**	**2012**	**2014**
Media	265.54	293.62	302.67	273.08	308.38	316.16	241.93	248.66	258.93
Mediana	260	278	288	264	303	306	240	244	250
Moda	260	250	250	260	250	258	240	242	242
Min.	93	98	96	93	110	108	96	98	96
1erQ	236	243	250	244	250	261	210	214	220
3erQ	298	336	344	308	344	356	268	275	290
Máx.	1659	2432	1479	1659	2432	1479	885	1884	1466
SD	54.36	87.51	85.82	53.53	87.23	84.85	49.99	71.58	73.47
CV	0.205	0.298	0.284	0.196	0.283	0.268	0.207	0.288	0.284
n	47863	46591	45611	36282	35076	34856	11581	11515	10755
sesgo	1.63	3.25	1.85	1.80	3.25	1.64	1.59	5.38	3.90
curtosis	21.95	41.46	10.71	27.34	43.30	8.43	13.15	82.84	39.48

Tabla 1: Parámetros de centralidad y dispersión de la variable tiempo de recorrido en el tramo de la calle Federico Tapia (paradas 194 a 197)

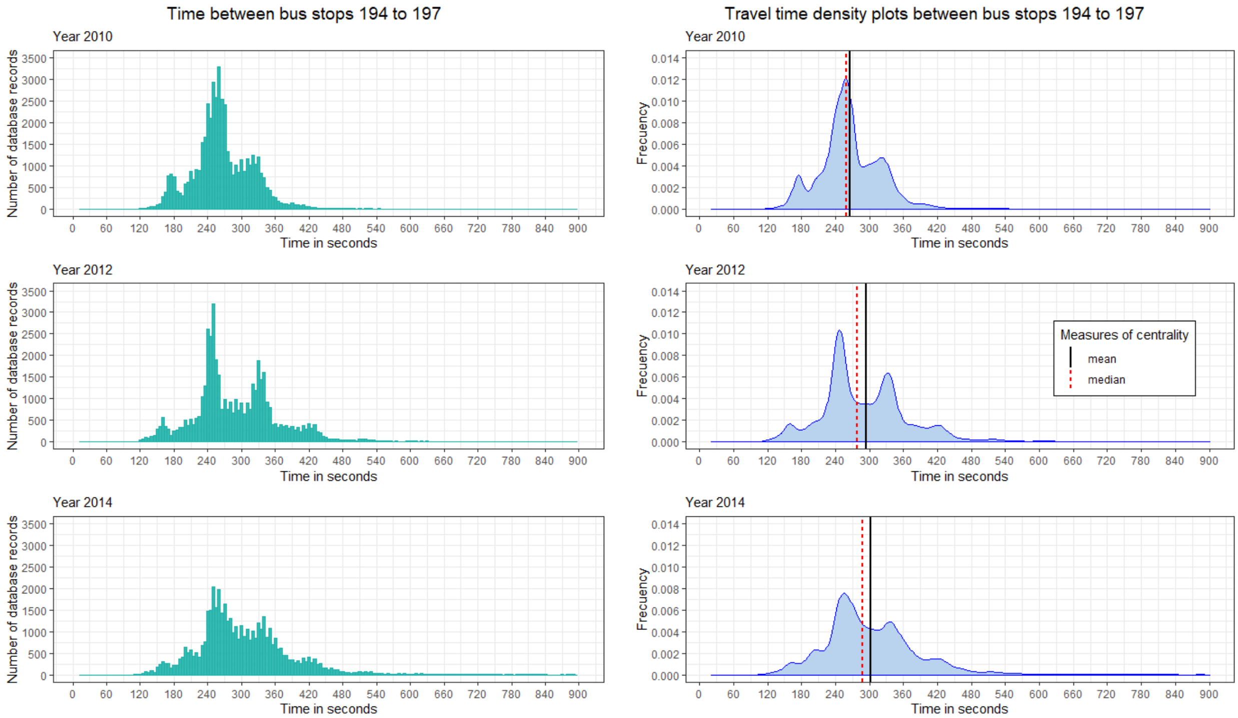

Figura 3: Histograma y estimador de densidad *kernel* del tiempo de recorrido en todos los días de la semana en el tramo de la calle Federico Tapia (paradas 194 a 197)

Como se puede observar, mientras funcionó la plataforma reservada, la media y la mediana de la distribución de los tiempos de recorrido son inferiores a la situación una vez que se elimina el carril bus. Los 945 m del tramo se recorren en las condiciones más rápidas en 93 segundos, pero los tiempos medios en el año estudiado con funcionamiento del carril bus fueron de 265,54 segundos.

El tiempo medio de recorrido del tramo aumentó entre 2010 (con carril bus) y 2012 (con la VPV recién implantada) en 28,08 segundos, con notables variaciones entre los días hábiles (35,3 segundos) y los días no hábiles (6,73), lo que es un resultado esperable al existir menor congestión en esos días. Si se compara la situación con carril bus en 2010 con la situación en 2014, donde es posible que el grado de supervisión de la VPV se haya reducido, el incremento medio del tiempo de viaje en el tramo es de 37,13 segundos (43,08 s en días hábiles y 17 s en días no hábiles). Si se evalúa en términos porcentuales, el tiempo medio de recorrido en general aumentó un 14,0% entre 2010 y 2014, valor que sube a 15,8% en días hábiles frente a un 7,0% en días no hábiles. En estas variaciones pueden influir otros factores, como podría ser una variación global del tráfico o de la demanda del autobús. El estudio de tramos de contraste presentado en el apartado 4.3 permite descartar cambios importantes debidos a la evolución temporal.

Como puede comprobarse, los valores obtenidos están en consonancia con los presentados en la revisión de la literatura por Tanaboriboon y Toonim (1983) y por Arasan y Vedagiri (2010), mencionados anteriormente, mientras que el efecto del carril bus es mucho más relevante que en el caso estudiado en Surprenant-Legault y El-Geneidy (2011) y Diab y El-Geneidy (2013).

Cuantificando la variabilidad involucrada, se observa cómo el coeficiente de variación general aumenta desde 0,205 en 2010 a valores de 0,298 y 0,284 en 2012 y 2014 respectivamente, lo que permite cuantificar el aumento de la variabilidad del tiempo de recorrido entre un 39% y un 46% de su valor, con porcentajes de incremento similares en días hábiles y no hábiles. Resulta de interés el análisis detallado de las distribuciones de los tiempos de viaje. Como puede observarse, la distribución es multimodal, observándose con claridad en algunos de los periodos dos modas y con otras de menor magnitud. La separación entre estas modas sugiere que pueden estar asociadas a los ciclos semafóricos. Debe tenerse en cuenta que, en situaciones de congestión sin reserva de plataforma, las colas en los semáforos y su tiempo de disipación pueden provocar que todos los autobuses tengan que sufrir un retraso aun cuando en flujo libre hubiesen encontrado el semáforo abierto. En ocasiones puede ser insuficiente la capacidad de la fase verde del semáforo para eliminar toda la cola y debe esperar un ciclo adicional. Como se ha mencionado, existen dudas sobre la efectividad de la priorización semafórica con la configuración de la zona.

En la situación con plataforma reservada, la mayor parte de los viajes se concentran en el entorno del tiempo medio y de la mediana en 260 – 265 segundos. Sin embargo, cuando se elimina el carril bus, además de subir el tiempo medio al entorno de los 300 segundos, los viajes se dispersan hacia la derecha de la distribución, apareciendo un primer pico relevante en torno a 240 s, un segundo pico en torno a 340 s e incluso se aprecia un tercer pico en torno a los 420 segundos. Existe un número relevante de valores que presentan tiempos de recorrido elevados, lo que no ocurría en el caso de existencia de un carril reservado para autobuses.

La distribución acumulada de los tiempos de viaje puede observarse en la Figura 4. En la situación de 2010, con la plataforma reservada, el 99,33% de los autobuses realizaban el recorrido en menos de 7 minutos. Una vez retirada esta plataforma, el tiempo de recorrido que no es superado por ese porcentaje de autobuses ha subido por encima de los 10 minutos. Con el carril bus, solo el 3,57% de los viajes superaban los 6 minutos, en 2014 el 18,67% de los viajes superaban esa cifra. Mientras que en 2010 el 75,28% de los viajes tenía una duración de menos de 5 minutos, en 2014 solo el 55,09% de los viajes se completaban en ese tiempo. Debe señalarse que lo esperable es que esos viajes de mayor duración se concentren en las franjas de mayor demanda y con mayor uso por parte de viajeros pendulares, ya que se tratarán de las horas punta de los días laborables. Por un lado, esto va a suponer que el número de viajeros perjudicados por estos incrementos de tiempo sea más elevado. Por otro lado, se trata de un tipo de viajero que requiere una mayor fiabilidad en su tiempo de viaje ya que puede no tener flexibilidad en su hora de llegada a destino, por lo que esta variabilidad va a ir en detrimento de su captación por el transporte público.

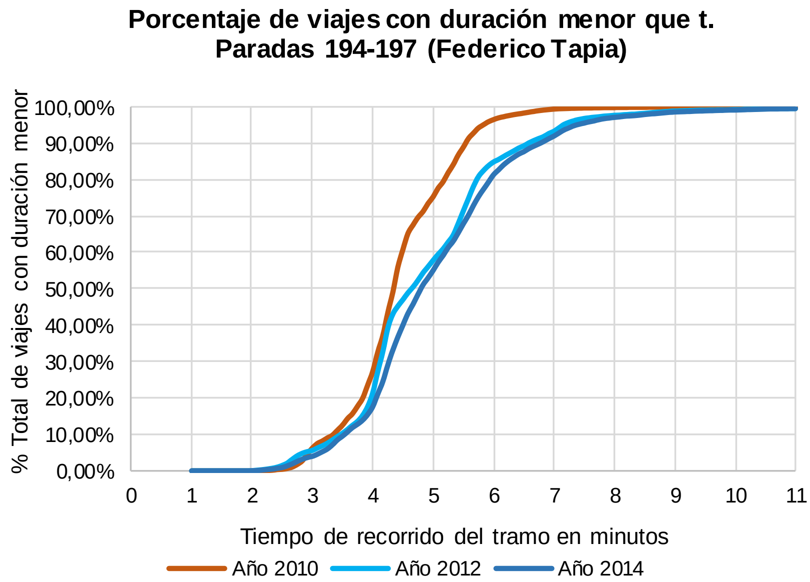

Figura 4: Distribución acumulada de los tiempos de recorrido en el tramo de la calle Federico Tapia (paradas 194 a 197)

4.3 Comparación con los tramos de contraste

Con el fin de verificar si esta evolución de los tiempos de viaje y de su variabilidad en el periodo 2010 – 2014 se puede atribuir principalmente a la retirada del carril bus, se han repetido los cálculos en otros dos tramos de la ciudad, previamente presentados.

En la Figura 5 se puede observar la evolución del tiempo medio de recorrido y del coeficiente de variación en los tres tramos analizados. Puede observarse cómo el notable incremento de la variabilidad en el tramo de la calle Federico Tapia tras la retirada del carril bus no se reproduce en los otros dos tramos, donde permanece aproximadamente estable. Como ya se ha señalado, la influencia de la reserva de plataforma en los tiempos medios es menos notable, pero igualmente se verifica que la tendencia observada en el tramo de la calle Federico Tapia no se observa en otros tramos de la ciudad, por lo es razonable atribuirlo a la influencia de la retirada del carril bus y su sustitución por una VPV.

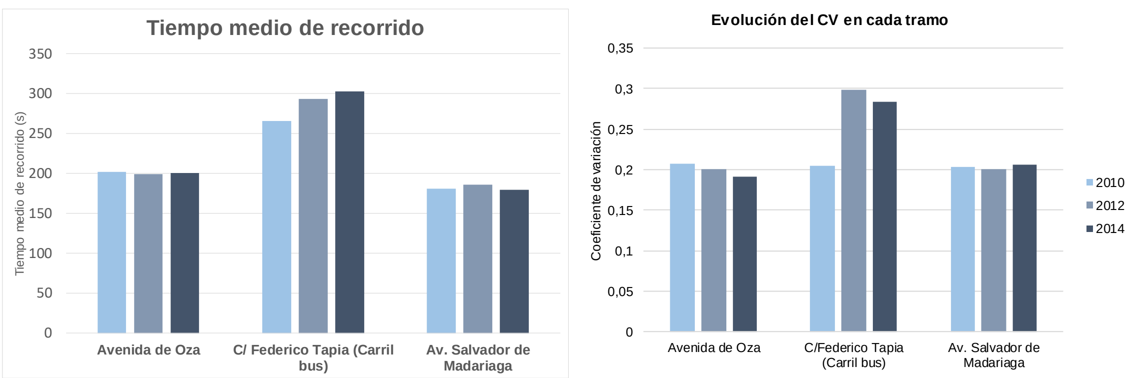

Figura 5: Comparación de tiempos de recorrido y variabilidad con tramos de contraste

Se ha realizado también la comparación de las distribuciones acumuladas, que se muestran en la Figura 6. De nuevo puede observarse que la diferencia que se apreciaba en la Figura 3 no se produce en estos tramos. Puede observarse también cómo estos tramos no están afectados por una congestión acusada, como sí existe en la zona de Federico Tapia, por lo que las gráficas son sensiblemente más verticales, con menores diferencias entre los recorridos más rápidos y los más lentos. Por lo tanto, un carril bus en estas vías tendría poca capacidad de mejorar la situación actual en cuanto a variabilidad del tiempo de recorrido y en cuanto a disminución de tiempos de recorrido. Esto está en consonancia con valores del efecto de la reserva de plataforma muy bajos reportados en otros estudios mencionados en la revisión de la literatura. Este tipo de análisis resulta de utilidad para decidir en qué tramos establecer reservas de plataforma.

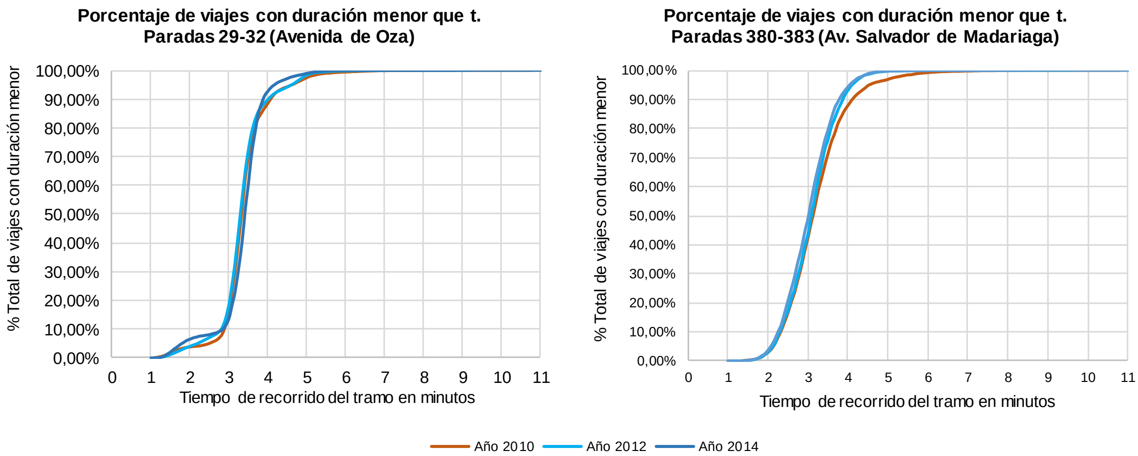

Figura 6: Comparación de distribuciones acumuladas con tramos de contraste

4. CONCLUSIONES

Las plataformas reservadas para el transporte público permiten evitar los efectos de la congestión del tráfico en las operaciones de estos sistemas. Sus ventajas se ponen de manifiesto en aquellas circunstancias en las que existe congestión en el tramo. En viales en que la congestión se produce solo en las horas punta de los días laborables, las plataformas reservadas van a ser más efectivas en eliminar los viajes de mayor duración y en reducir la variabilidad de los tiempos de recorrido que en reducir globalmente los tiempos de viaje promedio. Sin embargo, esos viajes de mayor duración van a producirse en general en los momentos de mayor demanda, lo que es relevante a efectos de evaluar los beneficios obtenidos con esta medida. Adicionalmente, la mayor variabilidad se va a producir en días hábiles y en horas punta, momento en el que es del mayor interés captar a los viajeros pendulares. Estos viajeros suelen tener además un horario fijo de entrada, por lo que el efecto atractor hacia el transporte público de una baja incertidumbre en el tiempo de recorrido puede ser más relevante para el cambio modal.

En el caso de estudio analizado de la ciudad de A Coruña se ha comparado la situación con un carril reservado para autobuses y taxis y un carril de circulación general frente a dos carriles para circulación general con priorización semafórica para los autobuses con retraso y especial vigilancia de los aparcamientos indebidos. La retirada del carril bus ha supuesto un incremento del tiempo medio de recorrido al finalizar el periodo analizado del 14,0% en general y del 15,8% en días hábiles. Desde el punto de vista de la variabilidad, el coeficiente de variación se ha incrementado un 46% en ese periodo. Se han analizado las distribuciones acumuladas, cuantificando la reducción de los viajes de mayor duración. En el caso de estudio los viajes que superan los 6 minutos de duración aumentaron del 3,57% al 18,67%, mientas que los viajes de más de 5 minutos han pasado del 24,72% al 44,91%. Se ha contrastado la variación de parámetros observada en el tramo en el que se ha retirado la plataforma reservada con otros tramos similares de la ciudad, donde se observa que no se han producido modificaciones relevantes en el periodo. El estudio de los histogramas de densidad y las distribuciones acumuladas del tiempo de recorrido pueden ser un instrumento útil para valorar la oportunidad de implantar plataformas reservadas, dado que estas actuarán fundamentalmente sobre los valores más elevados de la distribución.

Entre las líneas de investigación abiertas está el estudio de la distribución horaria de los viajes en los que se producen los mayores ahorros y la evaluación de los pasajeros que se benefician. También resulta de interés analizar la influencia de las operaciones en las paradas según la demanda de subidas y bajadas, el cumplimiento de intervalos, la modelización de los diferentes efectos, la comparación con los valores que se extraen de metodologías de cálculo existentes y la extensión de estos análisis a otros tramos de estudio.

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THE UNDELAYABLE LEGAL REFORM OF PUBLIC PROCUREMENT RULES IN THE MANAGEMENT MODELS FOR THE URBAN TRANSPORT PUBLIC SERVICE IN THE AUTONOMOUS COMMUNITY OF CASTILLA Y LEÓN

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ABSTRACT

The purpose of this paper is, on the one hand, to analyze the management models that Law 7/1985, of April 2, 1985, regulating the Local Regime Bases, offers to the Provincial Capital Cities of the Autonomous Community of Castilla y León in Spain, a Member State of the European Union, for the provision of public urban transport services. And on the other hand, in line with and in relation to the previous premise, to study how it influences and determines, depending on the form of management of the public service of urban transport chosen by each town council, which articles of Law 9/2017, of November 8, on Public Sector Contracts, should be applied.

From the study of these issues, it will be concluded that the level of application of the contractual legislation will not be the same, it will be disruptive and unequal, which requires a necessary legislative modification that equates the application of the contractual regulations, regardless of the model of management of the urban transport public service that the Municipalities decide to adopt.

1. INTRODUCTION

The aim of this research is to analyze the service management models of urban public transport in the provincial capital cities of the autonomous community of Castilla y León in Spain and their relationship with public procurement. We will corroborate that the system for contracting the urban public transport service within these municipalities is different and discriminatory. This treatment shows the violation of the principle of equality in the application of the rule (Carmona, 1994).

2. MODALITIES OF PUBLIC MANAGEMENT OF LOCAL ENTITIES

Spanish local legislation distinguishes two modes of management for local public services (Guayo, 2004): direct management and indirect management.

2.1 Modes of direct management of public services

The forms of direct management of a public service can adopt the following models: Provision of a public service by a local entity, in which the municipality, with its own resources, provides the service; provision of a public service by a local autonomous agency, in which an entity with legal personality (Quintana, 1992), dependent on the municipality, provides the public service; Public service's provision by a local Public Business Entity, according to which it is a separate and distinct entity from the municipality to which the service provider depends and is financed mainly by market income; and public service provision by a local Mercantile Society, according to which it is a private legal entity that provides the service and its assets must be public, either completely owned by e municipality, participated by it or owned by other public entities (Melania, 2011).

A recent legislative amendment established direct management as a preference over indirect management (Fernández, 2016). If the municipality opts for indirect management, it must be approved by the Plenary of the Local Government (Huergo, 2019).

2.2 Modes of indirect management of public services

The choice of municipalities for the forms of management is a prerogative of their local autonomy, constitutionally guaranteed (Fernandez-Miranda, 2008). When the municipality decides on the indirect management of a public service, the choice of the private or commercial entity that will provide it will follow the procedures of Law 9/2017, of November 8, on Public Sector Contracts.

The previous public procurement legislation included four types of public service management contracts or indirect management modes: the concession, the interested management (Nieves, 1958), the concert (Domínguez, 2011) and the provision of public services through a mixed economy company (Iglesias, 2010). The current public procurement regulations no longer include public service management contracts (López, 2017). However, it has maintained the administrative concession, although under the name of service contract in favor of citizenry, a notion that is highly criticized because it rethinks the classic concepts of public service contract and service contract (Fortes, 2019).

3. THE FORMS OF MANAGEMENT OF THE COLLECTIVE URBAN TRANSPORT PUBLIC SERVICE IN THE CITY COUNCILS OF CASTILLA Y LEÓN

In this section we will analyze the forms of public service provision of urban collective transport in the nine provincial capitals of the autonomous community of Castilla y León in Spain, which are: Ávila, Burgos, León, Palencia, Salamanca, Segovia, Soria, Valladolid and Zamora. It is a compulsory public service in accordance with local legislation. The population in Ávila is of 57,744 inhabitants, in Burgos of175,821, in León of 124,303, in Palencia of 78,412, in Salamanca of144,228, in Segovia of 51,674, in Soria of 39,398, in Valladolid of 298,412, in Zamora of 61,406.

3.1 Municipalities that provide urban public transport services under a service concession scheme

The municipalities that provide public urban transport services under a service concession are: Ávila, Palencia, Salamanca, Segovia, Soria and Zamora. All these municipalities opt for a form of indirect management. The municipalities selected this form of management because they only have to wait a the successful bidder to comply with the obligations of the service concession contract.

3.2 Municipalities which provide urban public transport services under direct management by the City Council itself

The Municipalities that provide the urban collective transport service under direct management by the City Council itself are Burgos and León. Both municipalities opted for this model to be implemented directly by the Local Council itself. These municipalities understood that the management of the service should be held by their City Councils, with their own means and with the aim of protecting the public interest at stake.

3.3 Municipalities that provide the urban collective transport service as a public company with entirely public capital

The only municipality that provides the urban public transport service as a public company is Valladolid, through a municipal company. One of the reasons for using this method of management was to reduce the application of public procurement rules.

4. PUBLIC PROCUREMENT REGULATIONS FOR URBAN COLLECTIVE TRANSPORT

The normative systems of public procurement that the state legal system includes (Moreno & Pintos, 2015) are going to be developed below.

4.1 Public procurement laws that affect, directly and indirectly, the management of urban collective public transport

The entrance of the Kingdom of Spain into the European Economic Community in 1986 meant that it was obliged to submit to its regulations, its institutions and the judicial resolutions of the courts that make up the Community. It also affected the matter of public procuring (Allain, 2006). The Community Directives on public procurement (Verdeaux, 2003), which have followed one another throughout the life of the European Union, amount to ten. One of them is Directive 2014/24/EU of the European Parliament and the Council, dated February 26, 2014, which has been transposed into the Spanish legal framework by Law 9/2017, dated November 8, on Public Sector Contracts.

A second rule that regulates public procurement is the one relating to special economic sectors. The European law currently in force in this area is Directive 2014/25/EU of the European Parliament and the Council, dated February 26, 2014. This rule has been transposed into Spanish law by means of Book I of Royal Decree-Law 3/2020, of February 4, on urgent measures.

And the third European law on public procurement is the one on concession contracts, known as Directive 2014/23/EU of the European Parliament and the Council of February 26, 2014, on the award of concession contracts (Graells, 2015), which has also been transposed in Spain through Law 9/2017, of November 8, on Public Sector Contracts.

4.2 Subjective scope of public sector contracts, in general

Article 3 of Law 9/2017, dated November 8, on Public Sector Contracts, lists three types or classes of public entities for the purposes of public procurement: Public Sector entities from a broad or generic point of view (it refers to the entire Spanish public sector), Procurement Authorities (this concept has been drawn up by the state legislator to cover the notion of a public company in the European Union) and Public Administrations (the Spanish public entities, bodies or agencies that fall into this group are the territorial or similar administrations, including the local Autonomous Bodies).

4.3 Subjective area in the special sectors of water, energy, transport and postal services

The subjective scope of Book I of Royal Decree-Law 3/2020, of 4 February, on urgent measures, is made up of three concepts which, according to its article 5.2, are Contracting Entity, Adjudicating Power and Public Company.

The public entities to which the contracting procedures provided for in the law on the special sectors of water, energy, transport and postal services are applied, are different from and more flexible than those established in the public sector contracting legislation that are considered to be Public Administrations.

4.4 Subjective scope of the contracts for the concession of works and the concession of services

The subjective scope of contracts for the concession of works and the concession of services (Bovis, 2005) is the same as that set forth in Law 9/2017, of November 8, on Public Sector Contracts, distinguishing, for the purposes of contracting, between Public Administration, the Awarding Authority and the Public Sector.

5. THE PUBLIC CONTRACTING REGIME WILL DEPEND ON THE PUBLIC SERVICE MANAGEMENT MODE CHOSEN BY EACH CASTILLA Y LEÓN CITY COUNCIL

From all the above, we can highlight the disparity in the mechanisms for public contracting in the Spanish legal system. The public procurement system will depend on the public sector entity that contracts, and in urban public transport, the model chosen by each municipality of Castilla y León. The list of the entire public procurement system of the state legal system that we have set forth, together with the management methods of the existing urban collective public transport services in the municipality, leads to the following perspective.

The City Councils of Ávila, Palencia, Salamanca, Segovia, Soria and Zamora, which manage urban public transport through service concessions, make the management model subject to the provisions for an administrative contract in Law 9/2017, of November 8, on Public Sector Contracts.

The City Councils of Burgos and León, as they are public administrations, will follow the procedures set forth in Law 9/2017, of November 8, on Public Sector Contracts for any type of work, service or supply required by the public collective transport service. There will be as many administrative contracts tendered as requirements to be satisfied by the service.

Finally, in the City Council of Valladolid, the urban public transport service is managed by a municipal public company. It has the legal nature of a Bidding Power and, therefore, it will have to be in accordance with the Law 9/2017, of November 8, of Contracts of the Public Sector for the Bidding Powers. It will have a much lower level of application of contractual rules than the ones the above-mentioned City Councils are subject to. In this case, moreover, when the object of the contract consists of the activities of making available or operating networks that provide a service to the public in the field of bus transport (Bermejo, 2008), they will be governed by the provisions of Book I of Royal Decree-Law 3/2020, of February 4, on urgent measures.

From what has been explained, we can affirm that there is a disparity of rules and procedures of public contracting in the provision of the service of collective urban transport. Their application will depend on the type of direct or indirect management - public or private

(Hansson, 2010) - chosen by each one of the nine provincial capital cities of Castilla y León, leading to dysfunctional public procurement regulations (Santamaria, 2016).

6. CONCLUSIONS

Firstly, the legal regime of Local Entities includes the possibility that Town Councils may, in the exercise of their constitutionally and legally granted local and organizational autonomy, opt for different modes of management of public services in general and of the public urban transport service in particular.

Secondly, the municipalities which are provincial capital cities in the autonomous community of Castilla y León in the Kingdom of Spain have different models for managing public transport services: indirect management (the municipalities of Ávila, Palencia, Salamanca, Segovia, Soria and Zamora), direct management by the Coruncil itself (the municipalities of Burgos and León) and direct management by means of a local commercial company with entirely public capital (the municipality of Valladolid).

Thirdly, the legislation on public procurement in the European (Community Directives) and Spanish (Spanish public procurement laws) legal systems is detailed and not homogeneous: its application will depend on the purpose of the contract, the area in which it conducts its activity and the public sector entity it contracts.

Fourthly, the public procurement rules applicable to the management of the public service of urban public transport are as varied as the forms of organization of the urban public transport’s public service that each capital city of Castilla y León follows.

Fifthly, the disparity between the contractual and public service regulations to be applied, which depend on many factors, leads to a regulatory dysfunction that should be modified so that no one is left out of the same public contracting procedures, which guarantee the efficient management of public resources managed through the public urban collective transport service.

Sixthly, the solution we propose would be a legislative modification in which it would be clear that, regardless of the method of management of the public service of collective urban transport chosen by each municipality - when the satisfaction of a need, expressed in a work, a service or a supply, is foreseen - the same rule would be applied, in all its virtuality. This will generate a great deal of legal security for those applying the Law and for the contracting bodies of all the public sector entities affected.

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CHARGING OPERATIONS IN BATTERY ELECTRIC BUS SYSTEMS AT THE DEPOT

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ABSTRACT

This paper analyzes the effect of the limited range of battery electric bus on the operation of the bus services charged at the bus garage. A model has been built to calculate the performance of the routes according to the type of charging scheme. It evaluates the total cost of the bus service, considering the necessary resources due to range limitations and electric constraints. Based on the analysis of the real data of a bus line in the city of Barcelona, diesel or hybrid vehicles are still found to be more competitive than electric vehicles because of the acquisition costs of electrical technology. The study shows that the charging operation at the bus garage, without being the most profitable option a priori, is adequate when the design and operation parameters of the bus route fall below certain values.

1. INTRODUCTION

Most of the largest bus fleets in our cities are made up of traditional vehicles that present internal combustion engines (ICE). A large part of the pollutants present in urban areas can be attributed to these vehicles, which contribute to the global warming problem and affect the health of citizens in metropolitan areas. Changing this type of vehicle to fully electric fleets would contribute to reducing carbon dioxide (CO2) emissions, reducing the consumption of fossil fuels, and improving energy efficiency, as can be seen in Jang et al. (2016), Corazza et al. (2016), Miles and Potter (2014) and Zhou et al. (2016).

Fully electric fleets involve the use of battery electric buses (BEB), whose only source of energy is a battery pack equipped on board. Charging these batteries can be done in various ways, but the most common are opportunity charging during the service and overnight charging (Miles and Potter, 2014). Opportunity charging is performed on the street using fast chargers, which take 5-10 minutes to restore full power. Overnight charging is performed in the bus garage, using slow or fast chargers, while the vehicles are not in service. In the case of overnight charging the battery size is significantly larger than in the opportunity charge to provide large travel ranges between two consecutive charging operations. This means long charging times (up to 5 hours).

To guarantee a wide deployment of BEB in cities, it is necessary to consider new operations and the limitations that their use implies in bus fleets, as explained in Mahmoudzadeh et al. (2017). In Li (2014) the operational limitations of these vehicles and the effect of different factors (driving, air conditioning, etc.) on energy consumption are explained. Likewise, Xylia and Silveira (2018) show the results of experimental implementations of electric buses in Europe.

A basic point in the implementation of BEB is its implementation cost. As shown in Teoh et al. (2017) and Feng et al. (2013) the cost of capital and charging stations are significantly high. On the contrary, this type of bus can reduce operating costs by up to 80% compared to ICE vehicles. In this way, it turns out that the total cost of ownership (TCO) and the life cycle cost of BEB are essential to evaluate the profitability of their implementation. In this sense, Lajunen (2014) presents an in-depth analysis of the TCO of electric buses, the conclusions of which show that there is a lot of uncertainty in its estimation.

In Lajunen and Lipman (2016) we can find a broad life cycle analysis for different bus technologies, considering capital, maintenance, energy consumption and emission costs. Here it is shown that diesel hybrid buses are still competitive in terms of life cycle cost with respect to other powertrains, but it is suggested that improved BEB will be able to compete with diesel and natural gas in the future. Another important point indicated in this work is that a significant public investment is necessary to create efficient fast charging infrastructures.

Regarding the influence of energy demand on the provision of bus services, we can highlight the work of Vepsäläinen et al. (2018), where the effect of a wide list of factors and characteristics of the route is analyzed, validating a predictive model of electricity demand. Bi et al. (2017) analyze the life cycle cost of charging infrastructure, comparing conductive and inductive systems. And, for their part, Chen et al (2018) compare the profitability of charging lane technologies, charging stations and battery exchange stations.

In this paper, the effect of the new requirements of battery electric vehicles on the operation of the bus services charged at the garage is analyzed. To do this, a model has been developed, that analyzes the most suitable charging operation and performance. They are evaluated based on the total cost of the system on a given bus route, and the calculation of the resources required due to electrical limitations. The model considers two different charging strategies or schemes: garage charging (day or night) and opportunity charging at bus terminal stations on the given route. The modeling of the charge at the garage is based on the proper scheduling of the vehicle deadheading movements to the garage, to satisfy the electrical limitations and the attributes of the service.

An improvement procedure has also been incorporated to optimize the total cost of the system, based on advancing the charging operations before the moment when the vehicles begin to run out of battery, similar to Gao et al. (2017). This minimizes the additional vehicles required, compared to the usual procedure where charging operations are performed just when the vehicles are running out of power.

Finally, the calculation of the performance and the resources required in the opportunity charging is based on the queue theory at the charging facilities, taking into account the irregular arrivals of buses to the on-route chargers and the available loading time. This severely limits the viability of electrical systems on routes with busy headways.

2. MODELING FRAMEWORK

2.1 Problem formulation

We consider a linear bus route of length *2L*, where the buses travel in two directions and the stops are evenly spaced at a distance s. Buses can enter and exit service only at the terminal stop furthest from the garage, located l_G units away.

We assume that the bus service is performed in a period of time hday on a typical day, with N stationary periods or time windows of size hi $(i = 1\ldots N)$, in which the external variables of the system, such as hourly demand Λ_i and the cruising speed vi, remain constant. It is assumed that the duration of the stationary periods is greater than the dead times of traveling to the garage, that is $(2l_G/v_i) \ll$ hi. Furthermore, a constant time headway H_i is assumed for each time window. The number of necessary vehicles $M^0(i)$ and the commercial speed $v_c{}^0(i)$ in time window i when no charging operation is required, are defined in Equation (1). From now on, the superscript *0* represents the value of the corresponding variable when the electric charge operation does not affect it, and the superscript *1* the opposite case. We also assume that at the end of the last stationary period an additional period of time of length h_{night} begins in which there is no bus service. All vehicles are sent to the garage for maintenance until the next day.

$$M^0(i) = (2L)/(H_i v_c^0(i)) \quad (1)$$

Using this notation, the fleet size required for bus route operation on a typical day would be $M_T^0 = max\, M^0(i)$. Said fleet size will not be constant, but we will have a fleet size variation $\Delta M^0(i)$ defined in Equation (2) and for which $M^0(0) = 0$ veh. This assumes that in each period there will be a number of vehicles introduced on route $M_{in}^0(i)$ and a number of vehicles removed from route $M_{out}^0(i)$ at the beginning of period i. These variables will be equal to zero if there are no restrictions that affect the autonomy of the vehicles, but they will present a positive value when the electric vehicles run out of batteries and must be charged.

$$\Delta M^0(i) = M^0(i) - M^0(i-1) = M^0_{in}(i) - M^0_{out}(i) \quad (2)$$

The energy consumption of a vehicle is calculated by the product of the distance traveled by the energy consumption factor associated with the vehicle technology in service f_C *(kWh/veh-km)*. The effective capacity of the batteries is calculated by $E = E'(1\text{-}SOC_{min})$, where we subtract from the nominal capacity of the battery E' the minimum energy value ($E' * SOC_{min}$) that the buses need at any time of service in emergency case. This minimum value depends on the minimum threshold for the state of charge of the batteries (SOC_{min}) defined by the manufacturer.

If in a time period *k* vehicles are introduced into the system ($M_{in}(k) > 0$), it will be necessary to check whether these vehicles can provide service throughout the day or should be recharged in an intermediate period $j>k$. We define the energy consumed by the vehicle until the beginning of period *i* as *C(i)* (determined by Equation 3) and the energy remaining in the battery at the beginning of period *i* by *B(i)*. For the vehicle to be able to provide service up to a period of time *i*, Equation (4) must be fulfilled, where *B(k)* represents the energy available when the vehicle was introduced in the period of time *k*. We generally assume $B(k) = E'$.

$$C(i) = f_c \sum_{j=k}^{i-1} h_j v_c(j) \quad (3)$$

$$B(i) = B(k) - C(i) \geq 0 \qquad k < i \quad (4)$$

We will define $T_{end}(i) = T_R(i) + \sum_{j=1}^{i-1} h_j$ as the absolute time in which the vehicles entered into the service at the beginning of time window *i* will remain without batteries, where $T_R(i)$ is the maximum operating time of the vehicles that start in the period of time *i*. To calculate this value, we need to know how many full-time windows and how long in the next time window (t_{k^*}) the vehicle will be able to travel until the batteries are exhausted, which results from solving Equation (5). In this way we can rewrite $T_R(i)$ as $T_R(i) = \sum_{j=i}^{k^*-1} h_j + t_{k^*}$.

$$t_{k^*} | \quad E = f_C\left(\sum_{j=i}^{k^*-1} h_j v_c^0(j) + t_{k^*} v_c^0(k^*)\right) y \quad 0 \leq t_{k^*} < h_{k^*} \quad (5)$$

A vehicle entered in time window *i* will run out of batteries in time window $N_{end}(i)$, the calculation of which involves complying with Equation (6). With the values of $T_{end}(i)$ and $N_{end}(i)$ we can define exactly the moment when a vehicle entered in the time window *i* needs a charging operation. We will consider that if a vehicle entered in time window *i* has enough charge to complete the service until the end of the day, then $N_{end}(i) = N + 1$.

$$\sum_{j=1}^{N_{end}(i)-1} h_j \leq T_{end}(i) < \sum_{j=1}^{N_{end}(i)} h_j \quad (6)$$

In this way, it will not be necessary to carry out charging operations during the h_{day} service period when T_{end} *(1) > hday* and N_{end} *(1) = N + 1*. In this case, the transport company can only carry out the night charging scheme in the garage (G-Scheme) if the hnight period is long enough to fully charge the battery pack. Under these conditions, the stored energy $B^0(i)$ will always be positive.

2.2 Overnight charging operations at the bus garage

In this case, we are going to consider that the buses are charged in the garage with slow chargers (with speed S_N) in the period of non-provision of the transport service, this being a complementary charging operation of the daily load in the garage (with speed $S_D > S_N$). In this way, the vehicles charged in this period can be used the next day according to service needs.

We will call T_{el} the moment at which the night charge scheme (G-Scheme) begins with respect to the initial service time, and N_{el} the time window after which the night charge begins ($T_{el} = \sum_{i=1}^{N_{el}} h_i$). The vehicles recharged at night must be those that belong to the subset $M_{inv,N}$ *(i)* in each period of time $i \leq N$.

To simplify the problem, we will assume that all daily services present the same stationary periods, demand, speeds and, therefore, vehicle needs in each time window *i = 1… N*. However, if the services corresponding to different days have different temporal patterns, this methodology can be easily adapted.

With these premises, Equation (7) shows the condition to be fulfilled in order to fully charge the batteries at the beginning of the period of time *k*, when the vehicle has arrived at the garage in period *i* of the previous day. If this condition is not met, it is not possible to recharge the batteries between time periods *i* and *k*.

$$E' < \left\{\left(h_{day} + h_{night} + \sum_{m=1}^{k-1} h_m\right) - \sum_{n=1}^{i-1} h_n\right\} \cdot 1/S_N \qquad (7)$$

3. COST ANALYSIS

The total cost of a day of service for the transport company will be calculated by $Z = Z_M + Z_B + Z_V + Z_C$, where ($Z_M$) represents the sum of the depreciation of the vehicle plus labor costs, (Z_B) is the cost of batteries, (Z_V) is the cost of the distance and (Z_C) is the cost of the charging infrastructure.

We will consider here a series of operational parameters that directly affect the variable costs of transport companies. The first of these is the total distance traveled by the bus fleet during the entire day of service, calculated as vehicles-kilometer traveled in one day, VKT (veh-km/day). The second in importance is the total time that the vehicle-driver pair is providing service throughout the day, either on the corresponding route or in the dead movement to the garage, defined as the vehicle-hours traveled in service, VHT (veh-h/day). Finally, the vehicle-hours depreciated throughout the day, VHD (veh-h/day), will be calculated, representing the total number of vehicles needed throughout the day, either on the road or in the garage.

Equation (8) shows the calculation of ZM. In this equation, the cost ratio c_{t1} represents expenses related to drivers, and cost ratio c_{t2} represents vehicle depreciation, insurance, and other fixed costs of the vehicle throughout the day.

$$Z_M = c_{t1}VHT + c_{t2}VHD \tag{8}$$

Equation (9) calculates the cost of the battery, considering the energy capacity of the batteries equipped in each vehicle (E') and the unit cost of the battery per kWh acquired c_b.

$$Z_B = E' \cdot c_b \cdot VHD \tag{9}$$

In Equation (10) the cost of the distance traveled is calculated, where c_d is the unit cost of the distance, which considers the cost of energy to operate the vehicles and other expenses related to the kilometers traveled.

$$Z_V = c_d VKT \tag{10}$$

Finally, Equation (11) calculates the cost of the charging infrastructure. Here, the c_{cg} parameter considers the cost of capital and the daily operating cost.

$$Z_C = c_{cg}\left(N_{ch,N}\right) \tag{11}$$

4. RESULTS

To verify the goodness of the generated model, an analysis of a real case of a bus line in the city of Barcelona has been carried out. Within the city's urban bus network, route V13 has been selected, on which the model has been applied to calculate the costs of the bus company when implementing a fully electric bus service with its auxiliary charging facilities.

In the short-term scenario, the values obtained in pilot tests in Barcelona for the operational parameters of the service and the average cost of capital in developed countries have been considered for the analysis. On the other hand, other scenarios have been considered and sensitivity analysis have been carried out to estimate the influence of the cost of electrical technology on long-term efficiency.

The reference values for the analysis of the performance of the battery, the charger and the electric vehicle, as well as those necessary to compare with the diesel and diesel-hybrid engines, have been obtained from the operational data monitored by the TMB bus operator in 2018 (TMB, 2018).

4.1 Discussion

Table 1 shows the values obtained for the most significant variables of the model carried out. With these values, it is possible to analyze the operational performance of the route, the amount of resources required, and the operational costs for the different types of engine and bus loading schemes on route V13 in the city of Barcelona.

	Diesel	**Hybrid**	**Electric**		
			G-Charge Opt.	**O-Charge Reg.**	**O-Charge Skip**
VHT (Veh-h/day)	281.5	281.5	281.5	291.9	281.5
VHD (Veh-h/day)	456.0	456.0	456.0	480.0	456.0
VKT (Veh-km/day)	2974.2	2974.2	2974.2	3010.6	2974.2
Charging/Fuel stations	1	1	0	0	0
Opportunity chargers	0	0	0	2	2
Overnight chargers	0	0	10	2	9
Fleet size (veh)	19	19	19	20	19
Z_M (Euros/day)	17,215.1 €	17,639.2 €	18,122.6 €	18,911.6 €	18,122.6 €
Z_V (Euros/day)	4,491.0 €	3,212.1 €	2,260.4 €	2,288.1 €	2,260.4 €
Z_C (Euros/day)	109.7 €	109.7 €	283.8 €	214.8 €	352.0 €
Z_B(Euros/day)	0.0 €	0.0 €	1,191.2 €	1,253.9 €	1,191.2 €
Z (Euros/day)	21,815.8 €	20,961.0 €	21,857.9 €	22,668.3 €	21,926.0 €

Table 1: Modelling results for different vehicle technologies and charging schemes in route V13

As we can see, the operating cost of fully electric vehicles is slightly higher than the cost corresponding to diesel or hybrid vehicles. This is because BEB technologies are more expensive than diesel and hybrid vehicles. In this way, the cost savings that can be obtained in the operation do not compensate for the higher cost of electric vehicles and batteries. However, the variation in operating cost between the different alternatives analyzed stands at 4%, so it is to be expected that a reduction in the prices of batteries and electric vehicles in the near future due to the maturity of these technologies will favor a competitive advantage of BEB systems.

Regarding the distribution of system costs, the time component of the cost (depreciation of the vehicle plus labor costs) is the most important in all cases (83% in BEB systems, 80% in ICE and 85% in hybrids), followed by the distance-based component (10% in BEB systems, 20% in ICE and 15% in hybrids), with the cost of batteries being 6% and the cost of installing charging systems 1% in the BEB systems. With these values, the G-Charge charging scheme can equalize the costs of diesel and hybrid systems if the price of vehicles and batteries decreases by 28% and 2%, respectively.

For the route that has been analyzed in this case, the most suitable BEB alternative is night charging in the garage (G-Charge). This is due to the fact that the buses have large battery packs to ensure their operation throughout the working day, which makes the size of the fleet in this case equal to that required in ICE and hybrid technologies. On the other hand, if the opportunity charge is used in the regular option (O-Charge Regular), it would be necessary to increase the size of the fleet in a vehicle with respect to the G-Charge scheme or the diesel system. This increase is justified by the time spent on the chargers installed on the street after completing each round trip on the route. To equalize the total cost of the G-Charge scheme, the company should skip the charge operation in predefined time windows throughout the day (O-Charge Skip).

4.2 Sensitivity analysis

The sensitivity analysis carried out aims to analyze the influence of the variation in battery capacity. For this, the same type of BEB analyzed in the real route V13 of Barcelona has been maintained, but allowing to modify the size of the battery pack installed in it. A variable energy consumption factor that depends on the weight of the batteries has been considered, as described in Gao et al. (2017). With the values of the analyzed route, a consumption factor - battery capacity relationship equivalent to $f_c = 0.0005E' + 1.2243$ *(kWh/km)* has been obtained for standard buses.

For the route analyzed, the most profitable charging scheme is the one of opportunity that allows to skip charging operations in certain periods of time (O-Charge Skip), provided that the capacity of the batteries is E'≤275 kWh, as you can see at Figure (1). On the other hand, if the omission of charge is not allowed in the opportunity charge (O-Charge Regular), it turns out that it is much more expensive than the optimal charge in the garage (G-Charge Optimum) for a capacity E '> 250 kWh.

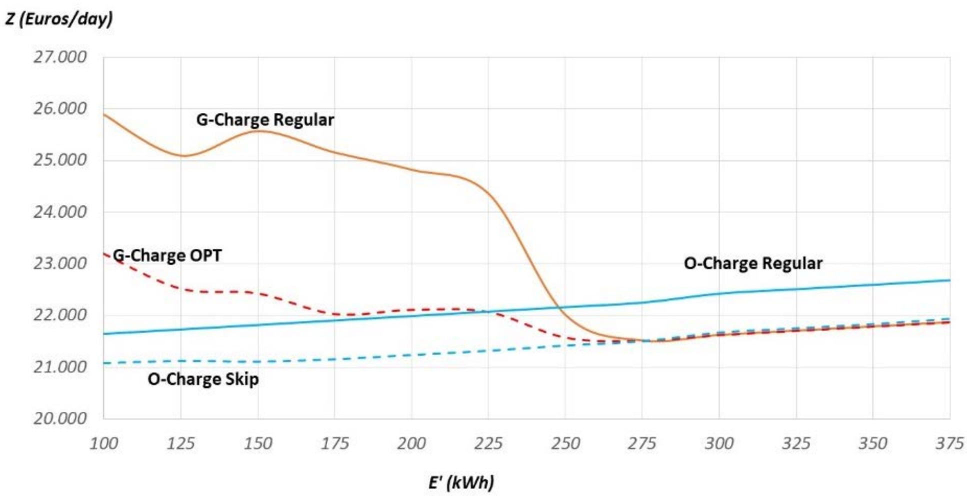

Figure 1: Total cost in the different charging schemes versus battery capacity

If we increase the capacity of the installed batteries, the cost of the O-Charge system increases linearly, thus approaching the cost of the G-Charge system. In this way, if the capacity of the batteries increases (E'> 275 kWh), the charge in the garage (G-Charge Optimum and G-Charge Regular) presents the same performance as the O-Charge scheme. In fact, the threshold E'= 275 kWh defines the minimum battery pack to provide all-day service on G-Charge.

With a capacity E'<275 kWh, the smaller the battery pack, the more vehicles are required in G-Charge Optimum. This means that G-Charge Optimum presents a monotonous decreasing fleet size with respect to the battery capacity until reaching the value E'= 275 kWh, which does not happen in the G-Charge Regular scheme.

An interesting fact is that in the G-Charge scheme the size of night charging facilities is minimal when the size of the fleet is maximum. This is because a charger can serve more vehicles in the night period the smaller the battery pack is and because there are idle vehicles that can be charged at time $t > T_{el}$.

5. CONCLUSION

After the analysis carried out, we can conclude that the costs of current BEB technologies are even higher than conventional ICE or hybrid technologies. However, this cost difference is at a fairly low level, located in a range of 4 to 8%, thus a reduction in the acquisition costs of electrical technology, combined with the greater awareness of reducing polluting emissions makes electric buses a more attractive option for companies. With the results of the line analyzed in Barcelona, a battery cost of less than € 300 / kWh and a reduction in the purchase cost of vehicles of 12% - 30% are needed, so that BEB systems will be more efficient than the ICE and hybrids, respectively.

It is important to note that operation with BEB implies a personalized design of the vehicle in terms of batteries and charging system, depending on the characteristics of the route to be served. This makes BEB vehicles, unlike ICE or hybrids, only interchangeable on routes with similar characteristics. If this premise is not met, it is very possible that the transport company needs to increase the size of its fleet to guarantee the correct provision of the service. Therefore, we can conclude that BEB technology does not allow flexible fleet management.

From the sensitivity analysis carried out, we can infer that the O-Charge opportunity charging system is always more profitable than the G-Charge garage charging if the service shows good regularity and the chargers are at the terminal stops along the route. As a condition it is necessary that the minimum capacity of the batteries is 100-125 kWh to guarantee a complete circuit. This charging system can be enhanced by allowing vehicles to skip charging during peak periods. This reduces vehicle travel times and equates the necessary fleet to that of ICE technology. In this sense, it is shown that it is more appropriate to carry out a configuration of several chargers in a single terminal stop of the route (scheme N-0) than to have chargers in both terminal stops (scheme N-N), which is only profitable on very long routes where the capacity of the batteries could not guarantee a complete round trip route. Therefore, if the loading operation can be skipped in the time windows of higher demand, the cost of the company can be reduced by 3 - 4%.

When the urban structure hinders or prevents the implementation of opportunity chargers at the terminal stops of the routes, the increase in the distance to travel to carry out the loading operation penalizes the opportunity load, favoring the use of the load in the garage. In this case, the garage charge equals the fleet size of the opportunity charge as long as the batteries have a capacity greater than 300-375 kWh, although it increases the cost of the batteries and requires long charging intervals.

On the other hand, if we analyze routes with low service regularity or routes with short distances, we obtain that the time spent charging is critical to guarantee the correct provision of the service. For this reason, the location of various tandem charging areas is required, which is difficult to implement in consolidated urban areas with a shortage of available public space and penalizes the opportunity charging system.

In this way, if we cannot implement the proper design of the opportunity charging facilities, we favor the use of garage charging. In this case, the buses must incorporate large capacity batteries to avoid having to go to the garage to charge during the service. If this is not fulfilled and the capacity of the batteries does not guarantee the complete provision of the service, it is necessary to increase the fleet to replace the vehicles that have to go to the garage to charge during the day.

In the analyzes carried out, a much higher performance of the G-Scheme Optimum algorithm has been demonstrated over the G-Scheme Regular algorithm, which tells us that we should not wait until the vehicles are about to exhaust the capacity of the batteries to perform the charge, but it is more appropriate to have a small additional fleet that begins to replace the buses from the start of the service.

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ANÁLISIS DE LA VARIACIÓN DE LA DEMORA EN PARADA EN CONDICIONES METEOROLÓGICAS ADVERSAS

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RESUMEN

El Bus Lost Time (BLT) o tiempo perdido por el autobús se define como el tiempo transcurrido desde que el autobús abre las puertas hasta que embarca la primera persona. Este concepto se incluye en la tercera edición del Transit Capacity and Quality of Service Manual para estaciones de autobús semirrápido (Bus Rapid Transit, BRT) con tres zonas de detención, pero no se considera para paradas de autobús regular en ningún caso.

En esta ponencia se presentan valores de BLT para paradas de autobús convencional, mostrando la influencia que la lluvia tiene en este parámetro. En concreto, se mostrará que los aumentos de BLT por efecto de la lluvia son mayores que los que se producen para tiempo seco cuando se utiliza la segunda posición de detención en una parada doble.

Los datos utilizados se han tomado mediante medidas realizadas por una persona in situ, distinguiendo diferentes niveles de intensidad de lluvia fácilmente identificables a través del comportamiento de los viandantes. Se ha realizado un tratamiento estadístico de los datos para determinar el ajuste a distribuciones estadísticas estándar (normal y lognormal) así como para confirmar que las diferencias obtenidas en los valores de BLT son significativas.

1. INTRODUCCIÓN Y REVISIÓN BIBLIOGRÁFICA

El conocimiento de los tiempos de operación de autobuses urbanos es una herramienta necesaria para el operador y el planificador. Este conocimiento es preciso para la organización de los horarios tratando de garantizar el cumplimiento de los intervalos en las diferentes condiciones, así como para el estudio de nuevas líneas o modificaciones en las existentes. Uno de los aspectos que va a influir en el funcionamiento del sistema son las condiciones meteorológicas y, en concreto, la existencia de lluvia.

Uno de los componentes del tiempo de operación es la demora en la parada (Dwell Time, DT). En este estudio se pretende determinar la influencia de la lluvia en la demora en parada de los autobuses urbanos convencionales.

El estudio de la demora de los autobuses en las paradas puede remontarse a Muzyka (1974), quien utilizó su distribución con el objeto de realizar simulaciones. Posteriormente, en 1980, se realizó una campaña de medidas de demoras en parada en EE. UU. (Levinson, 1983). Para una revisión de las primeras medidas de la demora en parada se puede consultar Dueker (2004).

El concepto de tiempo de demora se define en la segunda edición del Transit Capacity and Quality of Service Manual (Transportation Research Board, 2003) como: “el tiempo necesario para servir a los pasajeros en la puerta más cargada, más el tiempo necesario para la apertura y cierre de puertas”, de acuerdo con la Ecuación 1:

$$t_d = P_a t_a + P_b t_b + t_{oc} \quad (1)$$

donde:

- t_d=tiempo de demora medio (s);
- P_a = número de pasajeros desembarcando del autobús por la puerta más cargada (s);
- t_a=tiempo de servicio de los pasajeros que desembarcan (s/p);
- P_b = número de pasajeros embarcando al autobús por la puerta más cargada (s);
- t_b=tiempo de servicio de los pasajeros que embarcan (s/p); y
- t_{oc} = tiempo de apertura y cierre de puertas (s);

A los tiempos reflejados en la ecuación anterior se les puede añadir un tiempo adicional, que es el tiempo de espera del autobús entre el momento en que el autobús se detiene en su punto de parada y el momento en que la primera persona embarca. Este tiempo fue definido por Jaiswal (2010) y Jaiswal et al. (2010) como “tiempo perdido por el autobús” (Bus Lost Time, BLT). Los valores medios de BLT que obtuvieron, para una estación de un sistema de autobús semirrápido (Bus Rapid Transit, BRT) con tres zonas de detención, fueron de 4.3, 3.1 y 5.2 s para las zonas de detención 1, 2 y 3 respectivamente, mientras que los valores del percentil 85 fueron 7.2, 4.5 y 8.7 s.

Estos estudios condujeron a una modificación en la formulación de la demora en parada (DT) en la tercera edición del Transit Capacity and Quality of Service Manual (Transportation Research Board, 2013), pero únicamente para estaciones de sistemas de autobús semirrápido (BRT), objeto de los citados estudios. En este caso se consideró el término “Boarding Lost Time” (tiempo perdido en el embarque), definiéndolo como el tiempo transcurrido mientras los pasajeros caminan hasta la(s) puerta(s) del autobús desde sus posiciones de espera en la parada. La formulación de DT cambió a:

$$t_d = t_{pf,max} + t_{oc} + t_{bl} \quad (2)$$

donde:

- t_d = tiempo de demora medio (s);
- $t_{pf,max}$ = máximo tiempo de flujo de pasajeros de todos los canales de puerta (s);
- t_{oc} = tiempo de apertura y cierre de puertas (s), con valores típicos de 2-5 s; y
- t_{bl} = tiempo perdido en el embarque (s);

El valor de BLT se establece como 0 s en el caso de paradas con una única zona de detención. Para tres zonas de detención se propone un valor que varía entre 4.0 y 4.5 s para condiciones de mayor o menor congestión en la zona de espera de la parada. Finalmente, para estaciones de BRT con dos zonas de detención, el analista debe evaluar la frecuencia de utilización de la segunda zona de detención para determinar un valor entre 0 y 4 s (Transportation Research Board, 2013).

Finalmente, Kathuria et al. (2016a y 2016b) hacen hincapié en el hecho de que el BLT solo se debe considerar cuando no se solapa con la fase de desembarque, produciendo por tanto un aumento en el DT. En sus investigaciones determinaron los escenarios de embarque y desembarque en los que se debe considerar el BLT. Estudiaron el BLT para una estación de BRT con dos zonas de detención, obteniendo valores medios de 1.8 y 2.4 s para la primera y segunda zona de detención, con percentiles 85 de 2.1 y 2.7 s respectivamente (Kathuria et al., 2016a). La lluvia no era una variable relevante ni en estos estudios ni en los de Jaiswal (2010) y Jaiswal et al. (2010), por tratarse de estaciones cerradas o cubiertas completamente con marquesinas.

En Novales et al. (2021), se ha analizado el incremento del BLT debido a la lluvia en un caso de estudio de autobús convencional en A Coruña, considerando únicamente el valor del BLT. En esta ponencia se presenta un análisis análogo de ese caso de estudio, pero empleando como variable de análisis conjuntamente el BLT y el tiempo de apertura y cierre de puertas, tratando así de establecer qué medida es más adecuada de cara a su medición en campo y su incorporación a los cálculos de demora en parada.

En esta ponencia se analizan por tanto los valores de BLT, incluyendo apertura y cierre de puerta, para una parada de autobús regular en bahía con dos zonas de detención. Se considera de forma explícita el efecto de la lluvia, ya que se ha observado que afecta notablemente al comportamiento de los viajeros que esperan en la parada. En ausencia de precipitación los viajeros pueden esperar fuera de la marquesina y se empiezan a mover hacia el punto esperado de detención cuando observan que el autobús se acerca. En situaciones de lluvia, especialmente si es intensa, tienden a esperar bajo la marquesina hasta conocer el punto exacto de detención. Esto va a suponer una modificación del tiempo desde la detención del autobús hasta la subida del primer viajero, objeto de esta ponencia.

Para una revisión de la influencia de la lluvia en el comportamiento del viajero se puede consultar Liu (2017). El Transit Capacity and Quality of Service Manual (Transportation Research Board, 2013) señala que el porcentaje de circulación puntual puede caer por debajo del 80% durante condiciones de mal tiempo y que la meteorología influye en la velocidad de los peatones.

Esta ponencia está organizada como sigue: el apartado 2 presenta el caso de estudio y procedimiento de toma de datos; en el apartado 3 se realiza el análisis de la influencia de la lluvia en el parámetro analizado, en el apartado 4 se realiza un análisis de ajuste a distribuciones estadísticas estándar; finalmente, en el apartado 5 se presentan las conclusiones del estudio.

2. CASO DE ESTUDIO Y RECOGIDA DE DATOS

Tras un análisis de las condiciones requeridas, se seleccionó para la toma de datos una parada situada en frente a la iglesia de San Pedro de Mezonzo en la ciudad de A Coruña. Su configuración general se presenta en las figuras 1 y 2. Se trata de una parada en bahía situada tras una intersección en una calle de sentido único, con prioridad en la siguiente intersección. Los autobuses circulan en tráfico mixto sin ningún tipo de preferencia. Existe espacio para la detención de dos autobuses, siendo la longitud total de la zona de detención de 25 m. En esta parada la marquesina está situada a 3 m del borde del bordillo y adyacente a la primera zona de parada de los autobuses, hecho que va a tener influencia en el BLT, ya que se debe recorrer cierta distancia hasta la puerta del autobús bajo la lluvia.

Figura 1: Parada de San Pedro de Mezonzo. Fotografía de la configuración general

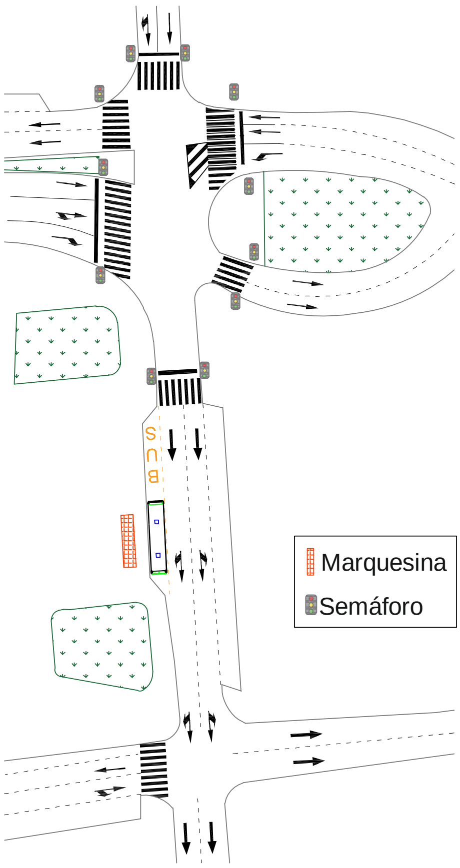

Figura 2: Parada de San Pedro de Mezonzo. Plano de la configuración general

La parada es servida por 6 de las líneas de la red, incluyendo la línea que presta el servicio específico a la Universidad (UDC), esta última con importantes variaciones en el servicio fuera de los días lectivos y según el horario. En la Tabla 1 se muestran los intervalos habituales programados y las consiguientes frecuencias de las líneas durante la campaña de toma de datos. En conjunto pasan por la parada en hora punta 27.8 autobuses/hora con un intervalo medio de 2.2 minutos, lo que supone que sea frecuente la utilización de la segunda posición de detención. En hora punta hay un refuerzo de la línea UDC que parte de esta parada. El número total de autobuses que emplearon la parada en 2019 fue de 126573.

Línea	Intervalo en día lectivo (min)	Frecuencia (autobuses/hora)
4	12	5
5	18	3.3
12	24	2.5
20	20	3
24	30	2
UDC (hora punta)	5	12
UDC (hora valle)	10	6
TOTAL (hora punta)	2.2	27.8
TOTAL (hora valle)	3.6	16.8

Tabla 1: Líneas, intervalos y frecuencias en la parada de San Pedro de Mezonzo

Para este trabajo fue necesario realizar una toma de datos manual, dado que los datos registrados por el Sistema de Ayuda a la Explotación no recogen los movimientos de los viajeros antes de subirse al autobús, por lo que no permiten el análisis del BLT. Aunque se tomaron datos adicionales, en esta ponencia se presentarán los relativos a lo que los autores han llamado T3 (s), que es el tiempo transcurrido entre la detención del vehículo y el embarque del primer pasajero, considerándolo embarcado cuando sus dos pies están dentro del autobús. En contraste con el artículo citado previamente, no se ha distinguido el tiempo de apertura de puertas, ya que hay ocasiones en que el pasajero empieza a embarcar antes de que la puerta haya completado su apertura y las diferentes tecnologías de los modelos de autobuses dificultan el establecimiento unívoco de los tiempos totales de apertura de puertas.

Se tomaron los datos de un total de 734 autobuses en días laborables de junio de 2019, en diferentes horarios (en Novales et al., 2021 se pueden consultar más detalles sobre la toma de datos). Se ha verificado que no se producen disparidades en los valores de la media de T3 para los datos sin lluvia en función del día de la semana.

Se realizó una limpieza de los datos para eliminar los registros correspondientes a situaciones inusuales que no son consistentes con el fenómeno que se pretende estudiar, tales como detenciones del autobús previas a la posición de parada definitiva sin abrir puerta, aparcamiento ilegal en parada, incidencias inusuales que demoran el embarque, etc. Sin embargo, se mantuvieron registros correspondientes a otras circunstancias que aumentan la demora pero que se consideran parte del uso regular del sistema. Es el caso, por ejemplo, de pasajeros embarcando al autobús con un carrito de la compra o un objeto similar. Tras este proceso de depuración de datos se mantuvieron los registros correspondientes a 718 autobuses, que constituyen la muestra estudiada.

Para el registro de información sobre la intensidad de lluvia se optó también por la observación directa. Se estudiaron los datos de precipitación recogidos en las tres estaciones meteorológicas autonómicas de la ciudad, pero se descartó su utilización por estar situadas a más de 2 km de distancia de la parada de estudio. Los registros cada diez minutos de lluvia recogida no permiten estudiar el fenómeno de interés por dos motivos: en primer lugar, la lluvia es un fenómeno muy local, por lo que los registros de estaciones a 2 km de distancia no son representativos de la situación en la parada (se verificó que, en varias ocasiones, pese a estar lloviendo en la parada, las tres estaciones registraban niveles diezminutales nulos de precipitación); en segundo lugar, para este estudio, el intervalo en el que interesa conocer si existe o no precipitación dura solamente unos segundos, los que transcurren desde que el autobús se está aproximando a la parada hasta el embarque del primer viajero. Por tanto, si se pretendiese realizar un registro automatizado de lluvia, serían precisos equipos de medición locales capaces de registrar intensidades de precipitación en periodos extraordinariamente breves.

Para permitir esta recogida manual de datos de precipitación se optó por establecer una clasificación cualitativa, pero con una definición precisa basada en comportamientos de los viandantes que la hiciese extrapolable. En todo caso, la totalidad de la toma de datos se realizó por el mismo observador para evitar sesgos en esta recogida. Las categorías de lluvia definidas (Novales et al., 2021) fueron:

- 0 – sin lluvia;
- 1 – llovizna: es difícil determinar si llueve o no. La mayoría de las personas ni siquiera se molesta en abrir el paraguas;
- 2 – lluvia ligera: es indudable que llueve, pero los viandantes no se empapan. Algunas personas no se molestan en abrir el paraguas, aunque la mayoría sí lo hace.
- 3 – lluvia moderada: el nivel de lluvia es molesto, y las personas que no están a cubierto se empapan tras un corto período de tiempo. Las personas que tienen un paraguas disponible lo abren, y todas las que pueden ponerse a cubierto lo hacen.
- 4 – lluvia intensa: el nivel de lluvia es intenso, y las personas que no están a cubierto se empapan totalmente. La mayoría de los viandantes detienen su movimiento temporalmente para ponerse a cubierto y esperar a que la precipitación remita.

3. ANÁLISIS DE LA INFLUENCIA DE LA LLUVIA EN T3

La estadística descriptiva de la muestra se presenta en la Tabla 2. El número de datos registrados para cada zona de detención fue de 576 para la primera y 142 para la segunda. El valor medio de la demora conjunta por apertura de puertas y BLT (T3) es de 3.84 s para la zona de detención 1 y 4.29 s para la 2. El valor máximo de T3 para la zona de detención 1 es de 8.68 s, pero los 5 valores por encima de 6.8 s para esta zona de detención corresponden a situaciones en las que el primer pasajero que embarcó portaba un carrito de la compra (u objeto similar). Para la segunda zona de detención, el valor máximo de T3 es de 7.97 s, con solo 3 registros mayores de 6.8 s, cada uno de ellos correspondiente a situación de lluvia ligera, moderada o fuerte.

	T3 (s)	
	Zona de detención 1	**Zona de detención 2**
count	576	142
mean	3.84	4.29
std	0.93	1.09
min	1.59	2.11
25%	3.20	3.54
50%	3.72	4.18
75%	4.35	5.09
max	8.68	7.97

Tabla 2: Estadística descriptiva de la muestra

Para realizar un análisis de mayor detalle se ha optado por realizar distintas agrupaciones de datos. En la Tabla 3 se presenta la estadística descriptiva de T3 agrupando los datos por zona de detención e intensidad de lluvia. En la primera parte de la tabla se presentan todos los niveles de lluvia por separado, mientras que en la segunda parte se han creado diferentes agregaciones para ambas zonas de detención al objeto de preparar los datos para el análisis estadístico posterior. En la Figura 2 se presenta el box plot para T3 con los datos agrupados en función de la zona de detención y la intensidad de lluvia.

La muestra puede considerarse pequeña para el caso de la primera zona de detención en los niveles de lluvia 3 y 4, así como para la segunda posición con lluvia. En algunos de los análisis se emplean estos datos con propósito ilustrativo, mientras que en otras ocasiones se agrupan para tener muestras de mayor tamaño en cada una de las categorías analizadas.

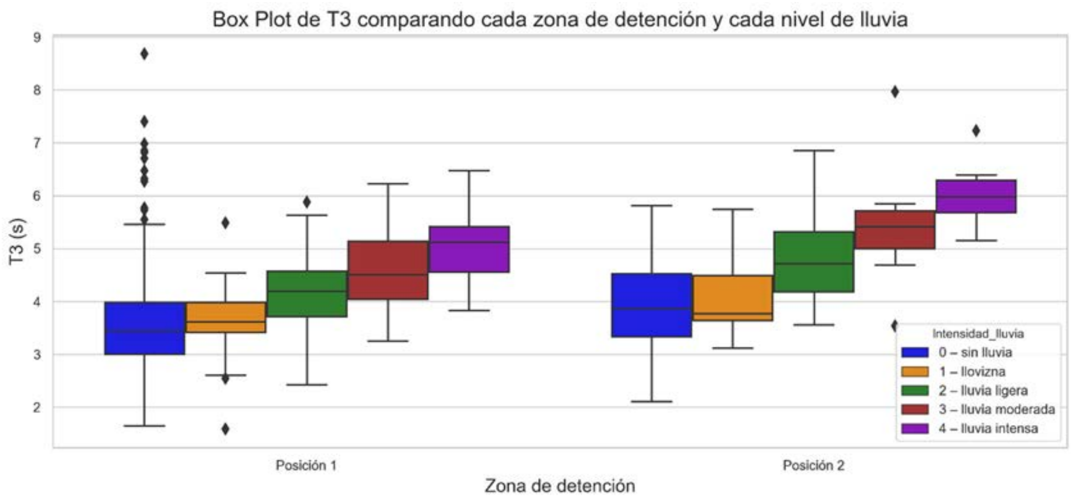

Figura 2: Box plot según zona de detención e intensidad de lluvia.

Zona de detención	Intensidad de lluvia	count	mean	std	cv	min	25%	50%	75%	max
1	0 – sin lluvia	358	3.57	0.89	0.25	1.65	3.00	3.45	3.99	8.68
	1 – llovizna	50	3.65	0.58	0.16	1.59	3.43	3.62	3.99	5.49
	2 – lluvia ligera	90	4.14	0.69	0.17	2.43	3.72	4.20	4.57	5.88
	3 – lluvia moderada	43	4.59	0.70	0.15	3.26	4.04	4.51	5.15	6.23
	4 – lluvia intensa	35	5.09	0.69	0.14	3.83	4.56	5.12	5.42	6.48
2	0 – sin lluvia	93	3.90	0.88	0.22	2.11	3.33	3.86	4.53	5.81
	1 – llovizna	10	4.10	0.88	0.22	3.12	3.64	3.77	4.49	5.74
	2 – lluvia ligera	19	4.77	0.87	0.18	3.56	4.19	4.72	5.32	6.85
	3 – lluvia moderada	10	5.43	1.12	0.21	3.54	5.00	5.42	5.72	7.97
	4 – lluvia intensa	10	5.99	0.60	0.10	5.16	5.69	5.98	6.29	7.23
1	0 + 1 + 2 + 3 + 4 – cualquier situación	576	3.84	0.93	0.24	1.59	3.20	3.72	4.35	8.68
2	0 + 1 + 2 + 3 + 4 – cualquier situación	142	4.29	1.09	0.25	2.11	3.54	4.18	5.09	7.97
1	0 + 1 – sin lluvia (o imperceptible)	408	3.58	0.86	0.24	1.59	3.06	3.50	3.99	8.68
1	1 + 2 + 3 + 4 – cualquier lluvia	218	4.27	0.81	0.19	1.59	3.71	4.24	4.73	6.48
1	2 + 3 + 4 – lluvia perceptible	168	4.45	0.78	0.18	2.43	3.96	4.43	4.97	6.48
2	1 + 2 + 3 + 4 – cualquier lluvia	49	5.02	1.08	0.22	3.12	4.13	5.16	5.73	7.97

Tabla 3: Estadística descriptiva de la muestra con datos agrupados por zona de detención e intensidad de lluvia

Del análisis de la tabla y la figura se pueden extraer algunas conclusiones. Cada aumento en el nivel de lluvia produce un aumento de la media de T3 de alrededor de 0.5 s para la primera zona de detención, excepto para el caso “1 – llovizna”. El incremento del valor medio de T3 debido a una lluvia intensa, en relación a la situación sin lluvia (1.52 s), es apreciablemente mayor que el que se produce por el uso de la segunda zona de detención en relación con la primera en situación sin lluvia (0.33 s).

En la segunda parte de la tabla puede observarse que los valores medios de T3 aumentan en alrededor de 0.9 s para el caso de “lluvia perceptible” en relación al caso de “sin lluvia o imperceptible”, para la primera zona de parada. Los datos de desviaciones típicas y coeficientes de variación muestran que los registros de cada categoría no tienen una dispersión acusada.

La figura muestra con mayor claridad cómo aumenta T3 con la intensidad de lluvia para cada una de las zonas de detención, excepto para el caso de llovizna en la segunda zona de detención. Se observa que los valores de T3 son mayores para la segunda posición de detención respecto a la primera. Para comprobar si estas diferencias son significativas se han realizado contrastes estadísticos formales, que se muestran en la Tabla 4. Los test empleados suponen normalidad de los estimadores de la media y tienen en cuenta el test de igualdad de varianzas. Se comprueba que todas las diferencias de medias son significativas a excepción de las diferencias entre los niveles “0 – sin lluvia” y “1 – llovizna” para la primera posición de detención.

Comparación $\mu_1 > \mu_2$				Test igualdad varianzas 95% dos colas H0: $\sigma_1^2 = \sigma_2^2$	Test igualdad medias 95% una cola H0: $\mu_1 = \mu_2$
Variable 1		Variable 2			
Posición	Intensidad de lluvia	Posición	Intensidad de lluvia		
2	0 – sin lluvia	1	0 – sin lluvia	Aceptar H0	Rechazar H0
1	1 – llovizna	1	0 – sin lluvia	Rechazar H0	Aceptar H0
	2 – lluvia ligera		1 – llovizna	Aceptar H0	Rechazar H0
	3 – lluvia moderada		2 – lluvia ligera	Aceptar H0	Rechazar H0
	4 – lluvia intensa		3 – lluvia moderada	Aceptar H0	Rechazar H0
1	1 + 2 + 3 + 4 – cualquier lluvia	1	0 – sin lluvia	Aceptar H0	Rechazar H0
1	2 – lluvia ligera	1	0 + 1 – sin lluvia (o imperceptible)	Rechazar H0	Rechazar H0
1	2 + 3 + 4 – lluvia perceptible	1	0 + 1 – sin lluvia (o imperceptible)	Aceptar H0	Rechazar H0
2	0 + 1 + 2 + 3 + 4 – cualquier situación	1	0 + 1 + 2 + 3 + 4 – cualquier situación	Rechazar H0	Rechazar H0
2	1 + 2 + 3 + 4 – cualquier lluvia	1	1 + 2 + 3 + 4 – cualquier lluvia	Rechazar H0	Rechazar H0

Tabla 4: Diferencias de medias de T3 para diferentes niveles de lluvia y posición de detención

Estos resultados respaldan la necesidad de considerar la influencia de la lluvia en T3, y por tanto en la demora en paradas, para calcular adecuadamente la capacidad de las paradas o para simular el funcionamiento del sistema de transporte público en estas situaciones. La diferencia de medias de T3 para cada uno de los niveles de lluvia perceptible es de alrededor de 0.5 s, dando lugar a una diferencia de alrededor de 1.5 s para el caso de lluvia intensa en comparación con la situación sin lluvia. Para un análisis binario de lluvia perceptible (2-4) frente a sin lluvia o imperceptible (0-1), la diferencia es de casi 0.9 s (0.87 s) para la posición de parada 1.

El valor medio de T3 para posición de parada 1 sin lluvia es de 3.57 s, lo que considerando un tiempo de apertura de puertas de alrededor de 1.66 s (valor obtenido en un número limitado de medidas con desviación típica 0.5 s) daría lugar a un valor medio de BLT de 1.91 s, muy similar al obtenido por Kathuria et al. (2016a) para su configuración (1.8 s). El uso de la segunda posición de detención da lugar a un aumento del valor medio de T3 (y por tanto de BLT) de 0.33 s con respecto a la primera posición para la situación sin lluvia, mientras que dicha diferencia era de 0.6 s en Kathuria et al. (2016a). Esta diferencia debida a la posición de detención es inferior a la influencia del aumento de un nivel de intensidad de lluvia.

De acuerdo con el análisis realizado, se puede proponer un incremento de BLT de 0.5 s para cada uno de los saltos entre niveles sin lluvia – lluvia ligera – lluvia moderada – lluvia intensa para la posición de detención 1, y de 1 s si solamente se considera la diferenciación entre lluvia perceptible y situación sin lluvia o imperceptible. El uso de la segunda posición de detención (en lugar de la primera) para la situación sin lluvia puede dar lugar a un incremento de 0.3 s, mientras que el incremento para cualquier situación de lluvia (niveles 1 a 4 combinados) es de 0.7 s. Estos valores son válidos para configuraciones de parada similares a la estudiada en este trabajo.

4. ANÁLISIS DE LA DISTRIBUCIÓN DE VALORES DE T3

En este apartado se realizará un análisis del ajuste de los datos de la muestra a distribuciones estadísticas estándar, y se presentarán conclusiones previas de otros autores.

La dispersión de los valores para cada nivel de precipitación y cada zona de detención se estudia mediante histogramas de frecuencias y estimación de densidades kernel (KDE). En la Figura 3 se muestra la frecuencia de observaciones para zona de detención 1 con cada nivel de lluvia y para zona de detención 2 sin lluvia. En la Figura 4 se presentan los histogramas con estimación de densidad kernel superpuestos para esos mismos casos.

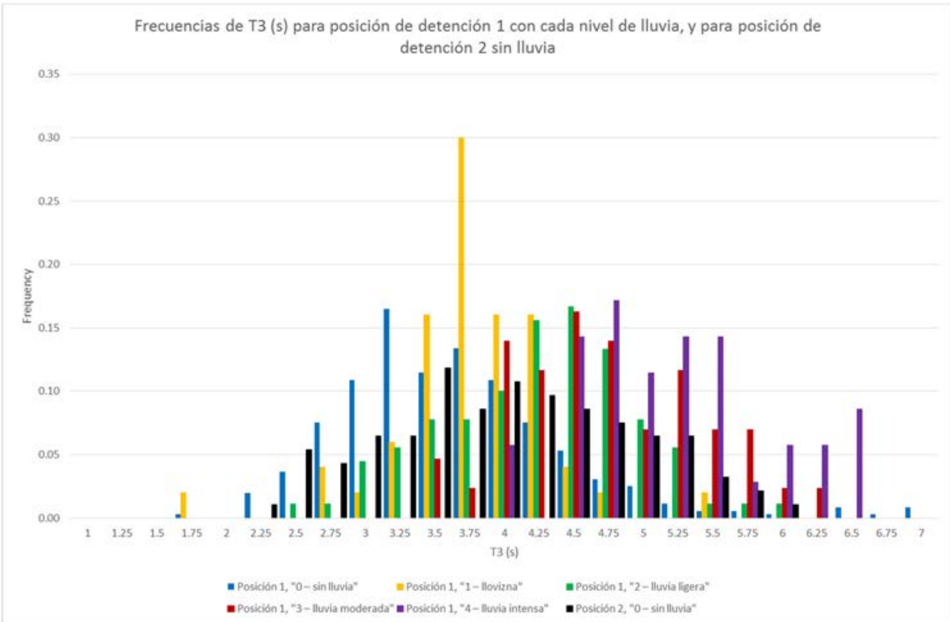

Figura 3: Frecuencia de observaciones para posición 1 con cada nivel de lluvia y para posición 2 sin Lluvia

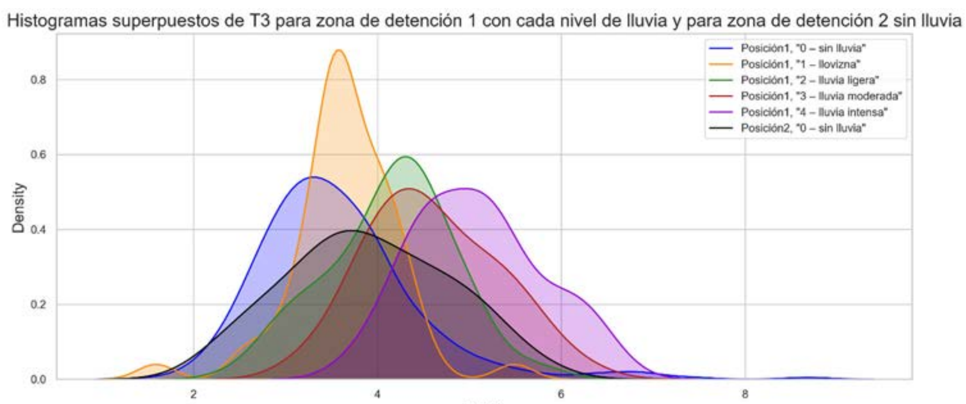

Figura 4: Estimación de densidad kernel para posición 1 con cada nivel de lluvia y para posición 2 sin lluvia.

Jaiswal et al. (2010) determinaron, mediante la utilización de gráficos de probabilidad, que el BLT sigue una distribución lognormal para cada una de las posiciones de detención analizadas. Widanapathiranage et al. (2015) determinaron que el tiempo de demora total en las estaciones de BRT sigue también una distribución lognormal, aunque no presentan contrastes formales. Kathuria et al. (2016) analizaron la distribución de BLT para cuatro períodos del día utilizando tests Kolmogorov – Smirnov y Chi-Square, concluyendo que el BLT parece seguir una distribución lognormal para dichos períodos. Estos estudios de BLT no consideran la influencia de la lluvia, como se indicó en el apartado 1, por lo que cabe esperar que el BLT en condiciones de no lluvia siga también una distribución lognormal.

Los datos recogidos en esta investigación se han analizado para diferentes agregaciones de niveles de lluvia, como se muestra en la Tabla 5. Las muestras se comparan con distribuciones teóricas normales y lognormales. Estos análisis son útiles para determinar las características de las variables, y se han empleado para seleccionar los contrastes realizados en el apartado anterior para analizar la influencia de la lluvia en T3. En general, desde un punto de vista de análisis estadístico, la normalidad es una propiedad deseable porque simplifica la aplicación de ciertas técnicas de análisis. Sin embargo, la distribución normal da lugar a ciertos inconvenientes en los procesos de simulación, debido a la presencia de valores negativos de T3 que no se pueden dar en la vida real. En este sentido, las distribuciones lognormales son más adecuadas para simulación, ya que no producen valores negativos, y pueden dar lugar a más valores en la cola derecha, lo que parece más acorde con lo que puede suceder en la realidad.

Posición	Intensidad de lluvia	Count	Mean estimation		Confidence interval 95%		Lognormal Fitting				Normal fitting			
			Value	s.e.	min	max	Test		p-value	95%	Test		p-value	95%
1	0 – sin lluvia	358	3.57	0.05	3.48	3.66	0.05	L	0.02	No	0.09	L	0.00	No
	1 – llovizna	50	3.65	0.08	3.49	3.81	0.16	L	0.00	No	0.12	L	0.08	Yes
	2 – lluvia ligera	90	4.14	0.07	4.00	4.28	0.11	L	0.02	No	0.07	L	0.3289 *	Yes
	3 – lluvia moderada	43	4.59	0.11	4.39	4.80	0.98	S-W	0.83	Yes	0.98	S-W	0.66	Yes
	4 – lluvia intensa	35	5.09	0.11	4.86	5.31	0.98	S-W	0.63	Yes	0.97	S-W	0.37	Yes
2	0 – sin lluvia	93	3.90	0.09	3.72	4.08	0.06	L	0.5776 *	Yes	0.05	L	0.8171 *	Yes
1	0 + 1 + 2 + 3 + 4 – cualquier situación	576	3.84	0.04	3.76	3.91	0.02	L	0.816 *	Yes	0.06	L	0.00	No
2	0 + 1 + 2 + 3 + 4 – cualquier situación	142	4.29	0.09	4.11	4.47	0.06	L	0.2755 *	Yes	0.07	L	0.08	Yes
1	0 + 1 – sin lluvia (o imperceptible)	408	3.58	0.04	3.50	3.66	0.05	L	0.01	No	0.09	L	0.00	No
1	1 + 2 + 3 + 4 – cualquier lluvia	218	4.27	0.06	4.16	4.38	0.05	L	0.2008 *	Yes	0.05	L	0.2049 *	Yes
1	2 + 3 + 4 – lluvia perceptible	168	4.45	0.06	4.34	4.57	0.07	L	0.07	Yes	0.06	L	0.2023 *	Yes
2	1 + 2 + 3 + 4 – cualquier lluvia	49	5.02	0.15	4.72	5.32	0.97	S-W	0.16	Yes	0.10	S-W	0.30	Yes

* Para p-value > 0.1 el test estadístico se compara con el valor asintótico en la tabla de Lilliefors

Tabla 5: Estimación de intervalos de confianza de la media de T3 (s) y ajuste a distribución normal y lognormal

Razali y Wah (2011) realizaron un análisis de la potencia de los principales contrastes estadísticos de normalidad, concluyendo que el contraste de Shapiro – Wilk es el más potente, aunque necesita modificaciones para muestras con n > 50. También establecieron que Lilliefoers siempre supera al contraste original de Kolmogorov – Smirnov en su análisis. Además, recomiendan que no se utilicen solamente técnicas gráficas en este tipo de comprobaciones, sino que se combinen con contrastes formales de normalidad y parámetros de inspección de la forma tales como los coeficientes de curtosis y asimetría estadística (skewness).

En este trabajo se usa el test de Shapiro – Wilk (S-W) para muestras de tamaño menor que 50 y el test de Lilliefors para los otros casos. Según Razali y Wah (2011) estos contrastes no dan resultados adecuados para muestras con n≤ 30, por lo que no se pueden aplicar a ciertos niveles de intensidad de lluvia para la posición de detención 2. Se han realizado también comparaciones gráficas mediante Q-Q plots así como análisis de parámetros de forma con Jarque – Bera que no se presentan en esta ponencia.

Los resultados muestran que la hipótesis de ajuste a la distribución lognormal no se puede rechazar al 95% para ninguna de las posiciones de detención cuando se consideran los datos agregados para cualquier intensidad de lluvia (niveles 0 a 4) o para situación de lluvia (niveles 1 a 4). Tampoco se puede rechazar con ese nivel de confianza para los casos de lluvia perceptible (niveles 2 a 4 agregados), lluvia moderada (nivel 3) y lluvia intensa (4) en posición de detención 1. Esto se da también para la situación sin lluvia en la posición de detención 2.

Por otra parte, la hipótesis de ajuste a la distribución normal solo se puede rechazar al 95% para los casos de posición de detención 1 sin lluvia (nivel 0), en cualquier situación (niveles 0 a 4 agregados) y en situación sin lluvia o imperceptible (niveles 0 y 1).

Para los casos de posición de detención 1 sin lluvia (0) o con lluvia imperceptible (0+1) se rechazan tanto la hipótesis de normalidad como de lognormalidad.

4. CONCLUSIONES

Esta ponencia muestra la influencia de la lluvia en los valores de T3 (y por tanto en el tiempo perdido por el autobús en la parada, BLT – Bus Lost Time –) para una parada de autobús convencional con dos posiciones de detención, considerando 5 niveles de intensidad de lluvia (de “0 – sin lluvia” a “4 – lluvia intensa”). Los valores y distribuciones obtenidas no serían directamente extrapolables a paradas con configuraciones diferentes de la presentada.

La conclusión principal es que se produce un aumento de BLT de alrededor de 0.5 s para cada aumento de nivel de intensidad de lluvia (obviando el nivel “1 – llovizna”) para la posición de parada 1. Este valor es mayor que la diferencia de BLT entre las dos posiciones de parada para tiempo seco, que con las hipótesis presentadas sería de 0.3 s. Si se considera solamente una situación binaria de “lluvia perceptible” frente a “sin lluvia o imperceptible” para la posición de parada 1, se debe considerar un aumento de BLT de 0.9 s.

Los datos recopilados, con diferentes niveles de agregación, se han comparado con las distribuciones teóricas normal y lognormal. Al objeto de realizar simulaciones, se puede suponer distribución lognormal para ambas posiciones de detención para el caso de no distinguir niveles de lluvia, así como para el caso de lluvia de cualquier intensidad. También para los casos de posición de detención 1 con lluvia moderada o intensa y para posición 2 sin lluvia. Para posición de detención 1 con llovizna o lluvia ligera se debe considerar distribución normal, en cuyo caso se pueden utilizar normales truncadas para evitar la obtención de valores negativos de T3.

Estos resultados son coherentes con valores previos obtenidos por otros autores y citados a lo largo de la ponencia. Por otra parte, en este estudio se presentan resultados de tiempo adicional de demora agregando el tiempo de apertura de puertas y el BLT, en contraposición con publicaciones previas de los autores en que se consideraban estos valores por separado. Las conclusiones obtenidas realizando esta agregación son similares a los resultados previos, pero la toma de datos puede resultar más sencilla teniendo en cuenta que la identificación visual del momento exacto en que las puertas han terminado de abrirse puede resultar compleja en algunas situaciones.

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ANALYSIS OF AN AUTONOMOUS DRIVING MODULAR BUS SYSTEM

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ABSTRACT

One of the main complaints about the performance of the bus systems is the time lost at recurrent stops along the route, that results in a low bus speed service. Among the potential measures to speed up the bus service, the introduction of the Autonomous Driving Modular Bus, able to adjust the transport unit by coupling or decoupled pods, will represent a new paradigm in the provision of service. This concept is able to maintain high stable cruising speeds to the transport unit, decoupling only one pod with passengers that may alight at the next stop. This paper analyze the potentialities of this concept in terms of user travel times and operationg cost. This work also features the formulation and analytical models to calculate the performance and oeprational variables, implementing them into two existing bus lines in Barcelona.

1. INTRODUCTION

The current commercial speed of buses in crowded areas (8-15 km/h, Vuchic, 2013) is significantly lower than other public transportation modes in competition (15-40 km/h in tramways, 24-55 km/h in subways). There are several strategies to speed up buses along the routes based on segregated lanes, double lanes, multiple boarding platforms at stops, traffic light synchronization, etc (see Kittelson and associates, 2013). Nevertheless, the travel time savings obtained are still marginal and require huge investments to deploy right of way measures or technological devices. In fact, these measures do not dramatically change the operation of buses: every transit vehicle, with passing passenger onboard, is still obliged to loose cruising speeds before and after a stop location, and is held at the stop facility during dwell time. The major challenge for bus operation would be whether the time lost performing these processes at intermediate stops can be removed from the bus motion. It means that bus services may resemble taxi systems, offering a direct door-to-door service from origins to destinations without intermediate stops. However, one of the innovation concepts that is gaining momentum and could meet this goal is the Autonomous Driving Modular Bus. With this new concept, travel times could be reduced considerably while the service quality could be upgraded. This paper is aimed at analyzing the potentialities of this concept by means of an analytical model. This model consists of several compact formulas to estimate both the user performance (travel time) and operational cost of the service. The model developed is applied to low and high demanded routes in the current Barcelona Bus Network, so the implementation of this new system will be analyzed. The less demanded line corresponds to the V5 (Zona Franca-Avinguda Pearson), while the crowded one to the H10 (Plaça de Sants-Olímpic de Badalona).

2. CONCEPT OF AUTONOMOUS DRIVING MODULAR BUS

Buses are still conceived as a classical configuration of one driver leading the bus and slowing at every stop that passengers request. In order to understand the meaning of this new technology, we must see beyond the concept of bus that we own. This new system is developed with the idea of not stopping at traffic lights neither at bus stops, with totally electric vehicles and, as its name suggest, driverless.

First, no-stopping at traffic lights is not anything new. Many on-streets public transport, like the Barcelona, Zaragoza, or Granada's tramways, rarely stop at them since activated traffic light priority measures are deployed (Estrada et al., 2009). This idea should be tested in buses with the aim to ease bus circulation in detriment of the private vehicle. Of course, this requests a complete restructuration of the current traffic lights configuration.

Second, this technology changes drastically our conception of buses. Nowadays, the word "bus" makes us thing about a large and indivisible vehicle to convey people. But the "modular" bus suggests something different; the current bus will be transformed into a convoy made of n-pods that will be able to couple and uncouple freely, like a train with its wagons. The key idea in this conception is that pods will be detached from the convoy to give service at the bus stop, while the other part of the convoy continues its journey. A brief scheme of the concept is shown in Figure 1.

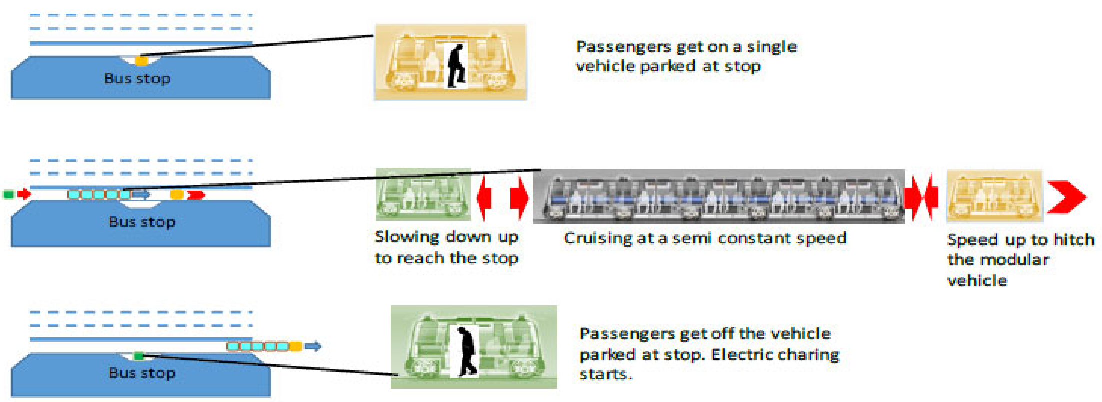

Figure 1: Operational scheme.

On the other side, there will always be a pod ready at the bus stop to depart when it detects that the convoy is approaching.This new pod will be attached to the front of the set, and the procedure will be repeated at the next bus stop. This ability of coupling and uncoupling gives passengers the chance of not stopping at every bus stop, as they will be able to move freely between pods when the convoy is running. In addition, it will be possible to couple and uncouple n-pods per stop depending on the demand that needs to be satisfied, and this ability will also ease the job when it comes to deploy more pods when the service requires it. Finally, these pods will be driverless and their traction will be based in electric batteries.

3. METHODOLOGY

The model proposed has some simplifications to make the estimation of performance variable easier to reproduce and understand. Despite this, the results obtained are not far from the real ones (Daganzo, 2009), and can therefore be taken as valid. These simplifications are to assume a uniform demand through all the line, and an equidistance spacing between stops. The model presented aims to reduce the total cost of the system (Z_T), as the sum of the agency's (Z_A) and users' (Z_U) costs (Eq. 1).

$$Z_T = Z_A + Z_U \tag{1}$$

3.1 Agency's Costs

The formula to determine all the cost incurred by the agency (Equation 2) is a combination of different factors that are introduced along the following subsections.

$$Z_A = €_L \cdot L_T + €_V \cdot V + €_M \cdot M + €_{ER} \cdot M + €_B \cdot C \cdot M \tag{2}$$

3.1.1 Infrastructure Cost (€L) and Route Length (LT)

These firsts terms of the equation do not vary regardless of the bus type: diesel, hybrid or electrical. The proxy $€_L$ represents de infrastructure deterioration, expressed in [€/km-h], and the variable L_T is the route length expressed in [km].

2.1.2 Unit Vehicle Distance Cost (€V) and Distance Covered by the Fleet (V)

The unit vehicle distance cost represents the energy cost per kilometer to run each pod plus its maintenance cost. It is expressed in [€/veh-km] and its values are (Estrada et al, 2021).

Concept	Value
Energy Cost	0,036
Pod Maintenance	0,66
$€_V$ Total	**0,696**

Table 1: Estimation of the unit distance cost, €V [EUR/veh-km].

It has been estimated that the pod's energy consumption will fall between the consumption of an electric car and bus. Considering a Tesla Model S (5 meters long) with an average consumption of 0,20 kWh/km (Motorpasion, 2019), and a 1,00-1,40 kWh/km as an average current standard bus (12 meters) consumption (Estrada et al, 2021), a pod energy consumption of 0,30 kWh/km will be considered. Then, multiplying this number by the electricity price (0,1199 €/kWh Spain average in April 2020) the energy cost is obtained. Regarding the maintenance cost, the value has been taken directly from Estrada et al (2021). On the other side, the distance covered by the fleet per hour (*V*) [veh-km/h] is calculated with the following equation.

$$V = L_T/H \cdot \#_{pods/convoy} \quad (3)$$

where H represents the headway [hours].

3.1.3 Unit Vehicle Temporal Cost (€M) and Number Vehicles (M)

The third term of the sum corresponds to the agency expenses related to temporal units, expressed in [€/veh-h], and the number of pods serving the line (*M*). These temporal expenses are determined in the following table.

Concept	Value
Driver Salary	0,00
Vehicle Amortization	1,587
Insurances, Technicians and Engineers	11,83
$€_M$ Total	**13,417**

Table 2: Estimation of the unit temporal cost, €M [EUR/veh-h].

The driver salary disappears because of the autonomous vehicles. Regarding the vehicle amortization, easymile (pod manufacturer) builds 4 meters long pods. So, considering the average acquisition price per meter of electric, hybrid and diesels buses according to Estrada et al (2021), an acquisition price of 100.000 €/vehicle will be approximated. If each pod runs for 15 years, 300 days/year and 14 hours/day, the value is obtained. The insurances and other salaries are also taken directly from Estrada et al (2021). On the other side, the number of pods needed per line are found with Eq. (4).

$$M = [V/v_{Net} + n \cdot L_T/s] \quad (4)$$

where n represents the number of pods stopped at each bus stop, v_{Net} stands for the commercial speed [km/h], and s is the separation between two bus stops [km]. Through all this model, "n" will be considered 1. Please, note that the second quotient represents the total number of stops thanks to the simplification of equidistance spacing between stops.

3.1.4 Unit Vehicle Charging Facility Cost (€ER)

The charging of pods will be performed during the 10 hours per day that they do not run. Because obtaining a reference value is quite complex, it has been taken the one from Estrada et al (2021) for electric buses with a slight modification. Now, it will be considered that each charger can supply energy to two pods simultaneously, and its lifespan should be 30 years, 300 days/year and 10 hours/day. This parameter is expressed in [€/veh-h].

Concept	Value
Facility Amortization (€/day)	9,60
Facility Maintenance (€/day)	10,00
Pods per Charger	2
$€_{ER}$ Total (€/veh-h)	**0,98**

Table 3: Cost of the Charging Facility, €ER.

3.1.5 Unit Temporal Battery Cost (€B) and Battery Capacity (C)

This new technology must satisfy that the battery endures for all day run without charging. Of course, a different charging scheme must be implemented with charging points along the road, but to simplify the model, it will be considered that pods can only be recharged at depots.

First, the term $€_B$ represents the battery cost expressed in [€/kWh-h] considering a battery lifespan of 4 years (Estrada et al, 2021). What is more, Estrada et al (2021) also suggests recommends using a battery price of 400$/kWh. So, if the pod runs 300 days/year and 14 hours/day, "€B" stands for a value of 0,021 €/kWh-h. The Battery Capacity, expressed in [kWh], is something to be determined with the results shown at the end, as it is totally related to the headway (H), stop spacing (s) and the number of pods per convoy. However, the pod's energy consumption per day is found in Eq. (5), and it satisfy the Battery Capacity (C) requirement.

$$Consump. = v_{Net}[\text{km/h}] \cdot f_{consump}[\text{kWh/km}] \cdot 14[h/day] \cdot (1 + S_{Factor}) < C \qquad (5)$$

The consumption factor is 0,30 kWh/km, the pod runs 14 hours/day, and a 20% safety factor has been taken, which is enough to cover extra consumptions like accelerations, air cooling and slopes. Finally, the commercial speed (or net speed) is approximated with the following equation.

$$v_{Net} \approx L_T/((L_T/v_{Cr}) + (H + \tau) \cdot (L_T/s \cdot \#_{pods/convoy} + 1)) \qquad (6)$$

where v_{Cr} represents de cruising speed of the pod [km/h], and "τ" the time lost by each pod for breaking and accelerating at a bus stop in comparison with a non-stopping one [hours].

3.2 Users' Costs

When users travel, they spend time and money. The money side is fully covered with the ticket price, but one way to transform this time into monetary units is using the so-called Value of Time, which takes into account the user salary. The formula used to determine the user's cost is the following one, where Λ represents the hourly demand expressed in [pax/h], β the value of time and the term into brackets is the expected door-to-door travel time of a single passenger.

$$Z_U = \Lambda \cdot \beta \cdot (A + W + IVTT) \tag{7}$$

3.2.1 Value of Time (β)

This first parameter of the equation is crucial because it translates the time spend on public transport into monetary terms. It is estimated to be 12,50 €/pax-h. This average value comes from considering a salary of 2.000 €/month and working 40 hours per week.

3.2.2 Access and Exit Time (A)

The first and last part of every journey by public transport corresponds to the walking time to the bus stop and to our destination once we get off the transport. Because one of the simplifications is to consider an evenly distributed demand, the expected access and exit time are the same, so the term "A", [hours], represents the sum of both.

$$A = ((s/4)/v_w + (s/4)/v_w = s/(2 \cdot v_w \tag{8}$$

where v_w is the walking speed of the pedestrian [km/h].

3.2.3 Waiting Time (W)

The waiting time includes factors like service regularity, traffic jams, and even smart-phones applications that tells the remaining time for the vehicle to come. Nevertheless, to simplify the calculous, considering a perfect regularity and no use of mobile phones, and with the aid of the same simplification used in 3.2.2., the expected waiting time is half the headway.

$$W = H/2 \tag{9}$$

3.2.4 In-Vehicle Travel Time (IVTT)

This is usually the bigger time when travelling by public transport. So, if an improvement of the service offered needs to be done, it is imperative to reduce the time spend by the user inside the bus. In this particular case of the autonomous and modular bus, the user will only perceive an acceleration, travelling at constant speed, and breaking time. So, the equation used is shown hereunder.

$$IVTT = (l/v_{Cr}) + \tau) \quad (10)$$

where l represents the length travelled by the user inside the pod (which has been considered as $L_T/4$ to be conservative) in [km], and "τ" the time lost by a pod to accelerate and brake in comparison with a non-stopping one.

4. RESULTS AND DISCUSSION

The Autonomous Driving Modular Bus has not been implemented yet in any city as a conventional mode of transport. Thus, these chapter will not study any real configuration but to give the optimal parameters to obtain the best configuration and minimize the total cost of the system (Z_T). These "key" parameters are the headway (*H*), the stop spacing (*s*), and number of pods per convoy. In addition, it will be also possible to determine the battery capacity (*C*).

Besides the battery capacity requirement, any public transport service must also satisfy the occupancy (O) one. It means that the service provided must be enough to cover the whole demand, otherwise there would be users that will not be able to go aboard. The occupancy is found with Eq. (11).

$$O = l/L_T \cdot \Lambda \cdot H \ \leq C_p \quad (11)$$

where Cp represents de pod capacity [pax/veh], with a value of 15 pax/pod according to Easymile. Finally, and before getting into detail with the results, it must be stated that a minimum and maximum threshold on those key parameters have been adopted to simulate a real solution, and not letting the optimization fall into an unfeasible one.

Concept	V5 Line	H10 Line
Headway (minutes)	5-15	1-7
Stop spacing (km)	0,30-0,75	0,30-0,75
Minimum pods/convoy	2	3

Table 4: Optimization thresholds.

4.1 Input parameters

The set of parameters (Guida et al., 2018; Estrada et al., 2021) used are presented below.

Parameter		V5 Line	H10 Line
Line Length (L_{Total})	km	15,20	23,70
Demand (Λ)	pax/h	396	6.247
Length covered by Users (l)	km	3,80	5,93
Free Speed (v_{Cr})	km/h	40,00	
Maximum Speed (v_{Max})	km/h	50,00	
Acceleration (a)	m/s^2	1,30	
Value of Time (β)	€/h	12,50	
Pedestrian Walking Speed (v_{walk})	km/h	4,00	
Infrastructure Cost ($€_L$)	€/km-h	7,61	
Unit Vehicle Distance Cost ($€_V$)	€/veh-km	0,696	
Unit Vehicle Temporal Cost ($€_M$)	€/veh-h	13,417	
Unit Vehicle Charging Facility Cost ($€_{ER}$)	€/veh-h	0,98	
Unit Temporal Battery Cost ($€_B$)	€/kWh-h	0,021	

Table 5: Input parameters.

4.2 Results

After combining all the equations and numbers seen up to now, and doing an optimization process with the main aim to reduce the total cost of the system (Eq. 1), the following optimal variables are found.

Parameter		V5	H10
Headway (H)	min	8,00	1,50
Stop spacing (s)	km	0,73	0,30
Battery Capacity (C)	kWh	63,96	118,03
Pods/Convoy	-	2	4
Total Pods (M)	veh	39	243
Occupancy (O)	pax/veh	13,20	39,04
Agency's Costs (Z_A)	€/h	888,40	6.922,44
Users' Costs (Z_U)	€/h	1.266,63	15.702,83
Travel Time per Trip	min	15,35	12,07

Table 6: Optimization results.

It can be clearly seen that the occupancy is always below the convoy capacity. What is more, all convoys have one extra pod in case any user wants to get off at the next bus stop.

4.3 Comparison with Current Configuration

If the optimal results obtained are compared with the current bus configuration in those lines (run by diesel, hybrid, and electric buses), the user's and total costs suffers a huge downfall. It must be clarified that the V5 is served with standard buses (12 meters), while H10 with articulated ones (18 meters).

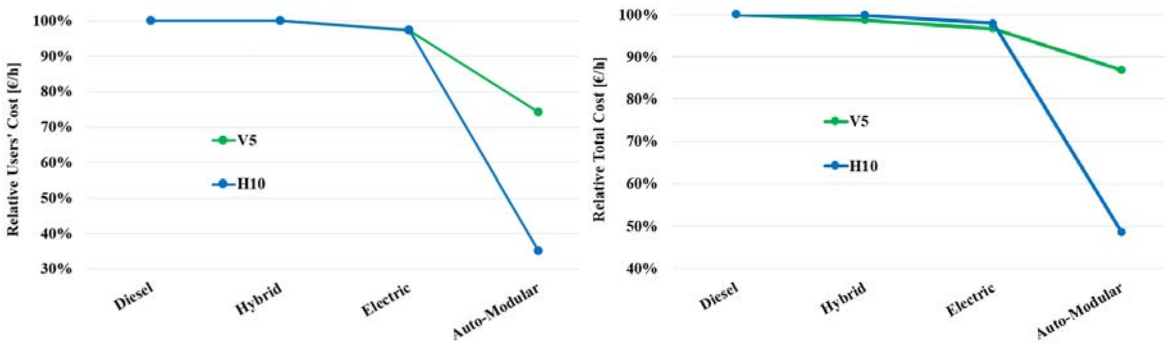

Figure 3: a) Relative Users' Cost to Diesel vehicles, b) Relative Total Cost to Diesel vehicles

As reflected in both figures, user and total costs are reduced when technology evolves to greener vehicles. In addition, one must notice the tremendous reduction the Autonomous Driving Modular Bus could bring to the system if it is implemented. However, it has been seen that the agency cost would increase considerably. In this sense, the current configuration for the H10 line run by electric buses, produces expenses up to 2.228 €/h, while the optimal one for the autonomous driving modular bus provides an agency cost of 6.922 €/h. This occurs due to the large number of pods needed in comparison with the number of buses deployed today.

5. CONCLUSION

It is inevitable to express the necessity for developing a more efficient and sustainable public transport. The results express it themself; as technology upgrades, the reduction in users' and total costs is significant. And not only that, but in environmental and health terms too.

The results also demonstrate that low-demanded lines do not perceive that change in the technology as much as the high-demanded ones. This means that for the low ones, the improvement in technology is not a key factor when it comes to determine the optimal type of bus (diesel, hybrid…). Nevertheless, the high-demanded lines experience a contrary effect; the need for a better and sustainable bus type rises in effigy while the total costs are more than halved. Thus, a first conclusion is the good behavior this new technology would have in high-demanded lines.

Although the results displayed demonstrate the high efficiency it presents, the model has been applied to a very particular case. So, it needs further study in other environments and situations, as well as an exhaust research in different operational schemes and charging itineraries within the lines, which will come in handy to reduce costs even more.

Finally, this further study also needs to focus on the elongation of these lines through the suburbs, which will improve the territorial cohesion with the peripherical neighborhoods and will connect them in a fast and efficient way.

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MULTIMODAL SHORTEST HYPERPATHS CONSIDERING CROWDING IN TRANSIT VEHICLES

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ABSTRACT

In rush hours, the onboard crowd level within transit vehicles is a problem of any large city. At the expense of time savings, some users will avoid riding crowded lines if they consider that transit vehicles do not have enough personal space. This paper presents a hypergraph model and an algorithm to find multimodal shortest hyperpaths considering the user constraints on the sequence of boarded modes and their preferences of onboard crowding levels. It is assumed that transit inter-arrivals are random. A penalty for riding transit vehicles is defined to model how the users perceive the onboard crowd levels. This penalty depends on the onboard crowd levels and the seating capacity of the vehicles. A state-automaton is used to model the user constraints on the sequence of boarded modes. To find the shortest hyperpaths, the user selects their origin, destination, the maximum number of modal transfers, and the onboard crowd level threshold. A use case on a sample multimodal network is presented.

1. INTRODUCTION

Saturated transit networks are a common issue in any large city. Whenever possible, some users will avoid large crowds or wait at stops for less crowded vehicles. Transit users not only want to reduce their travel time, other factors like cost, transfers, and occupancy also affect their route choice (Raveau et al., 2014). Haywood et al. (2017) pointed out that traveling in crowded vehicles affects users' sanity by decreasing their perception of security and increasing their anxiety and stress.

Expanding the fleet or transit routes may mitigate the effects of crowded vehicles, but these solutions are expensive or may take several years to carry out. An affordable solution to the onboard crowd problem is to display at the stops the crowd information of the incoming vehicles. This information leads to a shift in the passenger distribution among consecutive vehicles, thus reducing the onboard crowd levels (Zhang et al., 2017). Preston et al. (2017) found that it is unlikely that advanced information on onboard crowding will reduce crowd levels during peak hours; however, crowding information will reduce the users' stress and improves the passenger experience while traveling.

Since the onboard crowd information within transit vehicles is an important point to consider for some users, this paper presents a label-correcting algorithm to find multimodal shortest hyperpaths in a multimodal transport system where:

- The user restrict the sequence of boarded modes
- Selects the maximum onboard crowd levels they would like to face during their trip

To find the shortest paths and extension of the algorithm by Lozano & Storchi (2002) is developed. Since transit users experience the onboard crowd levels differently (Whelan & Crockett ,2009), a penalty is defined to model the user perception of the onboard crowd levels. It is considered that the transit modes have random-arrivals, i.e., the arrival-rate at stops is random and the waiting times can only be estimated based on particular distribution.

The subsequent sections are organized as follows. In Section 0, the related work is presented. Section 0 presents a brief introduction to hypergraph notation. Section 0 shows a hypergraph model of a multimodal transport system where: (1) the transit has random-arrivals, (2) the sequence of modes is restricted, and (3) the onboard crowd levels are considered. Section 0 presents the algorithm for finding the shortest hyperpaths bound by modal transfers and onboard crowd levels. An example of usage is shown in Section 0, and in Section 0, the conclusions are highlighted.

2. RELATED WORK

Assessing how users perceive the onboard crowding levels has been studied by conducting surveys. In 2009, Whelan & Crockett (2009) conducted a study in the UK trains to know how passengers perceive time while traveling in crowded vehicles. The authors conclude that standing passengers perceive longer travel times than seated passengers. The authors also found out that the perceived travel time of standing passenger is equal to the travel time multiplied by a scalar which depends on the onboard crowding. Let call this scalar the *riding penalty*. Qin (2014) uses the results of Whelan & Crockett (2009) and proposes three non-linear functions to estimate the *riding penalties*. Other authors like Batarce et al. (2016), Haywood et al. (2017), Tirachini et al. (2017), Bansal et al. (2019), and Márquez et al. (2019) also conducted surveys to estimate the *riding penalty*. As expected, few similarities are found in the mentioned studies as the *riding penalty* estimation depends on the network geometry, the infrastructure, and the idiosyncrasy of passengers. In the presented research, a non-linear function proposed by Qin (2014) is adapted to estimate the *riding penalty*.

Finding shortest paths in transit networks considering onboard crowd levels helps users find routes that accommodate to their personal preferences. Nuzzolo et al. (2015) and Comi & Nuzzolo (2016) developed tailored utility functions to model travel costs in scheduled transit systems. By using surveys and individual preference learning processes, the utility functions are defined and calibrated to model the user preferences on arrival times, onboard crowding levels, and total transfers. Rajapaksha et al. (2017) leverage the use of ubiquitous data sources to propose a framework that could be used to find the shortest paths with low onboard crowding levels. Katona et al. (2017) propose an ant-colony algorithm to find multimodal shortest paths where onboard crowd levels are considered. Unlike other works where the transit is schedule-based, the presented work aims to develop a routing algorithm and hypergraph model for a multimodal transport network where the transit has random-arrivals, such that the hyperpath algorithm considers:

- The user preferences on onboard crowd levels
- The user constraints on the sequence on board modes
- The user bounds of modal transfers.

In the presented paper, the crowd levels are modeled with a penalty that grows as more people get on the vehicles, and according to the reviewed research, this is how people perceive the crowd as the vehicle fills up. The penalty can be calibrated for a particular user or situation (commuting vs. leisure trip), but the calibration procedure is out of the paper's scope. Although the works mentioned in the last paragraph consider the onboard crowding levels for the path computation, the authors fail to present a model of how they estimate the crowding levels.

3. PRELIMINARIES

A directed hypergraph is a pair $H = (V, E)$, where V is the set of nodes and E is the set of arcs and hyperarcs. An arc $a \in E$ is defined as a pair of nodes $a = (i, j)$ where $\{i, j\} \subset V$. A hyperarc $e \in E$ is defined as the pair $e = \big(t(e), h(e)\big)$ where $t(e) \subset V$ is the set of *tail* nodes and $h(e) \subset V$ is the set of *head* nodes (Voloshin, 2009). A hyperarc $e = \big(i, h(e)\big)$ is a *support* hyperarc and a hyperarc $e' = \big(i, h'(e)\big) : h'(e) \subseteq h(e)$ is a *contained* hyperarc (Lozano & Storchi, 2002). Fig shows a directed hypergraph where $e_1' = (1,7)$ is a *contained* hyperarc of the *support* hyperarc $e_1 = (1, \{1,7\})$.

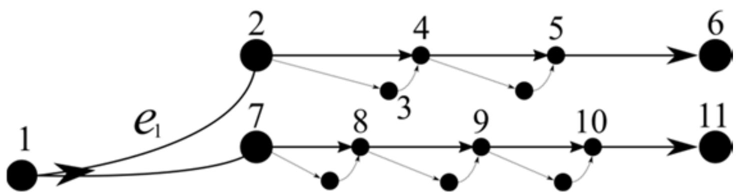

Figure 1: Representation of a directed hypergraph

Let $B(j)$ be a set of arcs $a \in E$ and *contained* hyperarcs $e' \in E : |h'(e)| = 1$ entering to the node j, i.e., $B(j) = \{a = (i,j) \in E$ and $e' = (i',j) \in E : \{i,i',j\} \subset V\}$ (López & Lozano, 2020). For example, in the hypergraph shown in figure 1 $B(4) = \{a = (2,4), e' = (3,4)\}$.
A path r_{id}, that connects an origin o and a destination d is a sequence of nodes, arcs and hyperarcs. A hyperpath p_{id} is the minimum set of acyclic paths r_{id}, such that the destination d is connected to any node that belongs to r_{id} (Nguyen & Pallottino, 1989). A sub-hyperpath $p_{id}(l)$ from the node i to the node d associated to the line l is compose by a *contained* hyperarc $e' = (i,j)$ and a set of consecutive arcs $\{(j,j_1),(j_1,j_2) \dots (j_{n-1},d)\}$, such that the *contained* hyperarc and all the arcs are associated to a unique transit line. In figure 1 the sub-hyperpath $p_{1,6}(l) = \{(1,2),(2,4),(4,5),(5,6)\}$.

4. HYPERGRAPH MODEL

Let H be a hypergraph that models a multimodal transportation system, such all transit modes have random-arrivals. The hypergraph $H = (V,E,M)$ where, V is the set of nodes, E is the set of arcs and hyperarcs and $M = \{M1, M2, M3, M4\}$ is the set of modes such that:

- $M1 \coloneqq$ Pedestrian mode
- $M2 \coloneqq$ Bicycle mode
- $M3 \coloneqq$ Non-rail transit modes
- $M4 \coloneqq$ Rail transit modes
- $M5 \coloneqq$ Modal transfers

The arcs $(i,j) \in E$ model the pedestrian, bicycle and modal transfers networks. The travel time of an arc $(i,j) \in E$ is defined as τ_{ij}. Two consecutive stops of the same transit line are modeled with one *contained* hyperarc $e' = (i,j)$ and two arcs (j,k) and (j,m), where e' represents boarding a transit vehicle at stop i, (j,k) represents riding the vehicle from stop i to stop k and descending at stop k and (j,m) represents riding the vehicle from stop i to stop k and not descending at the stop k.

Since the inter-arrival of transit vehicles is random, the waiting time at stops depends on the transit lines the user is willing to board to get to the destination. Let $e = \big(i,h(e)\big)$ be a *support* hyperarc representing the set of lines stopping at i. Each *contained* hyperarc of e is associated with one of the lines stopping at i. Let L_i be the set of transit lines stopping at i associated with the *support* hyperarc $e = \big(i,h(e)\big)$. Given an origin and a destination, it is defined the *attractive set* of lines, $L_i^{e^b} \subseteq L_i$, such that at stop i, the user is willing to board the first arriving line in $L_i^{e^b}$ to reach the destination. The *attractive set* defines the concept of *boarding* hyperarc $e^b = \left(i,h(e^b)\right) : h(e^b) \subseteq h(e)$ where each *contained* hyperarc of e^b is associated with one line in the *attractive set* (Lozano & Storchi, 2002).

Next are defined four concepts for the lines contained in the *attractive set* (Spiess & Florian, 1989):

- φ_{ij}^{l} is the arrival-rate of the line l associated with the *contained* hyperarc $e' = (i, j)$
- ϕ_{e^b} is the arrival-rate of the lines contained in the *attractive set*. It is defined as $\phi_{e^b} = \sum_{j \in h^b(e)} \varphi_{ij}^{l}$ such that, $l \in L_i^{e^b}$ and $e'_l = (i, j)$ is a *contained* hyperarc of the *boarding* hyperarc e^b
- $\omega_{e^b} = 1/\phi_{e^b}$ is the waiting time of the lines in the *attractive set*
- $\pi_{e^b, l} = \varphi_{ij}^{l}/\phi_{e^b}$ is the probability of boarding the line l in the *attractive set*

The user constraints on the sequence of transport modes are modeled with a state automaton and are described as follows. Lozano & Storchi (2002) defined the *viability* of a hyperpath for knowing which combinations of modes are admissible according to the constraints on the sequence of boarded modes. A hyperpath is *viable* if all the sub-hyperpaths satisfy the constraints on the sequence of boarded modes.

The combination of boarded modes in a hyperpath is indicated with the *state* of the hyperpath. In this paper, it is assumed that the bicycle and rail modes are constrained, i.e., if one of these modes is taken and then left, then the mode cannot be retaken in any other part of the trip. Since the hypergraph H has two constrained modes, eight combinations of modes are *viable*, and eight *states* can be associated with the hyperpaths.

The *deterministic finite state automaton* (DFA) shown in figure 2 defines the sequence of *viable states* and is used to know which hyperpaths are *viable*. The DFA is defined by the graph $A = (S, M, \gamma, 0, F)$ where: $S = \{0,1,2,3, \dots 8\}$ is the set of *states*, $M = \{M1, M2, M3, M4, M5\}$ is the set of modes, 0 is the initial *state*, and $F = \{1,4,6,8\}$ is the set of *states* for finishing trips. All trips end by foot so all *states* in F include the pedestrian mode (see figure 2). Finally, the function $\gamma(m, m', s) = s' : \gamma: M \times M \times S \rightarrow s$, models the arcs of the DFA, i.e., the tuple (s, s') is an arc in the DFA if it is possible to transfer from the mode m to the mode m' while maintaining the constraints on the sequence of boarded modes.

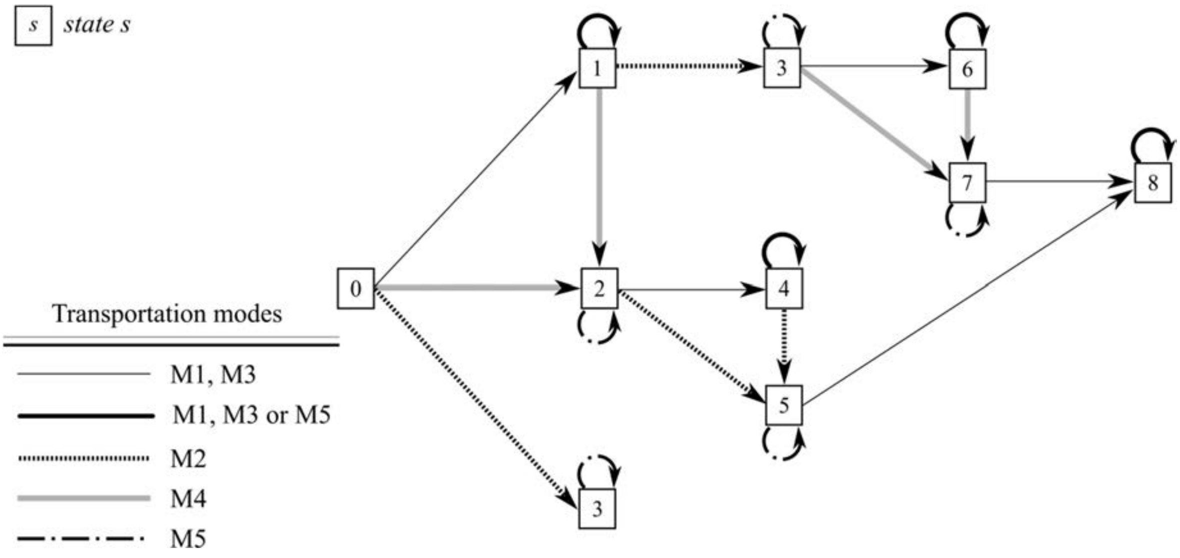

Figure 2: DFA graph with bicycle and rail transit mode restrictions

For each pair of *states* s and s', such that the modes accepted in s are also accepted in s', it is possible to define a relationship to know which *state dominates* the other. This relationship defines an order between any pair of hyperpaths for knowing which hyperpath has a better chance to grow. Artigues et al. (2013) defines the *dominance* between *states* as follows:

Definition 1. *Let s and s' be two states such that all modes accepted in s are also accepted in s'. Define $s \ll s'$, s' dominates s, if for any modes $m \in M$ and $m' \in M$, such that m is a feasible mode for s, one of the following conditions holds:*

- $\delta(m, m', s') = \emptyset$,
- $\delta(m, m', s') = \delta(m, m', s)$
- $\delta(m, m', s) = s$ and $\delta(m, m', s') = s'$.

With the Definition 1 the set of *states* dominating s, $PS_s = \{s' \in S : s \ll s'\}$, is obtained. The *hyper transition* of *states* is defined to get the resulting *state* when a boarding hyperarc e concatenates two hyperpaths. For example, if $e = (i, h(e) = \{j, k\})$ concatenates the hyperpaths $p_{jd}^{s_x}$ and $p_{kd}^{s_y}$, then *hyper transition* of the *states* is $s_x \circ s_y = s_e$, such that s_e indicates the combination of modes used in $p_{jd}^{s_x}$ and $p_{kd}^{s_y}$ (Lozano & Storchi, 2002).

Let p_{id}^{s} be a hyperpath from i to d with *state* s. The *expected travel time* of p_{id}^{s} (Lozano & Storchi, 2002) is recursively defined in Equation 1.

$$\lambda_{id}^{s} = \Big\{ \big[\tau_{ij} + \lambda_{jd}^{s'} \text{ if } (i,j) \text{ is an arc}\big] \; or \; [\omega_{e^b} + \textstyle\sum_{j \in h(e^b)} \pi_{e^b,l} \cdot \lambda_{jd}^{s'} \text{ if } e^b \text{ is a } boarding \text{ hyperarc}] \Big\} \tag{1}$$

The *penalty for riding* a transit vehicle models the user perception of the onboard crowding levels. It is assumed that:

- No penalty is given if the user travels seated or there is enough personal space in the vehicle.
- A penalty is given if the personal space in the vehicle is limited.
- The user will not board vehicles at full capacity.

The *penalty for riding* a transit vehicle is an exponential function that depends on the seating capacity and the people on board, this penalty is described as follows. Let $e' = (i, j)$ be a *contained* hyperarc and let (j, k) and (j, m) two arcs. The *contained* hyperarc e' represents boarding a transit vehicle at stop i. The arc (j, k) represents riding the vehicle from stop i to stop k and descending at stop k. The arc (j, m) represents riding the vehicle from stop i to stop k and continuing the trip.

Let $\theta_{jk}(l) = f_{jk}(l)/s(l)$ be the *seat load factor* of the arc (j, k) associated to the line l, such that $f_{jk}(l)$ is the average passenger flow of the arc (j, k) associated to the line l and $s(l)$ is the number of seats of a line l vehicle. Note that $\theta_{jk}(l) = \theta_{jm}(l)$ since both arcs (j, k) and (j, m) represent riding a transit vehicle of the line l from stop i to stop k.

The *seat load factor* may change from one stop to another. For example, consider the sub-hyperpath $p_{id}(l) = \big(e = (i, j), (j, j_1), (j_1, j_2), (j_2, j_3), (j_3, d)\big)$, such that $\{i, k_1, k_2, k_3, d\}$ are consecutive stops of l, see figure 3. A user boarding at stop i and going to stop d, will experience different levels of crowd during the trip, hence the *seat load factor* might change for consecutive arcs, i.e., $\theta_{jj_1}(l) \neq \theta_{j_1j_2}(l) \neq \theta_{j_2j_3}(l) \neq \theta_{j_3d}(l)$. An example of such phenomenon is represented in figure 3 where the passengers getting on and off the vehicle are represented with the red and green pawns, respectively, and the user going from i to d is the black pawn. For instance in figure 3 $\theta_{j_1j_2}(l) \neq \theta_{j_2j_3}(l)$, because from stop j_1 to stop j_2 there are three passengers in the vehicle while from stop j_2 to stop j_3 there are two.

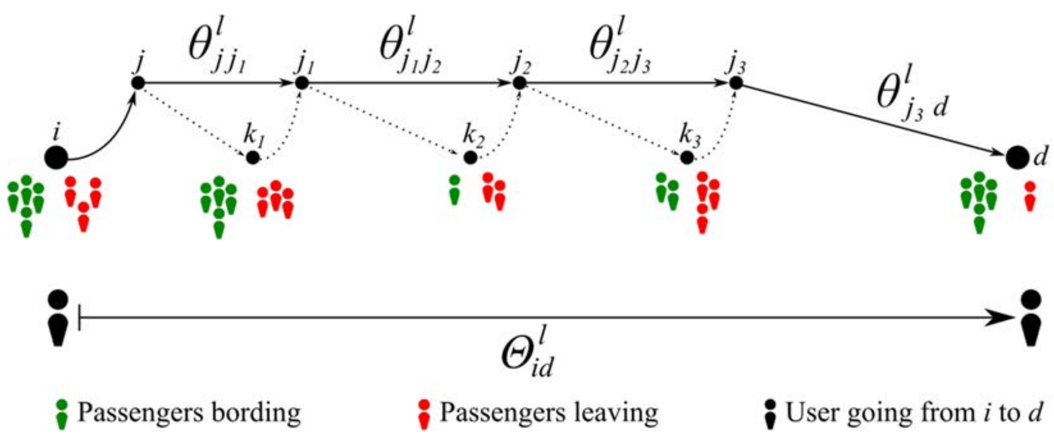

Figure 3: Seat load factor of the line l from the stop i to the stop d

To estimate the *seat load factor* variations of the sub-hyperpath $p_{id}(l)$, in Equation 2 is recursively defined the line *seat load factor* $\Theta_{id}(l)$ of the sub-hyperpath $p_{id}(l)$ as the incremental weighted average of the arc *seat load factors*.

$$\Theta_{id}(l) = \left\{\left[(\tau_{ij}\left(\theta_{ij}(l) - \Theta_{jd}(l)\right))/T_{id}(l) + \Theta_{jd}(l) \text{ if } (i,j) \text{ is an arc}\right] \; or \; [\Theta_{jd}(l) \text{ if } (i,j) \text{ is a } contained \text{ hyperarc}]\right\} \quad (2)$$

such that, $T_{id}(l)$ is the in-vehicle travel time of the sub-hyperpath $p_{id}(l)$.

To capture the dispersion of the arc *seat load factors* of $p_{id}(l)$, in Equation 3 is recursively defined the standard deviation of the arc *seat load factor*, $\sigma_{id}(l)$, of the sub-hyperpath $p_{id}(l)$.

$$\sigma_{id}(l) = \left\{\left[\sqrt{((\left(\sigma_{jd}(l)\right)^2 + \tau_{ij}\left(\theta_{ij}(l) - \Theta_{jd}(l)\right)\left(\theta_{ij}(l) - \Theta_{jd}(l)\right))/T_{id}(l))} \text{ if } (i,j) \text{ is an arc}\right], \; or \; [\sigma_{id}(l) \text{ if } (i,j) \text{ is a } contained \text{ hyperarc}]\right\} \quad (3)$$

Users are penalized for riding transit vehicles according to their preferences on onboard crowding levels. For example, some users might like to travel seated all the time, so they are penalized if $\Theta_{id}(l) > 1$. Two bounds are set; one is for know when a user is not penalized for riding transit vehicles, and the other is for know when a user will not board a transit vehicle. Let $\underline{\delta}$ be the *lower seat load factor*, such that if $\Theta_{id}(l) < \underline{\delta}$ the user is not penalized for riding the line l from the stop i to d. Let $\overline{\delta}$ be the *upper seat load factor*, such that if $\Theta_{id}(l) > \overline{\delta}$ the user will not ride the line l from the stop i to d. In Equation 4 is defined the *penalty for riding* the sub-hyperpath $p_{id}(l)$ (Qin, 2014).

$$r_{id}(l) = \{[0 \text{ if } \Theta_{id}^{l} < \underline{\delta}], \; [T_{id}(l)/(1 + e^{1000(1-\Theta_{id}(l))}) + \; \beta T_{id}(l) e^{4(\Theta_{id}(l)-\underline{\delta})} \text{ if } \underline{\delta} \leq \Theta_{id}^{l} \leq \overline{\delta}], \; [\infty \text{ if } \Theta_{id}^{l} > \overline{\delta}]\} \quad (4)$$

such that, $\beta \in [0, \infty\}$ is a parameter that models the user haste, bigger β's means the penalties are more considerable for ridding crowded buses. In contrast, with smaller β's, the user is less penalized. For $\Theta_{id}(l) > \overline{\delta}$ the penalty for riding the sub-hyperpath $p_{id}(l)$ is infinity, meaning that users will not ride the line l from node i to node d.

Figure 4 shows the plot of $r_{id}(l)$ over $\Theta_{id}(l)$ such that $T_{id}(l) = 1$, $\underline{\delta} = 1.4$, $\overline{\delta} = 2.5$ and $\beta \in \{0, 0.25, 0.5, 0.75, 1\}$.

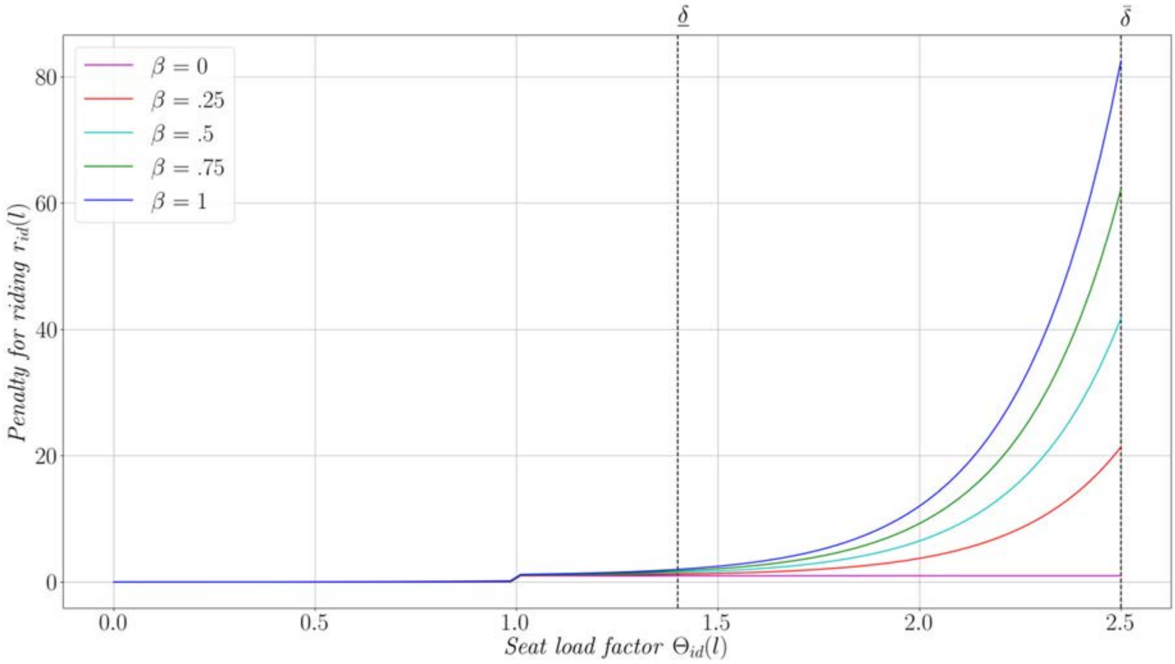

Figure 4: Penalty for riding with different β parameters

As shown in figure 4, $r_{id}(l)$ is close to zero when $\beta = 0$ (see magenta line), i.e., impatient or hasty users are not penalized for riding crowded transit since they value more their time and will ride any line that takes them fast to their destination. While with bigger β's, the penalty for riding transit grows exponentially, in this case, users are highly penalized, and therefore less crowded lines are preferred.

To compute the *penalty for riding* the hyperpath p_{id}^{s}, the *expected seat load* factor of p_{id}^{s} is recursively defined in Equation 5.

$$\Theta_{id}^{s} = \left\{\left[(\mathrm{T}_{id}(l)\left(\theta_{id}(l) - \Theta_{jd}^{s'}(-l)\right))/\mathrm{T}_{id}^{s} + \Theta_{jd}^{s'}(-l) \text{ if } (i,j) \text{ is an arc}\right],\ \left[\sum_{j\in h(e^b)} \pi_{e^b,l} \cdot \Theta_{jd}^{s} \text{ if } e^b \text{ is an hyperarc}\right]\right\} \quad (5)$$

such that, T_{id}^{s} is the in-vehicle travel time of p_{id}^{s}, $\Theta_{jd}^{s'}(-l)$ is *expected seat load factor* of the hyperpath $p_{jd}^{s'} \setminus p_{jd}(l)$, i.e., the sub-hyperpath $p_{jd}(l)$ is not included in the computation of $\Theta_{jd}^{s'}(-l)$.

The standard deviation of the *expected seat load factor* of $p_{id}(t)$ is recursively defined in Equation 6.

$$\Theta_{id}^{s} = \left\{\left[\sqrt{(((\sigma_{jd}^{s'}(-l))^{2} + \mathrm{T}_{id}(l)\left(\Theta_{id}(l) - \Theta_{jd}^{s'}(-l)\right)(\Theta_{id}(l) - \Theta_{id}^{s}))/\mathrm{T}_{id}^{s})} \text{ if } (i,j) \text{ is an arc}\right],\ \left[\sum_{j\in h(e^b)} \pi_{e^b,l} \cdot \sigma_{jd}^{s'} \text{ if } e^b \text{ is an hyperarc}\right]\right\} \quad (6)$$

such that, $\sigma_{jd}^{s'}(-l)$ is *expected seat load factor* of the hyperpath $p_{jd}^{s'} \setminus p_{jd}(l)$.

Finally, the *penalty for riding* the hyperpath p_{id}^{s} is defined in Equation 7.

$$r_{id}^{s} = \{[0 \text{ if } \Theta_{id}^{s} < \underline{\delta}],\ [\mathrm{T}_{id}^{s}/(1 + e^{1000(1-\Theta_{id}^{s})}) +\ \beta \mathrm{T}_{id}^{s} e^{4(\Theta_{id}^{s} - \underline{\delta})} \text{ if } \underline{\delta} < \Theta_{id}^{s} \leq \overline{\delta}], \\ [\infty \text{ if } \Theta_{id}^{s} > \overline{\delta}]\} \quad (7)$$

5. SHORTEST HYPERPATH ALGORITHM

A label-correcting algorithm is presented for finding the shortest hyperpaths. The algorithm finds a set of hyperpaths with minimum *expected travel time*, bounded by modal transfers and *seat load factors*. The pseudo-code of the algorithm is shown in Section 5.1. Before starting the shortest hyperpath computation, users select their origin $o \in V$, destination $d \in V$, maximum modal transfers w_{max}, and *seat load factors* bounds ($\underline{\delta}$ and $\overline{\delta}$). The interval from $\underline{\delta}$ to $\overline{\delta}$ is divided into two equal parts by δ' to obtain the *load factor levels* $\delta_1 = \underline{\delta}$, $\delta_2 = \delta'$ and $\delta_3 = \overline{\delta}$. The set P_i is created for storing all *viable* hyperpaths starting at node i.

The sets of node-*state* pairs P_{now}, P_{next}, and Q are created for looping through the arcs in $B(j)$. On the first iteration $P_{now} = \{[d, 0]\}$ and $P_{next} = \emptyset$ and $Q = \emptyset$. Storing elements in P_{now}, P_{next} and Q are for finding the shortest hyperpaths in incremental order with respect to *load factor levels* and modal transfers. The shortest hyperpaths with no modal transfers and *load factor level* below δ_1 are found in the first round. Then, the algorithm finds the shortest hyperpaths with no modal transfers and *load factor level* below δ_2. The hyperpaths with no modal transfers and *load factor level* below δ_3 are found on the next round. After all the *load factor levels* are scanned, the number of modal transfers w is incremented by one unit, and the algorithm finds the shortest hyperpaths with one modal transfer and *load factor level* below δ_1; the process is repeated for δ_2 and δ_3. The algorithm ends when $w > w_{max}$ or when all *load factor levels* are scanned for each modal transfer, i.e., $P_{now} = \emptyset$.

All labels of the algorithm are initialized as follows:

- $\lambda_{id}^{s} = \infty, w_{id}^{s} = 0 \ \forall\ i \in V$ and $s \in S$
- $C_{e^b}^{*} = \infty, \Phi_{e^b}^{*} = \infty, h_{e^b}^{*} = \emptyset \ \ \forall\ e^b \in E$
- $\lambda_{dd}^{0} = 0; w = 0; \delta = \delta_1\ ; P_{now} = \{[d, 0]\}; P_{next} = \emptyset; \mathrm{Q} = \emptyset$
- $P_i = \emptyset\ \forall\ i \in V \setminus \{d\}; P_d = \{p_{dd}^{0}\}$

If $P_{now} \neq \emptyset$, $\delta \leq \overline{\delta}$ and $w \leq w_{max}$, get $(i, j) \in B(j)$ and check if the last *expected travel time* of p_{jd}^{s} $(last(p_{jd}^{s}))$ is greater than the actual *expected travel time* of p_{jd}^{s}. This condition eliminates *dominated* hyperpaths by checking if in previous loops a fastest hyperpath was found.

The sub-procedures *getLambda* and *getHyperLambda* concatenates arcs and *contained* hyperarcs, respectively. The procedure *getLambda* concatenates (i,j) to hyperpath p_{jd}^{s} as follows:

- If $\Theta_{jd}^{s} > \overline{\delta}$ or $\theta_{ij}(l) > \overline{\delta}$ the concatenation is canceled because of the user restriction on *seat load factors*.
- With the function *getStateAndTransfers*, get the *state* s' that results from concatenating (i,j) with the hyperpath p_{jd}^{s} (see the DFA shown infigure 2). If the concatenation produces more than w_{max} modal transfers, the hyperpath is not *viable* and the procedure terminates
- Check if $\tau_{ij} + \lambda_{jd}^{s}$ is lower than $\lambda_{id}^{s'} : p_{id}^{s'} \in P_i$. If the condition does not hold, the new hyperpath is no generated because it is *dominated* by $p_{id}^{s'}$. Otherwise, continue to the next step
- Check if $\tau_{ij} + \lambda_{jd}^{s}$ is lower than $\lambda_{id}^{s''} : p_{id}^{s''} \in P_i$ for at least one $s'' \in PS_s$. If the condition does not hold, the new hyperpath is no generated because it is *dominated* by at least one $p_{id}^{s''} \in P_i : s'' \in PS_s$. Otherwise, continue to the next step.
- Concatenate (i,j) with the hyperpath p_{jd}^{s} to generate a *viable* hyperpath $p_{id}^{s'}$ and add $p_{id}^{s'}$ to P_i
- If the mode of (i,j) is $M2$ or $M3$. Compute $\Theta_{id}(l)$, $\sigma_{id}(l)$, $r_{id}(l)$, $\Theta_{id}^{s'}$, $\sigma_{id}^{s'}$, and $r_{id}^{s'}$ with Equations (2-7). If the mode of (i,j) is different from $M2$ or $M3$, then $\theta_{id}(l) = \theta_{jd}(l)$, $\sigma_{id}(l) = \sigma_{jd}(l)$, $r_{id}(l) = r_{jd}(l)$, $\Theta_{id}^{s'} = \Theta_{jd}^{s}$, $\sigma_{id}^{s'} = \sigma_{jd}^{s}$, and $r_{id}^{s'} = r_{jd}^{s}$
- If the mode of (i,j) is a modal transfer, add the pair $[i,s']$ to Q, unless it is already in there. If the mode of (i,j) is not a modal transfer consider the following cases:

    - If $\theta_{ij}^{l} \leq \delta$ add $[i,s']$ to P_{now}, unless it is already in there
    - If $\theta_{ij}^{l} > \delta$ add $[i,s']$ to P_{next}, unless it is already in there

The procedure *getHyperLambda* concatenates the *contained* hyperarc $e' = (i,j)$ to hyperpath p_{jd}^{s} as follows:

1. If $\Theta_{jd}^{s} > \overline{\delta}$, the concatenation is canceled because the restrictions on *seat load factors*
2. Check if $p_{id}^{\hat{s}} \in P_i$, such that $e^b = \{i, h^b(e)\}$ is the last hyperarc of $p_{id}^{\hat{s}}$. If $p_{id}^{\hat{s}} \neq \emptyset$ then $s_e = s \circ \hat{s}$, otherwise $s_e = s$
3. If $\lambda_{jd}^{s} \geq \lambda_{id}^{\hat{s}}$ the hyperpath p_{jd}^{s} is *dominated* by $p_{id}^{\hat{s}}$ and the concatenation does not proceed. Otherwise, continue to the next step

4. Let $e^b = (i, h^b(e) \cup \{j\})$, compute $\Phi^*_{e^b}$ as the sum of the average arrival-rates of all the lines associated to e^b. If $\Phi^*_{e^b} = \varphi_{ij}$ continue to step 4.1, otherwise continue to step 4.2
   4.1. Add the estimated waiting time of the *contained* hyperarc (i,j) to the *expected travel time* of the hyperpath p^s_{jd}, $C^*_{e^b} = \frac{1}{\varphi^l_{ij}} + \lambda^s_{jd}$. Since (i,j) is a *contained* hyperarc and p^s_{jd} is a hyperpath starting at i, then the *expected seat load factor* and the *penalty for riding* are exported inherited from the hyperpath p^s_{jd}, i.e., $\Theta^*_{id} = \Theta^s_{jd}$ and $r^*_{id} = r^s_{jd}$.
   4.2. Compute $C^*_{e^b}$ as the incremental weighted average of $C^*_{e^b}$ and λ^s_{jd}. In this case, the algorithm is concatenating the hyperpaths p^s_{jd} and $p^{\hat{s}}_{id}$ with the *contained* hyperarc (i,j). Hence is necessary to compute (in Section 5.1, see the sub-procedure *getIncHPenalty*):
      4.2.1. $\Theta^*_{e^b}$ as the incremental weighted average of $\Theta^*_{e^b}$ and Θ^s_{jd}
      4.2.2. $\sigma^*_{e^b}$ as the incremental weighted average of $\sigma^*_{e^b}$ and σ^s_{jd}
      4.2.3. $r^*_{e^b}$ with the Equation 7
5. If $C^*_{e^b} \leq \lambda^{s_e}_{id} : \lambda^{s_e}_{id} \in P_i, s_e = s \circ \hat{s}$, and $\Theta^*_{e^b} \leq \overline{\delta}$, get the set PS_{s_e} and continue to the next step, otherwise the new hyperpath is dominated by $p^{s_e}_{id}$ or the new hyperpath is restricted by the user *upper load factor*.
6. If $C^*_{e^b} \leq \lambda^{s''}_{id}$ for at least one $s'' \in PS_{s_e}$, continue to the next step. Otherwise, the new hyperpath is not generated because it is *dominated* by $p^{s''}_{id}$
7. Concatenate $e' = (i,j)$ with the hyperpath p^s_{jd} (and with the hyperpath $p^{\hat{s}}_{id}$, if exists) to produce a new *viable* hyperpath $p^{s_e}_{id}$
8. Make $r^*_{e^b} = r^{s_e}_{id}$, $\Theta^*_{e^b} = \Theta^{s_e}_{id}$, $r_{jd}(l) = r_{id}(l)$ and $\Theta_{jd}(l) = \Theta_{id}(l)$. Note that the penalty for riding the sub-hyperpath $p_{id}(l)$ and the *seat load factor* of $p_{id}(l)$ are inherited from the sub-hyperpath $p_{jd}(l)$ because (i,j) is a *contained* hyperarc.
9. Add $[i, s_e]$ to P_{now}, unless it is already in there.

When the algorithm ends, it generates a solution set, P_i, of *viable* hyperpaths. To obtain the *Pareto-Optimal* set of solutions, select from P_i the non-dominated hyperpaths regarding the *expected travel time*, the modal transfers, and the *penalty for riding*. From the *Pareto-Optimal* set, the users choose the hyperpath they prefer according to their personal views, such as the number of transfers or onboard crowding conditions of the ride. The *expected seat load factor* standard deviation, σ^s_{id}, can be used for comparing two hyperpaths in terms of the passengers onboard. For instance, if two hyperpaths have similar penalties but one of them has a smaller σ, a user may prefer the hyperpath with the small σ since the onboard crowd will be more stable during the trip.

5.1. Shortest hyperpaths algorithm pseudo-code

Procedure. *Combined Real-Time Shortest Hyperpaths*

$\lambda_{id}^{s} = \infty, w_{id}^{s} = 0 \; \forall \; i \in V$ and $s \in S$

$C_{e^b}^{*} = \infty, \Phi_{e^b}^{*} = \infty, h_{e^b}^{*} = \emptyset \;\; \forall \; e^b \in E$

$\lambda_{dd}^{0} = 0; w = 0; \delta = \underline{\delta}; P_{now} = \{[d, 0]\}; P_{next} = \emptyset; \mathrm{Q} = \emptyset$

$P_i = \emptyset \; \forall \; i \in V \setminus d; P_d = \{p_{dd}^{0}\}$

WHILE $w \leq w_{max}$ AND $P_{now} \neq \emptyset$

WHILE $\delta \leq \overline{\delta}$ AND $P_{now} \neq \emptyset$

WHILE $P_{now} \neq \emptyset$

SELECT $[j, s]$ FROM P_{now}

$P_{now} = P_{now} \setminus [j, s]$

FOR $(i, j) \in B(j)$

IF $\lambda_{jd}^{s} < last(\lambda_{jd}^{s})$

$last(\lambda_{jd}^{s}) = \lambda_{jd}^{s}$

IF (i, j) is an arc

$getLambda(s, (i, j), \lambda_{jd}^{s})$

IF (i, j) is a *contained* hyperarc

$getHyperLambda(s, (i, j), \lambda_{jd}^{s})$

$P_{now} = P_{next}; P_{next} = \emptyset; \delta = \delta + \delta'$

$P_{now} = Q; Q = \emptyset; w = w + 1; c = \underline{\delta}$

Sub-procedure. $getLambda(s_x, (i, j), \lambda_{jd}^{s_x})$

IF $\Theta_{jd}^{s} > \overline{\delta}$ OR $\theta_{ij}(l) > \overline{\delta}$

BREAK

$s, transfers = getStateAndTransfers(s_x, (i, j))$

IF $s \neq 0$ AND $\tau_{ij} + \lambda_{jd}^{s_x} \leq \lambda_{id}^{s}$

$PS_s = preferredStates(s)$

ELSE

$PS_s = \emptyset$

FOR $s_y \in PS_s$

IF $\tau_{ij} + \lambda_{jd}^{s_x} \leq \lambda_{id}^{s_y}$

$\lambda_{id}^{s} = \tau_{ij} + \lambda_{jd}^{s_x}$

$w_{id}^{s} = w_{jd}^{s_x} + transfers$

IF $(i, j) \in \{M2, M3\}$

$r_{id}(l), \Theta_{id}(l) = getLPenalty\left((i, j), p_{jd}^{s_x}\right)$

$r_{id}^{s}, \Theta_{id}^{s} = getHPenalty\left((i, j), p_{jd}^{s_x}\right)$

ELSE

$r_{id}(l), \Theta_{id}(l), r_{id}^{s}, \Theta_{id}^{s} = r_{jd}(l), \Theta_{jd}(l), r_{jd}^{s_x}, \Theta_{jd}^{s_x}$

IF $[i, s] \notin P_{now}$ AND $transfers = 0$ AND $\theta_{ij}(l) \leq \delta$

$P_{now} = P_{now} \cup [i, s]$

IF $[i, s] \notin P_{next}$ AND $transfers = 0$ AND $\theta_{ij}(l) > \delta$

$P_{next} = P_{next} \cup [i, s]$

IF $[i, s] \notin Q$ AND $transfers = 1$

$Q = Q \cup [i, s]$

BREAK

Sub-procedure. $getHyperLambda\left(s_x, (i, j), p_{jd}^{s_x}\right)$

IF $\Theta_{jd}^{s_x} > \overline{\delta}$

BREAK

IF $p_{id}^{s} \neq \emptyset$

$s_e = getHyperState(s_x, s)$

ELSE

$s_e = s_x$

IF $\lambda_{jd}^{s_x} < \lambda_{id}^{s}$

$\Phi_{e^b}^{*} = \Phi_{e^b}^{*} + \varphi_{ij}^{l}$

IF $\Phi_{e^b}^{*} = \varphi_{ij}^{l}$

$C_{e^b}^{*} = \frac{1}{\varphi_{ij}^{l}} + \lambda_{jd}^{s_x}$

$R_{e^b}^{*}, \Theta_{e^b}^{*} = R_{jd}^{s_x}, \Theta_{jd}^{s_x}$

ELSE

$C_{e^b}^{*} = C_{e^b}^{*} - \frac{\left(C_{e^b}^{*} - \lambda_{jd}^{s_x}\right)\varphi_{ij}^{l}}{\Phi_{e^b}^{*}}$

$r_{e^b}^{*}, \Theta_{e^b}^{*} = getIncHPenalty\left((i, j), p_{jd}^{s_x}, p_{id}^{s}\right)$

IF $C_{e^b}^{*} \leq \lambda_{id}^{s_e}$ AND $\Theta_{e^b}^{*} \leq \overline{\delta}$

$PS_{s_e} = preferredStates(s_e)$

ELSE

$PS_{s_e} = \emptyset$

FOR $s_y \in PS_{s_e}$

IF $C_{e^b}^{*} \leq \lambda_{id}^{s_y}$

$\lambda_{id}^{s_e} = C_{e^b}^{*}$

$h_{e^b}^{*} = h_{e^b}^{*} \cup \{j\}$

$w_{id}^{s_e} = \max\left\{w_{jd}^{s_x}, w_{id}^{s}\right\}$

$r_{id}^{s_e}, \Theta_{id}^{s_e} = r_{e^b}^{*}, \Theta_{e^b}^{*}$

$r_{id}(l), \Theta_{id}(l) = r_{jd}(l), \Theta_{jd}(l)$

IF $[i, s_e] \notin P_{now}$

$P_{now} = P_{now} \cup [i, s_e]$
BREAK

Sub-procedure. $getLPenalty\left((i,j), p_{jd}^{s_x}\right)$

$\Theta_{id}(l) = \frac{\tau_{ij}\left(\theta_{ij}(l) - \Theta_{jd}(l)\right)}{T_{id}(l)} + \Theta_{jd}(l)$

$T_{id}(l) = \tau_{ij} + T_{jd}(l)$

IF $\Theta_{id}(l) \leq \underline{\delta}$

$r_{id}(l) = 0$

ELSE

$r_{id}(l) = \frac{T_{id}(l)}{1+e^{1000\left(1-\Theta_{id}(l)\right)}} + \beta T_{id}(l) e^{4\left(\Theta_{id}(l) - \underline{\delta}\right)}$

Sub-procedure. $getHPenalty\left((i,j), p_{jd}^{s_x}\right)$

$\Theta_{id}^{s} = \frac{\mathrm{T}_{id}(l)\left(\theta_{id}(l) - \Theta_{jd}^{s_x}(-l)\right)}{\mathrm{T}_{id}^{s}} + \Theta_{jd}^{s_x}(-l)$

$\mathrm{T}_{id}^{s} = \tau_{ij} + \mathrm{T}_{jd}^{s_x}$

IF $\Theta_{id}^{s} \leq \underline{\delta}$

$r_{id}^{s} = 0$

ELSE

$r_{id}^{s} = \frac{\mathrm{T}_{id}^{s}}{1+e^{1000\left(1-\Theta_{id}^{s}\right)}} + \beta \mathrm{T}_{id}^{s} e^{4\left(\Theta_{id}^{s} - \underline{\delta}\right)}$

Sub-procedure. $getIncHPenalty\left((i,j), p_{jd}^{s_x}, p_{id}^{s}\right)$

$\Theta_{eb}^{*} = \Theta_{eb}^{*} + \frac{\left(\Theta_{eb}^{*} - \Theta_{jd}^{s_x}\right)\varphi_{ij}}{\Phi_{eb}^{*}}$

$\mathrm{T}_{eb}^{*} = \mathrm{T}_{eb}^{*} + \frac{\left(\mathrm{T}_{eb}^{*} - \mathrm{T}_{jd}^{s_x}\right)\varphi_{ij}}{\Phi_{eb}^{*}}$

IF $\Theta_{eb}^{*} \leq \underline{\delta}$

$r_{eb}^{*} = 0$

ELSE

$r_{eb}^{*} = \frac{\mathrm{T}_{eb}^{*}}{1+e^{1000\left(1-\Theta_{eb}^{*}\right)}} + \beta \mathrm{T}_{eb}^{*} e^{4\left(\Theta_{eb}^{*} - \underline{\delta}\right)}$

6. EXAMPLE

Figure 5 shows a multimodal hypergraph composed of three modes; pedestrian ($M1$), buses ($M2$), and private bicycles ($M3$). The mode $M5$ is the modal transfer arcs. The pairs $\left(\tau_{ij}, \theta_{ij}(l)\right)$ on top of the arcs are the arc's travel time and *seat load factor*. On the top of the *contained* hyperarcs is the associated average arrival-rate of the bus line.

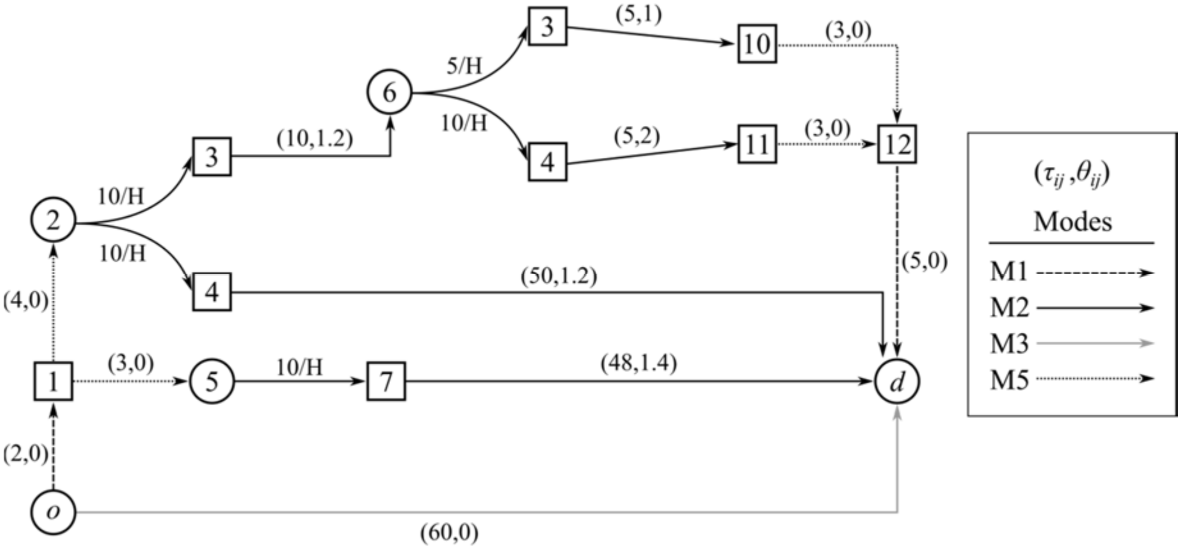

Figure 5: Example hypergraph with three modes and viable hyperpaths

Figure 6 shows the results of computing the shortest hyperpaths from the node o to the node d with a maximum of three modal transfers such that, $\underline{\delta} = 1$, $\overline{\delta} = 1.4$, and $\beta = 1$. The vector $(\lambda_{id}^s, w_{id}^s, s, r_{id}^s)$ near the nodes indicates the *expected travel time*, the maximum modal transfers, the *state*, and the *penalty for riding* of the *viable* hyperpath p_{id}^s. For example, the vector $(25,1,1,7.5)$ on top of node 6 is associated with the *viable* hyperpath p_{6d}^1, such that $\lambda_{6d}^1 = 25$, $w_{6d}^1 = 1$, $s = 1$ and $r_{6d}^1 = 7.5$. The *viable* hyperpath p_{6d}^1 is composed of the *contained* hyperarc $(6,3)$ and the arcs $(3,10)$, $(10,12)$, and $(12, d)$. Since $\theta_{4,11} = 2$ and $\overline{\delta} = 1.4$, the *contained* hyperarc $(6,4)$ and its consecutive arcs are not in p_{6d}^1 as the user prefers not to board vehicles with such onboard crowd levels. The *Pareto-Optimal* set of solutions are the starred vectors on top of node o.

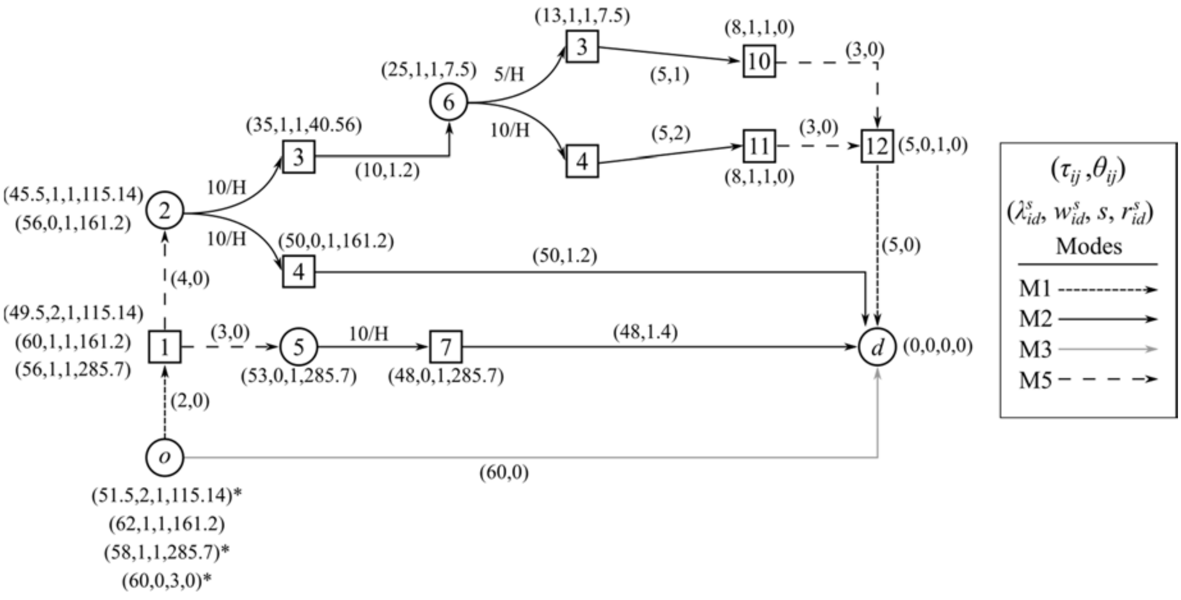

Figure 6: Solution set of viable hyperpaths

Figure 7 shows the three shortest hyperpaths in the Pareto-Optimal set. In the first solution, the user rides a bicycle for 60min to get to the destination. Solution 2 is 58 minutes long; to reach the destination, the user walks to location 1 and then goes to stop 5 for boarding a bus with high onboard crowd levels. Solution 3 is the fastest solution with the lowest onboard crowd levels. However, this solution has the most modal transfers. In solution 3, the user walks to location 1 and then at stops 2 boards the first arriving bus to reach the destination. The decision on selecting the path depends on the user inclinations. Take a long trip by bike to avoid buses (solution 1). Ride a single bus with high onboard crowd levels (solution 2). Alternatively, make many modal transfers to ride buses with low onboard crowd levels (solution 3).

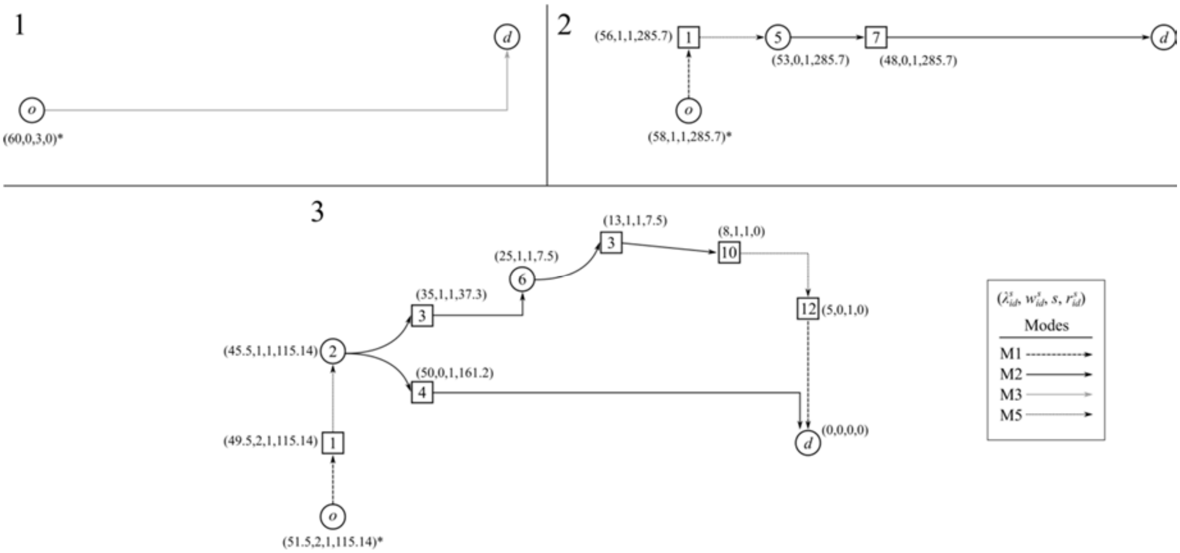

Figure 7: Shortest hyperpath in the Pareto-Optimal set

7. CONCLUSIONS

The presented paper describes a hypergraph model and routing algorithm to find the shortest hyperpaths in a multimodal network where the transit has random-arrivals and are considered the user constraints on the sequence of boarded modes and onboard crowd levels. The *states* and *seat load factors* transform the 'traditional' route planners (that only consider generic factors such as time, cost, or transfers) into personal trip assistants with tailored routes. Nowadays, the enormous amounts of accessible transportation-data set an ideal ground for developing tailored routing algorithms to user habits or idiosyncrasies. In light of the COVID19 pandemic, the presented model and algorithm could be used to find the paths with the lowest levels of onboard crowd and thus reduce the risk of contagion. However, for this tool to be valuable and accurate for COIVD19 applications, real-time information on onboard crowd levels is required.

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EL AUTOBÚS AUTÓNOMO: ANÁLISIS DE PERCEPCIÓN A TRAVÉS DE VARIABLES LATENTES

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RESUMEN

Desde hace unos años, los análisis mediante datos georreferenciados por telefonía se han convertido en una alternativa económica a las encuestas tradicionales. Si bien proporcionan datos más fiables, los móviles no permiten el análisis de la toma de decisiones que, en muchas ocasiones, ni el propio usuario es verdaderamente consciente de los factores que le condicionan.

En este contexto, el análisis factorial de variables latentes se convierte en una herramienta indispensable. Estas son aleatorias y no observadas directamente, siendo modeladas a través del estudio de la variabilidad en otras variables sí observables. En términos prácticos, a partir de las respuestas de los encuestados a preguntas sencillas, éstas se pueden agrupar en diferentes variables latentes. Estas preguntas por sí mismas no tienen valor alguno, sino que es la variable que obtenemos de manera indirecta la que nos va a resultar de utilidad.

En el presente artículo, se muestran los principales resultados del análisis factorial de las encuestas realizadas en el Puerto de Málaga dentro del proyecto AUTOMOST: Automated driving for dual-Mode System Transport, para el estudio de la aceptabilidad de la implantación de una línea de autobús autónomo que conectara la terminal de cruceros y el centro urbano. A partir de cinco temáticas que la bibliografía y la experiencia nos decían que podrían ser influyentes (Tecnofilia, Seguridad Vial, Valores Medioambientales y Seguridad Física), se ha podido identificar que la más determinante para el rechazo es la tecnofobia. Esta variable está determinada por la edad y el nivel de formación, por lo que el perfil que presentará mayor aversión es de una persona de avanzada edad con bajo nivel de estudios.

Aunque en líneas generales el modelo muestra gran aceptabilidad al vehículo autónomo para el transporte colectivo, será necesaria la realización de campañas específicas para reducir el rechazo de este tipo de usuarios.

1. ANTECEDENTES

La automatización del transporte es una de las principales metas del sector, pues implica una optimización de recursos, tanto en la amortización del material móvil como en la mejora de la capacidad de la red, en muchos casos ya saturada. Además, se estima un aumento en la seguridad, una mejora en la eficiencia energética y, por tanto, una reducción de las emisiones de gases contaminantes. En otras palabras, cambiará de manera significativa la movilidad y la relación del usuario con el transporte.

Ante este nuevo paradigma en la movilidad, surge la necesidad de comprender la aceptabilidad que pueda tener el vehículo autónomo y, sobre todo, si puede afectar a la elección modal o su rechazo si se trata del transporte público. Es en este contexto donde nace y se desarrolla el proyecto AUTOMOST (*Guiado Automatizado para Sistema de transporte dual*), cuyo objetivo declarado es *desarrollar tecnologías que permitan la automatización de vehículos en aplicaciones de transporte urbano e industriales, de cara a incrementar significativamente la eficiencia, seguridad y sostenibilidad*. En concreto, AUTOMOST permitirá la implementación de sistemas de control compartido (Dual-Mode) para futuros vehículos automatizados que permitan la operación de servicios de manera más eficiente y flexible, en un contexto de infraestructuras inteligentes y conectadas.

Automost es un proyecto del programa CIEN, convocatoria 2016, adjudicado a un Consorcio formado por Corporación Española de Transporte, S.L.U., AVANZA Spain S.A.U., IRIZAR S.Coop, DATIK Información Inteligente S.L., ETRALUX, S.A., Ingeniería INSITU, S.L., Novadays, S.L., Microelectrónica MASER, S.L., TECNALIA, Universidad Politécnica de Madrid (INSIA y TRANS*y*T), CEIT-IK4 y la Universidad de Vigo.

Dentro de las tareas asignadas al Centro de Investigación del Transporte de la Universidad Politécnica de Madrid (TRANSyT-UPM) en el marco del proyecto, se ha realizado un profundo análisis de la aceptabilidad y satisfacción de los potenciales usuarios de la futura línea de autobuses autónomos entre el puerto de Málaga y el centro urbano. En el presente artículo, se recogen los resultados obtenidos de las encuestas realizadas en el puerto a los usuarios de los autobuses que cubren el servicio de la actual línea. Con ayuda de las preguntas de caracterización y de variables latentes, ha sido posible realizar un modelo logístico multinomial con el objetivo de establecer las razones que motivan a un determinado participante a querer subirse o no a bordo de un autobús autónomo.

2. INTRODUCCIÓN Y OBJETIVOS

El vehículo autónomo se define como aquel que desplaza, pasajeros o mercancías, con determinado nivel de automatización, con el principal objetivo de asistir o sustituir el control humano (Stocker & Shaheen, 2017). Los fabricantes especializados en esta industria estimaban que para 2020 ya habría vehículos en el mercado con un alto nivel de automatización (European Commission, 2017).

AUTOMATIZACIÓN- ASPECTOS GENERALES	
Aspectos positivos	**Aspectos negativos**
• Reduce el coste de personal dedicado a la conducción • Se reducen los riesgos de accidente más comunes en la conducción (falta de atención, distancias de seguridad o adelantamientos inseguros) • Optimización de los recursos, como el combustible, y una reducción en las emisiones de gases contaminantes por medio de una conducción mucho más eficiente. • "Devaluar" el coste del tiempo de viaje (no se pierde tiempo en conducir, aprovechando ese tiempo para otras cosas) • Mejorará la equidad (mayores y niños tendrán mayor accesibilidad), y se reduce la cautividad (menos limitante para personas sin carné de conducir)	• Necesidad de importantes inversiones: equipos y material móvil específicos, rediseño de la infraestructura, necesidad de hiperconexión y un mantenimiento especializado. • Introduce nuevos riesgos: puede ser menos seguro en situaciones especiales o no previstas en la programación (fallos del sistema, terrorismo, decisiones que requieran razonamiento humano) • La automatización puede reducir la oferta de empleo, y puede afectar las barreras tecnológicas. • Aspectos territoriales (si disminuye el coste del transporte, y puede hacer que la gente viva más lejos)
AUTOBUSES AUTÓNOMOS- ASPECTOS ESPECÍFICOS	
Aspectos positivos	**Aspectos negativos**
• Potencial para aumentar la fiabilidad y la puntualidad • Posible reducción de costes fijos por la disminución de personal de conducción • Necesidad de un aumento en la inversión, tanto en la infraestructura como en el material móvil.	• Dificultad para controlar impagos • Dificultad en la gestión de incidencias (compra de billetes, requerimientos específicos de información, necesidades específicas de los pasajeros) • Posible disminución de la sensación de seguridad (al no existir una persona física que represente a la autoridad en el autobús). • Despersonalización de la imagen de la empresa.

Tabla 1: Aspectos importantes relativos a los vehículos autónomos. Fuente: López-Lambas & Alonso (2019).

No obstante, pese a existir distintos proyectos de automatización en el transporte público rodado, se siguen identificando barreras importantes: la aceptación de los usuarios, las políticas junto la regulación vigente (para facilitar e incentivar el desarrollo y las pruebas en terreno), la adaptación de la infraestructura y el desarrollo de la tecnología (ERTRAC Working Group, 2019) (Canis, 2019) (Litman, 2017; Fagnant & Kockelman, 2015; Buehler et al., 2009). En la tabla 1 se muestra un resumen de los principales condicionantes encontrados en los estudios sobre vehículos autónomos, destacando los relacionados con los autobuses, de los cuales, por cierto, existen pocos análisis científicos (Bösch et al., 2018).

En este artículo, se presentan los resultados de las encuestas que se llevaron a cabo en el marco del proyecto AUTOMOST para el servicio de autobuses que conectan el puerto de Málaga con el centro urbano. El objetivo es desarrollar un modelo que mida la aceptabilidad de los usuarios a la hora de introducir autobuses autónomos en la red de transporte público, así como identificar los perfiles de usuarios potenciales o reacios a los vehículos autónomos en general. La identificación de variables latentes ha sido fundamental para poder analizar la toma de decisiones en un área tan innovadora del transporte. Se ha considerado apropiada para el estudio, ya que ni el propio usuario es verdaderamente consciente de los factores que le pueden condicionar.

En el siguiente punto, se explica en mayor detalle la metodología de la encuesta presencial, al tiempo que se profundiza en el concepto de las variables latentes y los modelos factoriales realizados. En la sección cuatro, se detallará el proceso lógico llevado a cabo durante el análisis factorial, al igual que los pasos seguidos para la obtención del modelo. Finalmente, se mostrarán las principales conclusiones obtenidas y las futuras líneas de investigación que abre el presente artículo.

3. METODOLOGÍA

Al objeto de comprender la aceptabilidad del vehículo y su conducción, se han desarrollado un gran número de estudios a través de encuestas online (Payre et al., 2014; Zmud et al., 2016), encuestas presenciales (Eden et al., 2017; Nickkar et al., 2021; Payre et al., 2014) y Focus Group o grupos de discusión (López-Lambas & Alonso 2019). Aunque, en líneas generales, la aceptación del vehículo autónomo es extensa y hay un amplio conocimiento en la materia por parte de la ciudadanía, no hay suficientes evidencias para trasladar estas afirmaciones al transporte público colectivo. En este caso, es ventajosa la realización de un modelo de identificación a través de variables latentes, dada la peculiaridad de los autobuses autónomos.

Las variables latentes son una serie de características del individuo que no pueden ser preguntadas directamente, ya que el propio participante no tendría la capacidad de responder al ser constructos psicológicos que no se pueden inferir de forma directa. En otras palabras, no se pueden observar directamente: solo pueden ser medidas a través de otras variables o indicadores directamente observables.

Para la construcción de este modelo, el primer paso consiste en el estudio de todos aquellos factores que puedan influir en el uso del autobús autónomo. Para ello, es necesario comprender el ámbito del estudio, al igual que una revisión de la literatura y los distintos enfoques en la materia. A partir de los Focus Group, o grupos de discusión, realizados en el marco del proyecto AUTOMOST y tras el análisis del estado del arte en profundidad, se seleccionaron las siguientes variables:

- Tecnofilia: afición hacia la tecnología o dispositivos relacionados, generalmente con ordenadores, móviles, tabletas o el resto de los dispositivos informáticos y programables.
- Seguridad vial: prevención del riesgo de accidente en el tránsito de un vehículo.
- Valores medioambientales: conjunto de impactos sobre el medio ambiente y reducción de emisiones de gases contaminantes.
- Pertenencia a una comunidad: influencia o "presión social" sobre nuestras decisiones a partir de la opinión de amigos, conocidos, prensa o redes sociales.
- Seguridad física: miedo a sufrir agresiones, robos, atracos o caídas durante la conducción.

Una vez definidas las variables, el siguiente paso es el conocimiento de la estructura que subyace tras cada una de ellas. Esta puede ser ya conocida por el modelizador, o bien, debe ser descubierta. En ambos casos, es necesaria la utilización de técnicas de modelización con estructuras de covarianza, en particular el Análisis Factorial Exploratorio (AFE), el cual nos permite identificar esas posibles asociaciones entre los datos. La finalidad de los AFE es la determinación de las variables observables que pueden ayudar a evaluar y medir cada una de las variables latentes incluidas en el modelo. De este modo, se pueden obtener cuantas variables latentes estén relacionadas con las observables y que indicadores pueden asociarse a su valoración. A lo largo del proceso, se pueden suprimir del modelo aquellas variables observables que sean innecesarias en la estimación de las latentes, manteniendo aquellas que mejor ajuste proporcionen.

En nuestro caso de estudio, las variables observables son las respuestas de los participantes de la encuesta. Por este motivo, es necesario realizar varias preguntas para cada variable relacionadas con ella, a las que el encuestado puede responder de forma directa. En este tipo de estudios, las respuestas directas a las preguntas no son verdaderamente importantes al objeto de la investigación, sino las variables obtenidas a partir de dichas respuestas tras su análisis factorial. Por ejemplo, la variable latente Tecnofilia se obtuvo a través de la valoración de afirmaciones como "Me gusta probar nuevos dispositivos tecnológicos" o "Necesito herramientas tecnológicas en mi vida diaria". Siguiendo las recomendaciones de la bibliografía y experiencias previas, se combinaron en el cuestionario la escala de Likert (Likert, 1932) y el diferencial semántico (Osgood, et al 1957). En estos casos, es contraproducente preguntar directamente al usuario su grado de tecnofobia, ya que no es verdaderamente consciente de su influencia en las decisiones que toma en su día a día, pudiendo exagerar sus respuestas y distorsionar la muestra.

Para poder confirmar las hipótesis del análisis previo, es conveniente la realización de un Análisis Factorial Confirmatorio (AFC) a continuación. De este modo, se obtiene un modelo óptimo y significativo donde podemos valorar realmente las variables latentes a partir de indicadores medidos en las encuestas y confirmar las relaciones propuestas en las estructuras de datos. Además, en estos modelos ya están introducidas las variables latentes, estudiando la influencia de unas sobre otras. Sin embargo, debido a la complejidad de este análisis y el alcance del presente estudio, se descartó su realización.

Una vez estudiadas las variables latentes, y gracias a la recopilación y caracterización de los participantes, se pudo desarrollar un modelo logit multinomial que definiera el grado de aceptabilidad de los usuarios a una línea de autobús autónomo. En el siguiente apartado, se resumen los datos recogidos en la encuesta, la identificación de las variables latentes, al igual que las principales conclusiones de las preguntas de preferencias declaradas.

4. PROCEDIMIENTO Y ANÁLISIS DE LOS RESULTADOS BÁSICOS DE LA ENCUESTA

La encuesta se realizó en el puerto de Málaga durante el verano del 2019 de forma presencial, por lo que no se ha podido ver alterada por la crisis sanitaria sars-covid19 y sus restricciones sobre la movilidad. La muestra total es de 300 participantes. Teniendo en cuenta que durante ese mismo año hubo 16.051 cruceristas, se estima un margen de error muestral en torno al 5% (nivel de confianza del 95%)asumible para la realización del modelo.

La encuesta constaba de tres partes diferenciables: por un lado, una caracterización del individuo, por otro, una serie de preguntas relacionadas con las variables latentes, y finalmente, preguntas sobre la conducción autónoma y las preferencias declaradas del encuestado a la hora de abordarse en un autobús autónomo. A pesar de la elevada tasa de participación que presentan las encuestas online y de su menor coste, se seleccionaron las encuestas presenciales para una mejor definición de los perfiles de los usuarios afectados por la modificación del servicio y una mejor recogida de su nivel de aceptación (Berrada et al., 2020).

La muestra que participó en la encuesta presenta como perfil mayoritario a un hombre europeo entre los 46-60 años con formación universitaria. Sin embargo, hay una proporción razonable tanto en la distribución de género como de edad. De este modo, se estableció como representativa la muestra recogida.

Cabe destacar que la mayoría de los encuestados son extranjeros y que el ámbito de estudio es muy particular. Los españoles no representan ni el 1% del total de la muestra y los usuarios de la línea, una vez inaugurada, serán cruceristas mayoritariamente, usuarios esporádicos del servicio de transporte público al llegar a Málaga.

4.1 Caracterización de la muestra

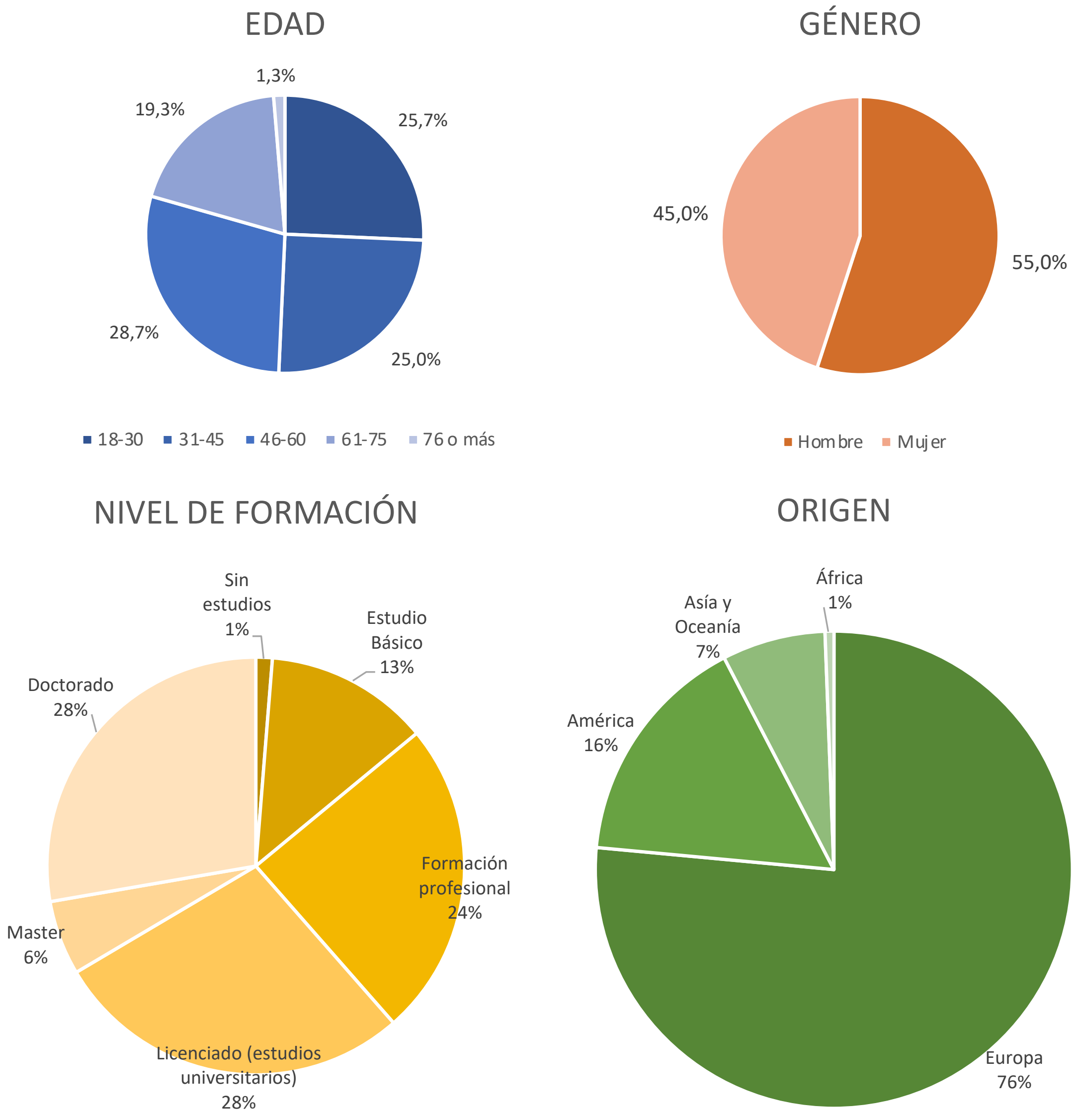

Figura 1: Caracterización de los participantes de la encuesta.

4.2 Análisis factorial y caracterización de variables latentes

Como se ha mencionado anteriormente, las variables latentes no se pueden obtener de forma directa, sino a través de otras variables observables. Para alcanzarlas, se hace una transformación de los resultados de las preguntas básicas, obteniendo unos nuevos resultados con media 0 y desviación estándar 1. En la siguiente figura se muestran los histogramas asociados a cada una de las variables latentes estudiadas a través del software estadístico SPSS.

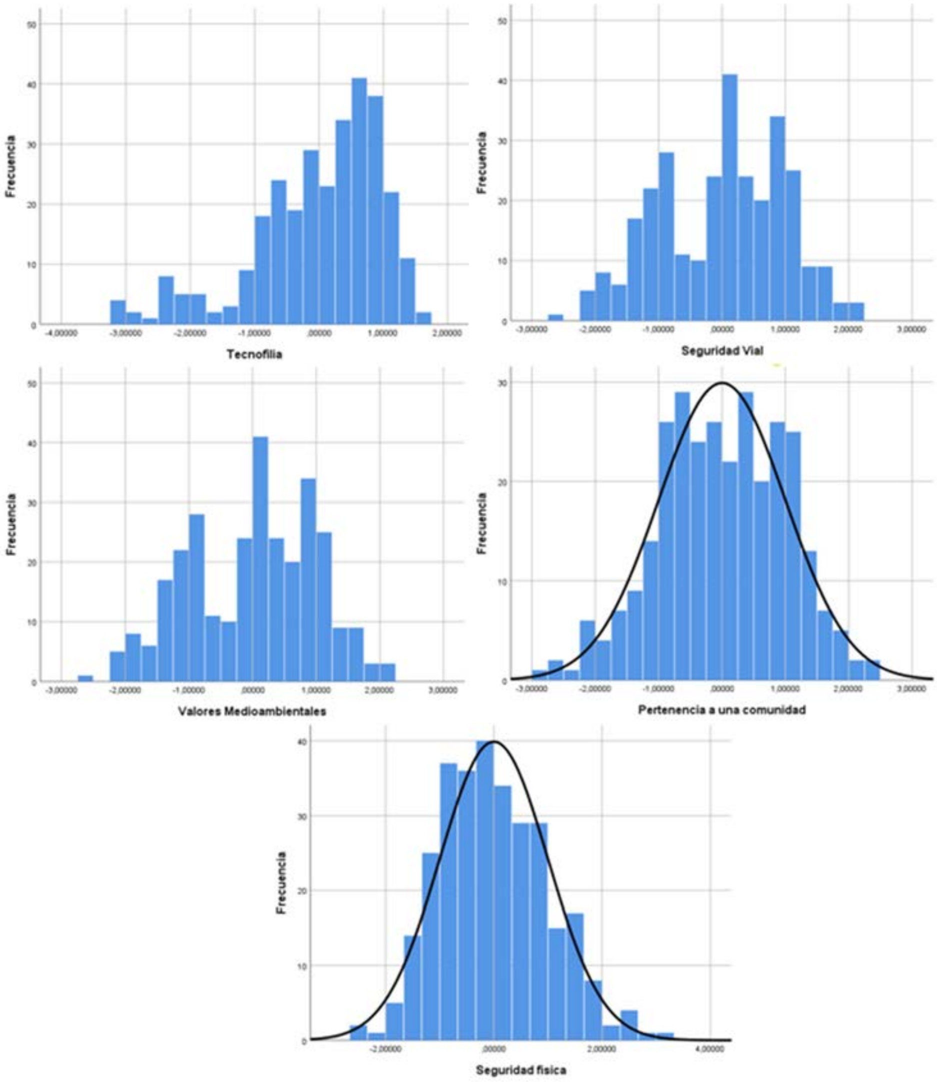

Figura 2: Histogramas de las variables latentes

- Tecnofilia: La mayor parte de las respuestas se concentran en torno al valor nulo. De manera general, la tendencia es hacia la indiferencia a la aparición de nuevas tecnologías. Sin embargo, hay valores extremos en la parte negativa, lo que indica que pueden existir perfiles de usuarios con alto rechazo hacia nuevas tecnologías, llegando a presentar tecnofobia.
- Seguridad vial: La distribución de las respuestas es mucho más repartida, sin casos significativamente extremos. Se identifican niveles similares entre las personas que tienen miedo a sufrir un accidente como aquellas a las que no les influye.
- Valores medioambientales: Los valores para este supuesto son también bastante neutrales. Sin embargo, existe cierta tendencia más visible hacia la no necesidad de tener en cuenta el cuidado del medio ambiente. En otras palabras, una parte de los encuestados no tienen interés en realizar acciones para mejorar el medioambiente en las ciudades y luchar contra el cambio climático.
- Pertenencia a una comunidad: A diferencia de las variables anteriores, se aprecia una tendencia a seguir la función normal. Sin embargo, hay valores y frecuencias más

altas en las cercanías del valor central que en el propio valor central. Esto indica una pequeña polarización en los dos posibles sentidos. No se le otorga una importancia suficientemente alta como para que se produzca un cambio significativo de la función normal.

- Seguridad física: También se aprecia una tendencia a seguir una distribución normal, aunque ligeramente descentrada hacia el lado negativo.

A la hora de planificar una estrategia de acción sobre la base de los resultados de la encuesta, es imprescindible comprender a que público objetivo hay que dirigirse, siendo necesario el estudio de las variables latentes a partir de los datos recopilados en la encuesta y la identificación muestral. Para realizar esta caracterización, se ha calculado una regresión lineal entre las variables latentes y los resultados con la primera parte de la encueta. A continuación, se muestran y explican los principales resultados del análisis.

	Coef. no estandarizados	**Desv.**	**Coef. estandarizados**	**t**	**Sig.**
	B	**Error**	**Beta**		
Tecnofilia					
(Constante)	0,305	0,17		1,793	0,074
Edad	-0,561	0,038	-0,623	-14,683	0
Nivel de formación	0,313	0,041	0,322	7,596	0
Seguridad Vial					
(Constante)	-0,441	0,191		-2,313	0,021
Edad	-0,287	0,045	-0,318	-6,385	0
Género	0,79	0,1	0,394	7,899	0
Valores medioambientales					
(Constante)	0,025	0,228		0,111	0,912
Edad	-0,172	0,051	-0,191	-3,367	0,001
Nivel de formación	0,116	0,055	0,119	2,104	0,036
Pertenencia a una Comunidad					
(Constante)	-0,748	0,228		-3,276	0,001
Edad	0,143	0,051	0,159	2,791	0,006
Nivel de formación	0,115	0,055	0,119	2,092	0,037
Seguridad Física					
(Constante)	0,223	0,255		0,875	0,382
Edad	0,146	0,082	0,105	1,78	0,076
Tipo de ciudad de residencia	-0,124	0,057	-0,128	-2,183	0,03

Tabla 2: Resultados de las regresiones lineales para la caracterización de las variables latentes.

- Tecnofilia: Esta variable viene determinada por la edad, principalmente, y por el nivel de formación, como se puede apreciar en la anterior tabla. Conforme aumenta la edad del individuo, mayor aversión hacía las nuevas tecnologías. Por el contrario, a mayor nivel educativo, mayor predisposición a las nuevas tecnologías.
- Seguridad vial: En este caso, la variable viene determinada por la edad (A medida que aumenta hay una menor preocupación por la seguridad vial) y el género, siendo está última la más influyente.
- La peculiaridad de la variable género es que no se trata de una variable ordenada, por lo que los resultados varían en función del orden en el que se han introducido las respuestas. En el presente estudio, se introdujeron primero las respuestas de género masculino (al ser mayoritarias) y después las de género femenino. Una tendencia positiva, como es el resultado obtenido, indica que el último grupo de variables tiene una mayor influencia sobre la variable latente. En otras palabras, las mujeres presentan mayor preocupación por la seguridad vial.
- Valores medioambientales: Las variables edad y nivel de formación son las de mayor influencia, aunque sus valores B son pequeños. En lo que respecta a las tendencias, mientras conforme aumenta la edad la preocupación por el Medio Ambiente disminuye, en el caso del nivel de formación se aprecia una mayor preocupación medioambiental conforme aumenta el nivel de estudios.
- Pertenencia a una comunidad: En este caso, vuelven a aparecer la edad y el nivel de formación como las variables que caracterizan a las variables latentes. Sin embargo, ambas muestran tendencias positivas: a mayor edad y nivel de formación, mayor sentimiento de pertenencia a una comunidad.
- Seguridad física: En el caso de la seguridad física, además de la edad, entra en juego la variable ciudad de residencia. Los resultados muestran que, cuanto mayor sea el tamaño de la ciudad y más la edad del individuo, existe una mayor preocupación por la integridad física individual.

4.3 Conocimiento sobre la conducción autónoma y preferencias declaradas

Una vez se ha caracterizado la muestra de la encuesta, e identificado y estudiado las variables latentes, hay que entender el nivel de conocimiento sobre el vehículo y autobús autónomo de los participantes, al igual que su comportamiento en situaciones hipotéticas relacionadas con su conducción autónoma.

En primer lugar, se preguntó a los participantes sobre su conocimiento y experiencia en vehículos autónomos, así como sus preferencias declaradas sobre su uso. En líneas generales, el conocimiento sobre esta tecnología es bastante alto, si bien apenas ha sido experimentada.

Respecto a la preferencia declarada, apenas un 9% de los participantes afirmó que bajo ningún concepto se subirían a un vehículo autónomo. Por otro lado, hay un porcentaje nada desdeñable (un 28,3%) que precisaría de más información o conocimiento de determinadas características para decidirse.

	Sí	No	Quizás
¿Ha oído hablar del vehículo autónomo?	90,3%	9,7%	n/a
¿Ha montado alguna vez en un vehículo autónomo?	5,3%	91,3%	n/a
¿Se montaría en un vehículo autónomo?	62,7%	9,0%	28,3%

Tabla 3: Resultados sobre las preguntas sobre el conocimiento del vehículo autónomo.

Una vez caracterizado el conocimiento sobre conducción autónoma, se contextualizó en el caso particular del autobús autónomo. Por un lado, se preguntó sobre las preferencias declaradas respecto a la conducción autónoma del autobús, así como la influencia que tendría mantener un componente humano, en el caso de las personas que presentaran dudas.

	Sí	No	Quizás
Si este autobús no llevara conductor, ¿se habría montado?	62,30%	9,30%	28,30%
Si el autobús sin conductor llevara a bordo una persona para ayudar a los pasajeros, ¿se montaría?	82,40%	17,60%	n/a
Si esta persona pudiera tomar el control del autobús en caso de que fuera necesario, ¿se montaría?	100,00%	0,00%	n/a

Tabla 4: Resultados sobre las preguntas de preferencias declaradas sobre el autobús autónoma.

Los resultados sobre las preferencias declaradas relacionadas con la conducción autónoma son muy similares con los obtenidos para el caso del autobús. Además, el porcentaje de personas que se subirían al autobús va incrementándose a medida que se aumenta el factor humano en su conducción autónoma. Más del 80% de las personas que presentaban dudas a abordar en un autobús autónomo, lo harían si existiera la figura de un ayudante para los pasajeros. Todos afirman que se subirían al autobús con la figura de un conductor que tomara el control del vehículo en caso de que fuera necesario.

Después se preguntó por la importancia que dan los participantes a la figura del conductor en una serie de tareas. De este modo, se puede comprender el papel que representa el conductor del autobús para los usuarios y su posible futuro desempeño en la conducción autónoma.

Los resultados muestran que la principal función está relacionada con la seguridad operacional. En otras palabras, los usuarios valoran muy positivamente sus labores durante la conducción. Sin embargo, la figura del conductor no proporciona mayor seguridad frente agresiones (físicas o verbales), intimidaciones, robos o hurtos. Además, cabe destacar que la experiencia como usuario se valora muy negativamente por los participantes de la encuesta.

	Media	Mediana	Moda	Desviación
Seguridad (física: temor a una agresión, intimidación, hurto/robo),	2,93	3	3	1,261
Seguridad (operacional: fallos del vehículo que comportan accidentes)	4,24	5	5	1,036
Experiencia como usuario (Subir a bordo, bajar, compra del billete, información a bordo o antes de subir sobre rutas, paradas, tiempo de viaje y espera del próximo bus, etc.)	2,12	1	1	1,364

Tabla 5: Resultados sobre el vehículo autónomo.

5. MODELO DE DECISIÓN

Una vez analizados los resultados directos de la encuesta y las variables latentes, se genera un modelo logit multinomial para estimar la aceptabilidad del autobús autónomo. Se ha elegido este modelo porque la variable dependiente que se quiere analizar es categórica, y tiene más de dos opciones de respuesta: Sí, No o Quizás. Con este modelo se identificarán las variables socioeconómicas y latentes que sean más influyentes en la toma de decisiones de los usuarios potenciales de un servicio de transporte público con autobuses autónomos.

En un primer momento, se consideraron todas las variables, tanto de caracterización como las variables latentes obtenidas, así como las posibles interacciones que existieran entre ambas. Sin embargo, para que un modelo sea útil, ha de ser capaz de pronosticar correctamente el mayor número de casos con el menor número de variables. Con esta idea, se han eliminado aquellas que no eran estadísticamente significativas o que no aportasen valor significativo. En otras palabras, con coeficientes de significación superiores al 0,05.

Siguiendo estas recomendaciones, dos variables latentes finalmente no se emplearon en el modelo – Seguridad física y Pertenencia a una comunidad- al tener valores de significancia muy elevados (0,269 y 0,139, respectivamente), así como bajos valores de chi-cuadrado (2,6 y 3,9 frente a 270,77, 12,24 y 27,76 del resto de variables latentes). Por tanto, se han utilizado en un primer momento Tecnofilia, Protección del Medio Ambiente y Seguridad Física, con las variables de caracterización del usuario.

En un modelo multinomial se compara una opción definida como base con todas las demás opciones posibles. En este caso, se ha definido como base la opción positiva (“Sí”). La estimación obtenida del modelo es la siguiente:

		B	Desv. Error	Wald	Sig.	OR (Exp(B))	OR para cambio de ½ unidad	95% de intervalo de confianza para Exp(B)	
								Límite inferior	Límite superior
NO	(Intersección)	-6,544	1,137	33,131	0,000				
	Tecnofilia	-6,714	0,827	65,925	0,000	0,001	0,03	0,000	0,006
	Protección Medioambiental	-0,975	0,402	5,892	0,015	0,377	0,61	0,172	0,829
	Seguridad física	1,068	0,407	6,900	0,009	2,911	1,71	1,312	6,460
QUIZÁS	(Intersección)	-0,532	0,182	8,557	0,003		0,77		
	Tecnofilia	-2,949	0,364	65,609	0,000	0,052	0,23	0,026	0,107
	Protección Medioambiental	-0,617	0,192	10,334	0,001	0,540	0,73	0,370	0,786
	Seguridad física	1,012	0,213	22,572	0,000	2,750	1,66	1,812	4,174

Tabla 6: Resultados del modelo multinomial logit aplicado con tres variables latentes: tecnofilia, protección al medio ambiente y seguridad física.

Durante el análisis de la importancia de cada término en el modelo, hay que fijarse en el Exponente B. (Odds Ratio)Este indicador nos proporciona el incremento de las posibilidades de éxito de una de las opciones de resultado respecto a la otra cuando se incrementa una unidad en el término estudiado. Debido a que el rango de las variables latentes es pequeño, se ha calculado también para un incremento de media unidad, de manera que se hace más comprensible el significado e influencia de este valor.

Como se puede apreciar en la anterior tabla, existe una variable que destaca sobre el resto de las empleadas: la tecnofilia. La tecnofilia es especialmente influyente en la comparación entre Sí vs No, si bien también destaca en la comparación entre Sí vs Quizás, aunque en menor medida. Para comprender la importancia de esta variable, valga el siguiente análisis para su visualización: es 33 veces más probable (1/0,03) que una persona con una puntuación de 2 esté dispuesta a subirse a un autobús de conducción autónoma que una persona de 1,5, comparando Si vs No. En el caso de Sí vs Quizás, este valor se reduce a 4,4 veces. El resto de las variables presentan valores muy similares y mucho más bajos, todos ellos entre 1 y 2. En otras palabras, mientras que los valores de protección medioambiental y seguridad física, e incluso el de Tecnofilia para Sí vs Quizás, se encuentran en los rangos de lo que se suele obtener en modelos logarítimicos, el resultado de Tecnofilia en Sí vs No es muy superior al habitual.

Esto indica que, si bien existen más factores, el tratamiento de la aceptación de las nuevas tecnologías ha de ser un elemento clave en la implementación del autobús autónomo. De este modo, para lograr el éxito de este modelo de conducción en el transporte público sin afectar gravemente a la demanda, se ha de conseguir que el mayor número de usuarios, independientemente de sus habilidades con las tecnologías y los dispositivos, no solo puedan utilizar el servicio, sino que se sientan cómodas haciéndolo.

Finalmente, se ha analizado qué valores son más influyentes en los indecisos (que hayan contestado quizás) a la hora de subirse un autobús autónomo si hubiese un asistente a bordo. En este caso, se ha optado por una regresión logarítmica binomial. Las variables estadísticamente significativas son Seguridad Vial y Física.

	B	**Error estándar**	**Wald**	**Sig.**	**Exp(B)**	**95% C.I. para EXP(B)**	
						Inferior	**Superior**
Seguridad Vial	0,702	0,346	4,114	0,043	2,018	1,024	3,977
Seguridad Física	0,744	0,305	5,975	0,015	2,105	1,159	3,824
(Constante)	-2,084	0,427	23,801	0,000	0,124		

Tabla 7: Resultados del modelo binomial logit aplicado con las variables latentes de Seguridad Vial y Seguridad Física.

6. LÍNEAS DE INVESTIGACIÓN FUTURAS

El presente estudio abre nuevas líneas de investigación sobre la conducción autónoma en el transporte público rodado. Aunque, en líneas generales, se muestra un gran conocimiento sobre el vehículo autónomo y aceptación de este modelo de conducción cuando se trata de un autobús, los resultados no son completamente extrapolables al servicio completo de la red de transporte público.

Los participantes de la encuesta, en su totalidad, eran cruceristas y extranjeros. En otras palabras, usuarios esporádicos de una red de transporte público desconocida y con alto porcentaje de cautividad. Además, gran parte del itinerario que realizaría el autobús sería dentro del puerto, una situación de tráfico acotada y limitada con influencia mínima de las externalidades típicas de la conducción del día a día en una gran ciudad.

Con el objeto de validar el actual modelo desarrollado, por medio de la diversificación y ampliación de la muestra, es recomendable extender este análisis a usuarios fidelizados en el transporte público de la ciudad. De este modo, se podría comprender la aceptabilidad de este modelo de conducción en ámbitos mucho más urbanos. Al mismo tiempo, sería interesante estudiar su influencia sobre la elección modal, su capacidad de atracción de usuarios del vehículo privado al transporte público.

7. CONCLUSIONES

En muchos casos, se puede explicar la toma de decisiones de un individuo sen función de sus características socioeconómicas, relativamente fáciles de obtener. Sin embargo, cuando se trata de decisiones en las que no se necesita meditar mucho, o que incluso no se es verdaderamente consciente de las motivaciones, esta caracterización se torna más compleja.

En el presente artículo se demuestra la necesidad de considerar las variables latentes en el estudio de la aceptabilidad del autobús autónomo, ya que su estudio ha sido fundamental para el desarrollo del modelo. Mediante una serie de sencillas preguntas, ha sido posible caracterizar a los participantes en aspectos no accesibles de manera directa. Aunque lo ideal es obtener un modelo con las variables básicas de caracterización, no se han conseguido resultados adecuados hasta introducir las variables latentes validadas: Tecnofilia, Protección del Medio Ambiente y Seguridad Física. Con ello, se ha logrado un modelo válido y fiable, con el que se pueden explicar las razones que motivan la decisión de abordar un autobús autónomo.

Al mismo tiempo, con este análisis se ha podido demostrar cómo el vehículo autónomo en general, y el autobús autónomo en particular, tiene un nivel de aceptación bastante alto, si bien existen aún potenciales usuarios que muestran dudas a la hora de abordar un vehículo de estas características. A medida que se incremente el factor humano, se reduce el número de usuarios indecisos hasta desaparecer. Esta situación es muy similar a la conducción autónoma: a medida que aumenta su nivel de autonomía, aumenta el estrés y su rechazo (Hewit, et al., 2019¸ Rödel et al., 2014). De este modo, se aprecia una estrecha relación entre la conducción autónoma, tanto en transporte individual como en el transporte colectivo.

Finalmente, el factor más influyente en la toma de decisiones a la hora de abordar un autobús de conducción autónoma es la tecnofilia. Esta variable está determinada por la edad y el nivel de formación, por lo que el perfil de persona en el que más hay que centrarse es el de personas de avanzada edad con bajo nivel de estudios.

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VARIACIÓN ESPACIAL Y TEMPORAL DE LA SATISFACCIÓN DE LOS USUARIOS EN SISTEMAS DE TRANSPORTE PÚBLICO POR CARRETERA

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RESUMEN

Las encuestas son un método comúnmente utilizado para establecer los niveles de satisfacción de los usuarios con un sistema de transporte público. Independientemente del tipo de encuesta realizada y de la metodología empleada, los estudios presentan habitualmente una imagen puntual y concreta del servicio mostrando los resultados de forma agregada o diferenciando por líneas y características socioeconómicas de los usuarios. Sin embargo, no se analiza la satisfacción como una variable con variación temporal o espacial. En este artículo se presenta un caso práctico aplicado a la ciudad de Santander donde se realiza un análisis de la evolución de la satisfacción con el servicio a lo largo de un día en varias líneas que conforman el sistema de transporte público de la ciudad. A su vez, se analiza cómo cambia esta percepción en los distintos puntos de la ciudad. Los resultados muestran que la satisfacción general de los usuarios con respecto al servicio disminuye en las horas punta del día, al igual que se detecta una variación con respecto a los distintos puntos de la ciudad analizados. Además, algunos atributos fueron más relevantes que otros, mostrando diferencias significativas en su importancia en diferentes franjas horarias y líneas de autobús. Estos resultados pueden ayudar a mejorar los servicios de transporte de forma más precisa, mostrando las diferencias espacio-temporales que existen en las evaluaciones realizadas por los usuarios.

1. INTRODUCCIÓN

La mejora de la calidad del servicio ofertado y de la satisfacción del usuario permite potenciar el uso del transporte público y la fidelización del cliente. A su vez el fomento del uso del transporte público es uno de los pilares de la promoción de la movilidad sostenible, dada su capacidad para transportar personas de forma más eficiente que el transporte privado motorizado, reduciendo la congestión (Nguyen-Phuoc, Young, Currie y De Gruyter, 2020), la emisión de contaminantes (Beaudoin, Farzin y Lin Lawell, 2015; Borck, 2019; Gendron-Carrier, Gonzalez-Navarro, Polloni y Turner, 2018) y ofreciendo una mayor equidad social (Cuthill, Cao, Liu, Gao y Zhang, 2019; Foth, Manaugh y El-Geneidy, 2013; Manaugh y El-Geneidy, 2012).

Entre las herramientas que se han utilizado para promover una mejora de la satisfacción de los usuarios con el servicio de transporte público se encuentran los Customer Satisfaction Surveys (CSS) (J. de Oña y de Oña, 2015). Este tipo de encuestas intentan medir cual es el grado de satisfacción de los usuarios con el servicio, dado que una satisfacción más elevada puede identificarse como el factor más determinante de una intención comportamental favorable al uso del transporte público (Lai y Chen, 2011). Además de la satisfacción general, los CSS también miden la percepción de la calidad de los atributos particulares del servicio, con el objetivo de detectar aquellos aspectos que podrían mejorarse obteniendo el mayor impacto en términos de satisfacción y por lo tanto de uso del transporte público. Estos atributos pueden ser muy variados por lo que suelen clasificarse en distintos grupos, como los propuestos por la norma UNE-EN 13186 (2003), siendo estos la oferta de transporte público (servicio ofertado, accesibilidad), la realización del servicio (información, tiempo, atención al cliente, confort, seguridad) y el impacto medioambiental. Otros autores han señalado la existencia de atributos de tipo básico (ocupación, cobertura del servicio, fiabilidad) en los que, si la percepción de la calidad es baja, la demanda del servicio puede verse seriamente comprometida, mientras que otros son de tipo no básico y contribuyen a la satisfacción, pero no son determinantes para la elección del servicio (características de las paradas, limpieza de los vehículos, amabilidad de los empleados) (Eboli y Mazzulla, 2008).

Sin embargo, la satisfacción del usuario no es un fenómeno estático, sino que puede variar tanto en términos espaciales como temporales. En términos espaciales entre distintas zonas de prestación del servicio dentro del mismo área urbana (Cordera, Nogués, González-González y dell’Olio, 2019), entre distintas ciudades o incluso entre distintos segmentos de las líneas de transporte. En términos temporales la satisfacción puede ser variable entre distintas partes del día (hora punta/hora valle) o entre distintos intervalos temporales. Conocer esta variabilidad en la satisfacción de los usuarios puede ser importante para diagnosticar cuando y donde el servicio presenta problemas. Este estudio plantea profundizar en esta línea de investigación mediante el análisis y la modelización de la satisfacción de los usuarios obtenidas a través de un CSS realizado en Santander (Cantabria, España) considerando las variaciones espacio-temporales de las respuestas. El CSS tuvo en cuenta tanto la satisfacción de los usuarios con el servicio a nivel general como la percepción da la calidad del mismo en 28 aspectos específicos.

En la literatura técnica sobre la medición de la calidad del servicio y sobre la satisfacción de los clientes del transporte público la atención prestada a estos fenómenos de diversidad espacial y temporal ha sido limitada. Un ejemplo es el trabajo de Allen, Muñoz y de Dios

Ortúzar (2020), los cuales combinaron datos de encuestas sobre la satisfacción de los usuarios del Metro de Santiago de Chile con datos sobre la operación del servicio como los niveles de ocupación, las frecuencias, la velocidad comercial y la ocurrencia de accidentes críticos. Además, los autores desagregaron el análisis en las distintas líneas del sistema, periodos del día, días de la semana, estaciones y años, siendo por lo tanto el ejemplo más notable encontrado de consideración de la variabilidad espacial y temporal de la satisfacción. Sin embargo, este estudio no consideró la variabilidad de la satisfacción y la percepción de la calidad a nivel de distintos segmentos de la misma línea, lo cual puede dar más detalles sobre los factores que influyen en las elecciones de los usuarios.

Tanto Cats, Abenoza, Liu y Susilo (2015) como Börjesson y Rubensson (2019), J. de Oña, de Oña, Eboli y Mazzulla (2016) y Kawabata et al. (2020) han utilizado datos de serie temporal que les permitió analizar la evolución de la satisfacción de los usuarios en el tiempo. Cats et al. (2015) examinaron cómo la satisfacción de los usuarios cambió en Suecia entre los años 2001 y 2013, mostrando un declive de ésta generado por la peor interface con el cliente y el aumento del tiempo de viaje. Börjesson y Rubensson (2019) utilizaron también datos sobre la satisfacción de los usuarios en Suecia, en este caso entre los años 2008 y 2016, encontrando una relación importante entre satisfacción y el nivel de aglomeración y fiabilidad del servicio. J. de Oña et al. (2016) realizó una investigación sobre la evolución de la satisfacción y la percepción de la calidad del servicio mediante el uso de index numbers y datos obtenidos de una CSS realizada entre 2007 y 2013. Esto permitió detectar un ascenso en la satisfacción con el servicio en los primeros años de la serie (2008-2010) junto con una caída en los años posteriores (2010-2012) y una ligera recuperación al final (2013). Sin embargo, este estudio no tuvo en cuenta diferencias espaciales en la satisfacción con el servicio ni los factores explicativos de estos cambios. Kawabata et al. (2020) utilizaron datos del Benchmarking in European Service of Public Transport para los años 2001-2015 con el objetivo de apoyar la hipótesis de que la mejora en la calidad del servicio influye positivamente tanto en la satisfacción del usuario como en la frecuencia de uso del servicio. Aunque los autores demostraron la existencia de esta relación, también detectaron la existencia de un retardo temporal desde que se produce la mejora en la calidad hasta que ésta se traduce en una mayor frecuencia de uso por parte de los usuarios. Otras investigaciones han tenido en cuenta además el efecto de la crisis financiera de 2008 en la satisfacción de los usuarios, como las realizadas por de R. de Oña, de Abreu e Silva, Muñoz-Monge y de Oña (2018) y Efthymiou y Antoniou (2017) para los casos español y griego respectivamente.

Entre los estudios que se han centrado más bien en diferencias espaciales, J. de Oña (2020) utilizó los datos de cinco ciudades europeas: Madrid, Roma, Berlín, Lisboa y Londres, para examinar cual era el rol de la involucración en el transporte público, demostrando su papel mediador entre la satisfacción del usuario y la intención comportamental de usarlo. Esta línea de investigación fue ampliada por el mismo autor en J. de Oña (2021), considerando si la satisfacción era un factor mediador parcial o completo entre la calidad del servicio y las intenciones comportamentales, utilizando datos recogidos en las mismas cinco ciudades.

Esta comparación espacial permitió establecer que el modelo de ecuaciones estructurales (SEM) que consideró la satisfacción como un factor mediador completo se ajustó mejor en todas las ciudades con la excepción de Londres. Además, en las cinco ciudades factores como la frecuencia, la puntualidad, la velocidad y la intermodalidad fueron los más relevantes.

Como puede verse de la revisión de los estudios anteriores, la mayor parte de las investigaciones que han tenido en cuenta la diversidad de la satisfacción de los usuarios, lo han hecho más en términos temporales que espaciales y más a escala de diferentes áreas de estudio (ciudades) que dentro del mismo sistema de transporte. Esta investigación se centrará más bien en la diversidad espacial y temporal de la satisfacción de los usuarios a escala intraurbana, un enfoque que ha sido menos explorado y puede ser interesante para la detección de los factores que expliquen esta diversidad.

En el apartado siguiente se repasan los datos disponibles mediante la CSS que han sido básicos para la realización de este estudio. En el apartado 3 se describe la metodología empleada, tanto para estimar la contribución de los diferentes factores específicos a la satisfacción global como para la diferenciación de las valoraciones a nivel espacial y temporal. En el apartado 4 se presentan los resultados obtenidos, prestando especial relevancia a las variaciones temporales y espaciales en la satisfacción. Por último, se ofrecen una serie de conclusiones y recomendaciones de política obtenidas a partir de estos resultados.

2. DATOS

2.1 Encuesta

La recogida de datos se basó en una CSS dividida en 2 grandes partes. En la primera parte de la encuesta se preguntaba al usuario un total de 7 cuestiones relacionadas con sus características socioeconómicas y las del viaje. Las preguntas fueron: edad, género, situación laboral, nivel de ingresos mensual, nivel de uso del autobús, motivo del viaje (origen y destino) y si disponían de algún modo de transporte alternativo para realizar ese mismo trayecto que estaban realizando en autobús. La segunda parte de la encuesta se centraba en obtener la información referente a la satisfacción y percepción de los usuarios de la calidad del servicio. En total, los usuarios establecieron su percepción sobre la calidad de 24 atributos relacionados con el sistema de transporte, al igual que evaluaron la satisfacción general del servicio en su conjunto.

Para definir la percepción sobre la calidad de los atributos, los encuestados debían realizar dos actividades. Para facilitar la realización de dichas actividades, los atributos se agruparon en grupos de 4 atributos escogidos aleatoriamente. Cada encuestado solo evaluaba 3 grupos de atributos, evaluando de esta forma solo 12 de los 24 atributos definidos para el conjunto de la encuesta. Se optó por este diseño para facilitar que las encuestas pudieran realizarse dentro de unos márgenes de tiempo aceptables. El primer ejercicio a realizar, dentro del grupo de atributos, se basaba en una evaluación del nivel de calidad convencional basada en ítems de Likert de 5 puntos (de Muy Mal a Muy Bien). Una vez evaluados los atributos, a los encuestados se les pedía que escogieran de entre los cuatro atributos mostrados aquel que consideraban más importante y aquel que consideraban menos importante, realizando de esta forma un ejercicio de tipo Best-Worst Caso 1. Para acabar la encuesta los encuestados evaluaban la satisfacción general utilizando los mismos niveles definidos anteriormente.

2.2 Muestra

La CSS se realizó entre los meses de octubre y noviembre de 2017 en la ciudad de Santander. Las encuestas se completaron mediante entrevistas presenciales en 4 líneas de la ciudad operadas por la empresa pública de transportes. Se consiguieron un total de 808 encuestas válidas comprendidas en una franja horaria entre las 8 de la mañana y las 8 de la tarde. El número de encuestas realizadas se muestra en la Tabla 1.

Hora del día	Encuestas completadas				
	Línea 1	Línea 2	Línea 3	Línea 13	Total
<= 9:00	24	28	30	16	98
9:01 - 10:00	35	36	31	34	136
10:01 - 11:00	21	28	8	11	68
11:01 - 12:00	15	12	9	4	40
12:01 - 13:00	18	9	13	20	60
13:01 - 14:00	28	10	50	16	104
14:01 - 15:00	10	8	12	4	34
15:01 - 16:00	14	28	5	8	55
16:01 - 17:00	10	33	15	18	76
17:01 - 18:00	14	17	19	19	69
18:01 - 19:00	21	13	3	17	54
19:01+	4	4	3	3	14
Total	214	226	198	170	808

Tabla 1: Tamaño de la muestra

En la Tabla 2 se muestran las variables socioeconómicas de la muestra para cada una de las líneas de transporte analizadas y para el total de encuestas. Referente al género, se puede observar que las mujeres están sobrerrepresentadas en todos los casos. La edad de los encuestados se reparte de forma más uniforme, si bien existen más observaciones de personas de menos de 25 años y un menor número de las personas de más de 75. Otro aspecto a destacar en cuanto a la edad es la variación entre las líneas 1, 2 y 3 frente a la línea 13. Las tres primeras muestran un mayor número de usuarios jóvenes, mientras que la línea 13 muestra un número muy superior de usuarios de más de 65 años. En lo que respecta a la situación laboral, la mayoría de los encuestados son trabajadores, seguidos de estudiantes y jubilados. En la línea 13, en relación a la diferencia de edad, el número de jubilados es mayor que en el resto de las líneas. Prácticamente la mitad de los encuestados podría realizar el mismo viaje en coche ya que lo tienen disponible. El potencial uso de la bicicleta es muy bajo, al igual que el de la moto. El motivo de viaje principal es aquel relacionado con el hogar, siendo el segundo motivo principal el trabajo. El motivo del viaje por líneas es a grandes rasgos similar, sin embargo, en la línea 3 se observa un número de viajes menor relacionados con el ocio, mientras que en la línea 13 existe un número mayor de viajes por motivo compras. Más de la mitad de los usuarios encuestados pueden considerarse viajeros recurrentes, ya que la mayoría de los encuestados realiza entre 5 y 15 viajes semanales. En cuanto a nivel de ingresos de la muestra, el reparto es similar en todas las líneas, sin embargo, cerca del 40% de los encuestados prefirió no responder a esta pregunta al tratarse de un aspecto sensible.

Atributo	**Nivel**	**Lín. 1**	**Lín. 2**	**Lín. 3**	**Lín. 13**	**Total**
Genero	Hombre	36%	31%	33%	31%	33%
	Mujer	64%	69%	67%	69%	67%
Edad	< 25 años	25%	23%	35%	16%	25%
	25 – 34 años	15%	14%	16%	9%	14%
	35 – 44 años	15%	17%	15%	11%	15%
	45 – 54 años	12%	17%	13%	26%	17%
	55 – 64 años	19%	14%	11%	18%	15%
	65 – 75 años	10%	12%	7%	23%	11%
	> 75 años	4%	2%	3%	6%	4%
Situación laboral	Labores del hogar	4%	6%	4%	4%	5%
	Trabajador	43%	45%	47%	54%	47%
	Desempleado	9%	9%	5%	8%	8%
	Estudiante	27%	23%	34%	11%	24%
	Jubilado	17%	17%	11%	23%	17%
Otro modo de transporte disponible	Coche (conduciendo)	35%	34%	36%	38%	35%
	Coche (acompañando)	12%	11%	11%	12%	12%
	Bicicleta	9%	6%	4%	4%	6%
	Moto	2%	5%	3%	1%	3%
	Otro	41%	44%	46%	46%	44%
Motivo del viaje (O/D)	Casa	36/31%	57/15%	54/38%	34%34%	46/29%
	Trabajo	24/23%	18/27%	17/21%	29/29%	22/25%
	Estudios	12/12%	5/12%	15/18%	4/7%	9/13%
	Sanidad	4/6%	3/8%	4/3%	5/3%	4/5%
	Compras	6/6%	4/8%	3/7%	8/8%	5/7%
	Ocio	12/14%	9/21%	3/5%	14/11%	10/13%
	Otro	4/9%	4/10%	5/7%	6/9%	5/9%
Numero de viaje en bus realizados por semana	< 5	29%	27%	24%	29%	26%
	5 - 15	52%	49%	62%	52%	54%
	15 - 30	17%	21%	15%	17%	18%
	> 30	2%	2%	0%	2%	1%
Nivel de ingresos	< 900€	9%	7%	7%	5%	7%
	900€ - 1500€	20%	19%	19%	23%	20%
	1500€ - 2500€	13%	12%	23%	20%	17%
	> 2500€	17%	13%	9%	18%	14%
	Sin respuesta	41%	48%	42%	35%	42%

Tabla 2: Variables socioeconómicas consideradas en la encuesta

La Tabla 3 muestra el nivel de calidad percibida de los atributos ordenados de mayor a menor valor.

El atributo mejor valorado es el uso de vehículos con combustibles alternativos (vehículos híbridos en la fecha de realización de la encuesta).

En segundo lugar, están los tiempos de acceso y egreso de las paradas, lo cual demuestra una buena densidad de paradas a lo largo de la red.

Por otro lado, en la parte inferior de la tabla se encuentran atributos característicos del servicio de transporte público como son las frecuencias de los servicios o el precio.

Por último, las variables ambientales como los sistemas de aire acondicionado y el ruido también muestran una baja calificación.

Orden	Atributo	Acrónimo	Media	Desv. Est.
1	Uso de autobuses híbridos	HY	8,10	1,91
2	Tiempo de acceso a la parada	AT	7,34	2,24
3	Tiempo de egreso desde la parada al destino final	DT	7,29	2,22
4	Limpieza del vehículo	CL	7,04	1,75
5	Facilidad de transbordo	TR	6,96	2,24
6	Información en las paradas	IS	6,90	2,43
7	Información a bordo	IB	6,83	2,24
8	Confort de los buses	CM	6,77	1,86
9	Fiabilidad / puntualidad	SR	6,75	2,16
10	Amabilidad del conductor	DK	6,57	2,12
11	Calidad de las paradas	ST	6,56	2,03
12	Información en la aplicación móvil	IM	6,53	3,19
13	Cobertura de las líneas	LC	6,50	2,07
14	Información en la página web	IW	6,46	2,39
15	Espacio para las personas con movilidad reducida	RM	6,27	2,22
16	Tiempo de espera	WT	6,26	2,27
17	Nivel de ocupación	OC	6,25	2,17
18	Facilidad de entendimiento del mapa de líneas	MD	6,21	2,46
19	Tiempo de viaje	TT	6,18	2,14
20	Servicio ofertado (frecuencias y horarios)	SE	6,10	2,42
21	Forma de conducción	DS	5,98	2,15
22	Precio	PR	5,83	2,35
23	Calefacción / aire acondicionado	CA	5,77	2,49
24	Ruido	NO	5,71	2,06
	Satisfacción general	OS	6,73	2,01

Tabla 3: Niveles de calidad percibida de los atributos

3. METODOLOGÍA

3.1 Obtención de la satisfacción general

Disponer de varias observaciones en diferentes momentos del día requiere varios métodos de agregación para poder comparar los resultados de las diferentes líneas de transporte público y los grupos horarios en diferentes tramos de las líneas.

El proceso que se ha seguido comienza con la división de las líneas de transporte público en tramos que coinciden con las paradas de subida y bajada de pasajeros de cada una de las líneas. Dividiendo la línea en tramos, se procesan los datos de las encuestas recogidas a los viajeros de forma que se ha asignado la satisfacción global del viaje (OS) a los tramos que discurren entre el punto de subida y bajada de los viajeros. De este modo, para establecer la puntuación del viaje, se agregan los datos de cada uno de los trayectos entre las paradas (Figura 1). Para ello, se recopilan las puntuaciones individuales de cada usuario y se asignan a cada uno de los tramos de línea que el usuario utiliza en su trayecto entre la parada de subida y la de bajada. La puntuación media de los usuarios que han utilizado cada tramo se emplea para obtener la puntuación de ese tramo. Para poder visualizar correctamente los datos, la puntuación de cada usuario se ha extrapolado a una escala entre 1 y 10, respecto a la escala inicial que valoraba entre 0 y 4 los viajes.

Finalmente, para obtener las puntuaciones registradas en las líneas en distintos segmentos temporales, el procedimiento seguido consiste en agrupar las observaciones por franjas horarias y aplicar una división como la realizada en el agregado de todas las líneas, dividiendo las puntuaciones por el número de franjas de las líneas en función del número de viajeros que suben y bajan del autobús.

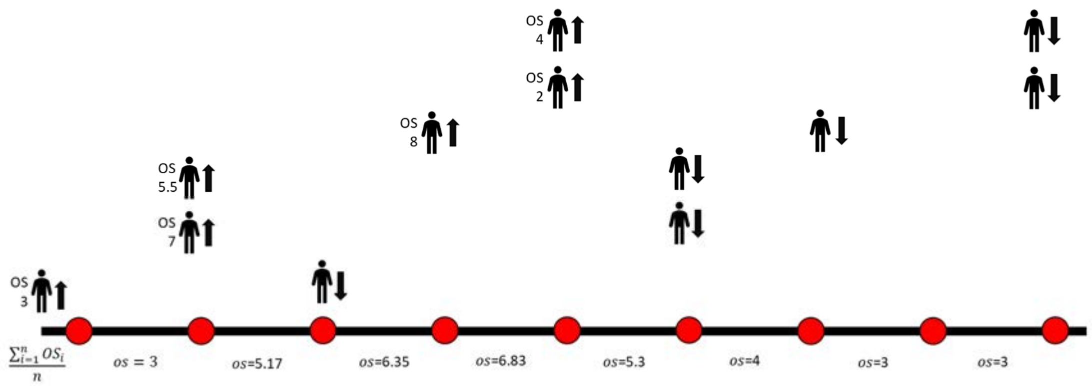

Figura 1: Estimación de la satisfacción general por segmentos

3.2 Modelización Best-Worst

La encuesta realizada se basó en ejercicios Best-Worst (BW) caso 1 (Louviere, Flynn y Marley, 2015). Los modelos basados en BW se han realizado considerando una especificación tipo Logit Multinomial (MNL), donde se asume que la parte no observable de la utilidad se distribuye de acuerdo a una distribución generalizada de valor extremo tipo

1 (distribución Gumbel) con las variables aleatorias independientes e idénticamente distribuidas.

Se han definido un total de K atributos en la encuesta. En cada ejercicio se mostraba un subconjunto Y de 4 atributos diferentes. La probabilidad de escoger una alternativa b como mejor opción (*best)* y una alternativa $w \neq b$ como peor opción (*worst)* se define como $P_{BW}(bw \mid Y)$. La encuesta no permitía escoger una misma opción como opción best y opción worst.

La probabilidad de elección calculada mediante una especificación Logit se define como un modelo Maxdiff (Marley y Louviere, 2005). La expresión del modelo es:

$$P_{BW}(\, b_w|Y) = \exp[v(b) - v(w)] / \sum_{l,k \in Y} \exp[v(l) - v(k)] \;\; \text{con } l \neq k \qquad (1)$$

Donde $v(.)$ es la utilidad observable calculada como una función de los atributos $v(k) = \delta_k y_k$ donde y_k es un vector indicador de 0 y 1 que presenta el valor 1 cuando un atributo k se muestra en la pregunta y 0 en caso contrario. De esta forma, el parámetro δ_k representa la importancia relativa de un atributo frente al atributo base, al cual se le asigna $\delta_0 = 0$. Para incluir la variabilidad temporal en el modelo es necesario considerar cierta heterogeneidad de la muestra. Se define el parámetro del modelo como $\delta_i = \boldsymbol{\delta} + \boldsymbol{\Lambda t_i}$, donde $\boldsymbol{\delta}$ continúa siendo un parámetro constante dependiente del atributo k, mientras que $\boldsymbol{\Lambda}$ representa la variación sobre el valor del parámetro para cada franja temporal $\boldsymbol{t_i}$ al que pertenece cada individuo i.

4. RESULTADOS

4.1 Variación espacial de la satisfacción

En la Figura 2 se muestra el análisis espacial de las 4 líneas encuestadas diferenciando los distintos tramos entre paradas. La satisfacción media de cada tramo se ha calculado de acuerdo con lo establecido en el apartado 3.1. De forma general se puede observar que la variación en la satisfacción a lo largo de una línea no es muy grande. De la misma forma, la satisfacción es muy similar a lo largo de las cuatro líneas de la red, siendo este un nivel de satisfacción medio.

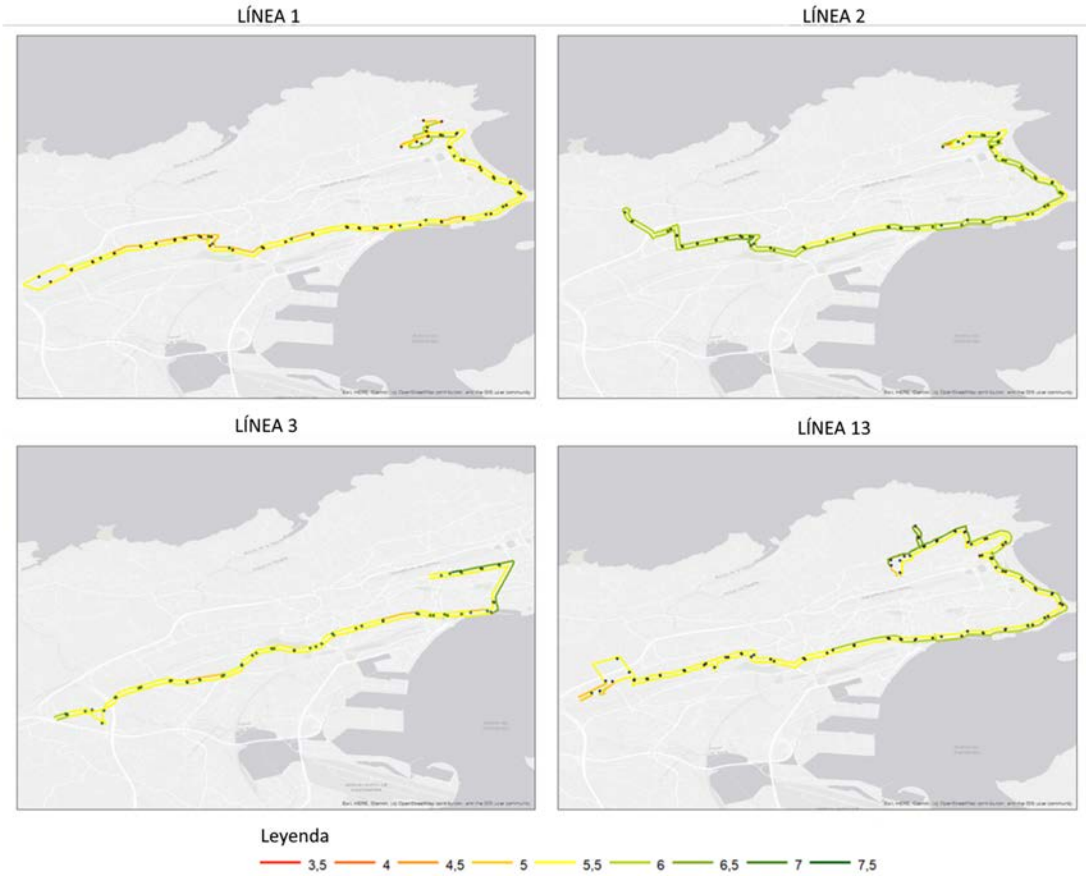

Figura 2: Variación espacial de la satisfacción general

Analizando la línea 1, se puede observar que existe mayor variación en los extremos de la línea, correspondiendo estas zonas a las áreas de la ciudad con una menor densidad de líneas. En la zona noreste se observan niveles de satisfacción contrapuestos, donde algunos usuarios muestran una satisfacción positiva con la línea, mientras que otros usuarios se muestran menos satisfechos con el servicio. En el extremo oeste también se observa una menor satisfacción con la línea.

La línea 2 muestra un nivel de satisfacción mayor que el resto de las líneas, aunque la satisfacción es algo menor en la zona central de la línea y en la zona oeste. La satisfacción en la zona oeste refleja un carácter direccional, mostrando los usuarios una satisfacción mayor al utilizar el servicio en dirección sur.

La línea 3 muestra una satisfacción media en prácticamente la totalidad de la línea, a excepción de varios tramos de satisfacción baja y un tramo en la zona oeste con satisfacción mayor. Esta última parte corresponde a un tramo de la línea que solo se realiza en horas concretas del día y sirve para conectar el centro de la ciudad con la zona universitaria. Se observa además que la satisfacción en este tramo es direccional siendo mayor en dirección a la universidad. La razón de esto puede deberse a que la alternativa en transporte público para acceder a la zona universitaria desde el centro de la ciudad requiere de un trayecto más largo y por lo tanto esta línea supone la mejor alternativa disponible.

Por último, la línea 13 muestra una mayor satisfacción en la zona noreste de la misma, en especial cuando se utiliza el servicio en dirección norte. El resto de la línea muestra un nivel de satisfacción medio, a excepción del extremo oeste, donde la satisfacción de los usuarios es menor. Esta última zona corresponde también a un área de la ciudad con una densidad de transporte público muy bajo.

4.2 Variación temporal de la satisfacción

Con los datos obtenidos en las encuestas se ha realizado un análisis sobre cómo varía la satisfacción a lo largo de un día. Para ello, se han agrupado las respuestas obtenidas en franjas de 1 hora, para un periodo comprendido entre las 8 de la mañana y las 8 de la tarde. En la Figura 3 se puede observar la variación del promedio de la satisfacción general a lo largo del día. Los momentos de menor satisfacción corresponden con los periodos punta de utilización del sistema de transporte, obteniendo la menor puntuación en la hora punta del mediodía. En las horas valle del día la satisfacción general es superior a la media siendo el momento de mayor satisfacción la hora valle de la tarde.

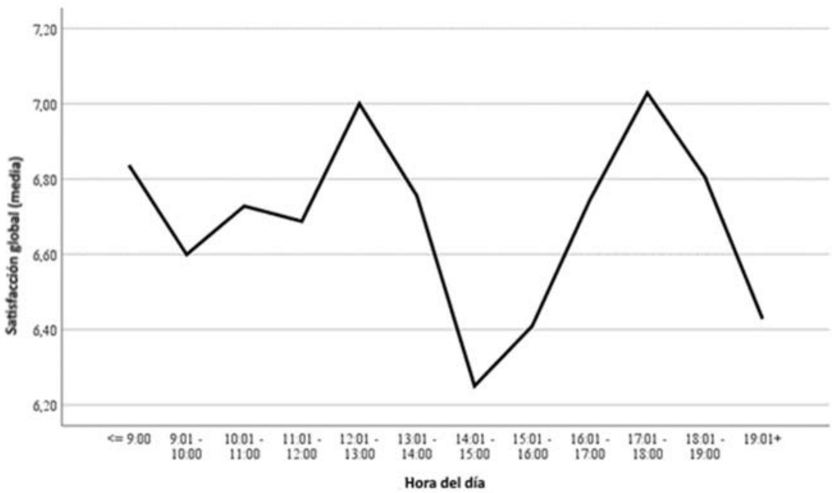

Figura 3: Variación temporal de la satisfacción general

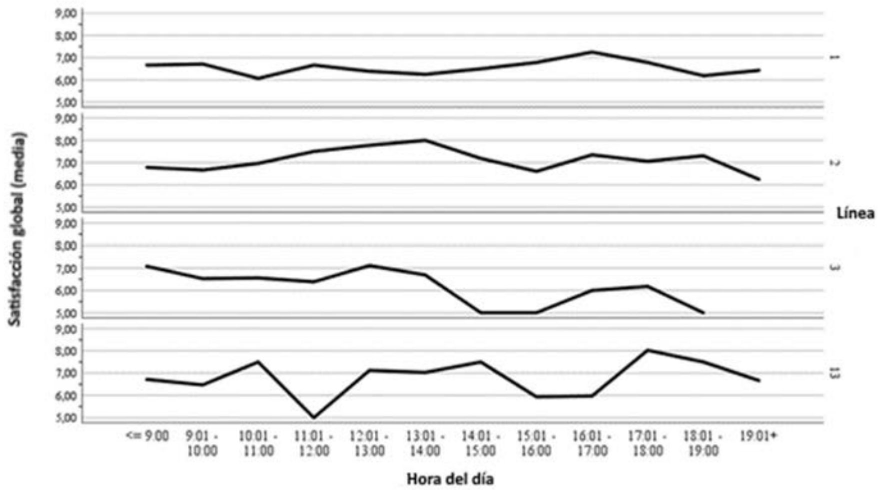

Figura 4: Variación temporal de la satisfacción general por líneas

Se ha realizado un análisis similar segregando los resultados por líneas (Figura 4). Los resultados muestran que la variación de la satisfacción general a lo largo del día es distinta dependiendo de la línea. Las líneas de mayor frecuencia y mayor número de usuarios (líneas 1 y 2) muestran una variación diaria de la satisfacción menor. Sin embargo, las líneas de menor frecuencia muestran una variación en la satisfacción mucho mayor. La línea 13 muestra un perfil de satisfacción distinta a las demás, observándose el menor nivel de satisfacción en la hora valle teórica de la mañana. Este fenómeno puede darse debido a que los usuarios principales de esta línea son personas de avanzada edad que tienden a tener horarios de movilidad distintos al resto de usuarios.

Para comprobar si la variabilidad de la satisfacción es significativa a lo largo del día, se ha realizado un test ANOVA para la satisfacción general y todos los atributos evaluados. Igualmente, el test ANOVA se ha realizado considerando 3 tipos de condicionantes: en primer lugar, se ha analizado la variación por hora del día, en segundo lugar, por periodo del día (hora punta mañana, hora valle mañana, hora punta mediodía, hora valle tarde y hora punta tarde) y, por último, se ha realizado el mismo test considerando las diferentes líneas analizadas. Los resultados de los tres test se muestran en la Tabla 4. Aquellas variables cuyas variaciones han resultado ser significantes se han resaltado en negrita.

Observando los resultados del test ANOVA, se puede concluir que la variabilidad de la mayoría de los atributos no depende ni del momento del día ni de la línea. Sin embargo, algunos atributos sí que se perciben distintos. La variación por cada hora es por lo general menor que si se consideran franjas horarias. El precio (PR), la cobertura de las líneas (LC), la ocupación (OC) y el ruido (NO) son atributos que se han evaluado de forma distinta dependiendo de la hora del día. En el caso de las franjas horarias, los atributos con mayor variación a lo largo de los distintos periodos del día son el precio, la cobertura de las líneas, la ocupación, la calefacción / aire acondicionado (CA), el confort de los autobuses (CM) y la amabilidad del conductor (DK). En menor medida, el tiempo de viaje (TT), la información en el móvil (IM) y la facilidad de entendimiento del mapa (MD) también varían en los distintos periodos del día. A diferencia de la variación temporal, la satisfacción general del servicio sí que varía dependiendo de la línea analizada. Muy relacionado con lo anterior, tanto la percepción de la frecuencia (SE) como la fiabilidad del servicio (SR) cambian también dependiendo de la línea. Otros aspectos relacionados con las líneas y que varían por línea son la información en el bus (IB), el nivel de ocupación, el sistema de calefacción / aire acondicionado, el ruido y la información en dispositivos móviles.

ANOVA test	Por hora		Por franja horaria		Por línea	
	Valor F	Sig.	Valor F	Sig.	Valor F	Sig.
OS	0,653	0,784	0,535	0,750	**4,045**	**0,007**
AT	0,986	0,459	1,389	0,227	1,762	0,154
WT	1,376	0,181	0,857	0,510	0,746	0,525
TT	1,553	0,111	**1,988**	**0,080**	1,517	0,210
DT	1,514	0,124	0,692	0,630	1,499	0,214
PR	**2,940**	**0,001**	**2,783**	**0,017**	0,975	0,404
TR	0,840	0,600	1,192	0,313	0,540	0,655
SE	1,046	0,405	1,455	0,204	**10,128**	**0,000**
SR	0,650	0,785	0,649	0,662	**2,448**	**0,063**
LC	**2,679**	**0,003**	**3,464**	**0,004**	1,718	0,163
IS	1,119	0,344	1,413	0,219	1,806	0,146
IW	1,606	0,101	1,134	0,344	0,783	0,505
IB	1,123	0,342	1,200	0,309	**2,903**	**0,035**
OC	**2,655**	**0,003**	**4,154**	**0,001**	**9,317**	**0,000**
CA	1,381	0,179	**2,710**	**0,020**	**5,952**	**0,001**
RM	0,977	0,467	1,257	0,282	0,381	0,767
CM	1,541	0,115	**2,188**	**0,055**	2,039	0,108
CL	1,042	0,408	1,285	0,269	0,724	0,538
DS	0,996	0,450	0,993	0,422	1,959	0,120
DK	1,550	0,111	**2,295**	**0,045**	1,302	0,273
HY	1,126	0,340	0,494	0,781	0,662	0,576
NO	**1,948**	**0,033**	1,551	0,173	**3,292**	**0,021**
IM	1,265	0,245	**1,900**	**0,094**	**6,411**	**0,000**
ST	0,869	0,571	0,772	0,570	1,516	0,210
MD	1,021	0,427	**1,947**	**0,086**	1,478	0,220

Tabla 4: Test ANOVA considerando diferencias temporales y por línea

4.2.1 Resultados de la modelización

En la Tabla 5 se muestra el modelo MNL estimado considerando la variación temporal de los distintos atributos recogidos en la CSS. Para incluir la variable tiempo se han utilizado las franjas horarias de hora pico mañana (7:00 – 9:00), hora valle de mañana (9:00 – 13:00), la hora pico de mediodía (13:00-15:00), hora valle de tarde (15:00 – 17:00 y 19:00 en adelante) y hora punta tarde (17:00 – 19:00). Se han considerado estas franjas horarias para disponer de observaciones suficientes para estimar el modelo. Los valores de los parámetros muestran el nivel de importancia de cada atributo, es decir, a mayor valor mayor es la importancia de ese aspecto. Las variables que consideran interacción aportan una variación debido a la franja horaria con la que interactúan.

Por lo tanto, si una interacción muestra un parámetro negativo, ese atributo tiene una menor importancia en esa franja horaria, mientras que, si muestra un valor positivo, la importancia aumenta. En el modelo definitivo solo se han considerado aquellas interacciones que han resultado ser estadísticamente significativas.

Variable	Acrónimo	Parámetro	Valor z
Tiempo de acceso a la parada	AT	1,517	12,13
Tiempo de espera	WT	2,042	15,96
Tiempo de viaje	TT	2,296	17,50
Tiempo de egreso	DT	1,678	13,29
Precio	PR	1,912	15,24
Facilidad de transbordo	TR	1,193	9,48
Facilidad de transbordo *Hora punta mañana	H1TR	-0,595	-2,97
Facilidad de transbordo * Hora punta tarde	H3TR	0,580	3,01
Frecuencias y horarios	SE	2,313	17,99
Fiabilidad del servicio	SR	2,401	18,84
Cobertura de las líneas	LC	2,317	17,84
Cobertura de las líneas * Hora punta mañana	H1LC	0,321	1,86
Información en las paradas	IS	1,420	11,20
Información en las paradas * Hora punta mañana	H1IS	0,547	2,49
Información en las paradas *Hora punta mediodía	H2IS	-0,553	-2,98
Información en las paradas * Hora punta tarde	H3IS	0,578	2,92
Información en la página web* Hora punta mañana	H1IW	-0,536	-3,17
Información a bordo	IB	0,299	2,38
Nivel de ocupación	OC	1,503	12,02
Nivel de ocupación * Hora punta mañana	H1OC	-0,303	-1,95
Calefacción / aire acondicionado	CA	0,467	3,74
Espacio para personas de movilidad reducida	RM	1,669	13,07
Confort de los buses	CM	1,158	9,26
Confort de los buses * Hora punta tarde	H3CM	-0,325	-2,21
Limpieza del vehículo	CL	0,942	7,67
Forma de conducción	DS	1,514	11,95
Amabilidad del conductor	DK	0,557	4,33
Amabilidad del conductor * Hora punta mediodía	H2DK	-0,465	-2,79
Amabilidad del conductor * Hora valle mañana	H4DK	0,555	4,06
Uso de vehículos híbridos	HY	1,121	8,84
Ruido	NO	0,506	4,09
Información en la aplicación móvil	IM	1,011	7,99
Calidad de las paradas	ST	0,630	4,96
Facilidad de entendimiento del mapa de líneas	MD	1,266	9,81
Facilidad de entendimiento del mapa de líneas * Hora valle mañana	H4MD	-0,501	-4,05

Tabla 5: Modelo MNL basado en Best-Worst considerando variación temporal

Con los modelos estimados es posible establecer el nivel de importancia de cada atributo para cada franja horaria analizada. En la Tabla 6 se muestran los valores normalizados de la importancia y el promedio de la calidad percibida para cada atributo en cada franja horaria. Al atributo más importante de cada franja horaria se le ha asignado el valor 10 mientras que al menos importante se le ha asignado el valor 0 y el resto de valores se han ponderado de forma lineal entre estos dos valores de acuerdo a los resultados del modelo.

Las variables más importantes para los usuarios han resultado ser aquellas más relacionadas con las características operativas de las líneas, siendo estas la cobertura de las líneas, la fiabilidad del servicio y el servicio ofertado (horarios y frecuencias). Estas tres variables han resultado ser importantes, dejando claro que la variación de la importancia de los atributos a lo largo del día no es muy notable.

Los atributos menos importantes para los usuarios han resultado ser aquellos relacionados con servicios adicionales o secundarios, como son la información en la página web, la información dentro del bus, el sistema de calefacción o el ruido. En el caso de estas variables menos importantes, la variabilidad a lo largo del día es mayor que en el caso de los atributos importantes, y aunque su importancia crezca no llegan a alcanzar niveles de importancia altos.

Los atributos cuya importancia cambia de forma significativa son la facilidad de realizar transbordos (TR), que es mucho más importante en la hora punta de la tarde en comparación al resto del día, y la información en las paradas (IS) y la amabilidad del conductor, que son más importantes en las horas punta de todo el día frente a las horas valle.

Var	Hora punta mañana		Hora valle mañana		Hora punta mediodía		Hora punta tarde		Hora valle tarde	
	Imp.	Cal.	Imp.	Cal.	Imp.	Cal.	Imp.	Cal.	Imp.	Cal.
AT	6,47	7,39	6,32	7,67	6,32	7,21	6,32	7,00	5,80	7,08
WT	8,12	6,08	8,51	6,18	8,51	6,20	8,51	6,50	8,29	6,47
TT	8,92	5,92	9,56	6,04	9,56	6,60	9,56	6,27	9,50	6,35
DT	6,97	7,44	6,99	7,38	6,99	6,92	6,99	7,30	6,56	7,42
PR	7,71	5,82	7,96	5,74	7,96	6,06	7,96	5,64	7,68	6,25
TR	3,57	7,62	4,97	7,02	4,97	6,94	7,38	6,67	4,32	6,71
SE	8,98	5,55	9,64	5,99	9,64	5,98	9,64	6,41	9,58	6,45
SR	9,25	6,37	10	6,94	10	6,59	10	6,81	10	6,64
LC	10	5,69	9,65	6,78	9,65	6,25	9,65	6,27	8,07	6,94
IS	7,89	6,49	3,61	6,94	5,92	6,50	8,32	7,50	2,62	6,94
IW	0	5,36	0	6,46	0	6,74	0	6,67	1,13	6,77
IB	2,63	7,13	1,24	6,85	1,24	7,15	1,24	6,33	0	6,75
OC	5,47	6,12	6,26	6,48	6,26	5,83	6,26	5,81	7,17	6,82
CA	3,16	6,07	1,94	5,55	1,94	6,07	1,94	5,21	0,80	6,48
RM	6,95	6,55	6,95	6,36	6,95	6,37	6,95	6,18	6,52	5,64
CM	5,34	7,20	4,82	6,73	4,82	6,33	3,47	6,60	5,63	7,09
CL	4,66	7,40	3,92	7,09	3,92	6,95	3,92	6,63	3,06	7,06
DS	6,46	5,45	6,31	6,22	6,31	5,90	6,32	7,00	5,80	7,08
DK	3,44	6,19	0,38	6,82	4,63	6,89	8,51	6,50	8,29	6,47
HY	5,22	8,08	4,67	8,01	4,67	7,98	9,56	6,27	9,50	6,35
NO	3,28	5,56	2,11	5,42	2,11	5,99	6,99	7,30	6,56	7,42
IM	4,87	6,90	4,21	6,14	4,21	6,19	7,96	5,64	7,68	6,25
ST	3,67	6,20	2,62	6,52	2,62	6,89	7,38	6,67	4,32	6,71
MD	5,68	6,41	5,27	6,38	3,19	6,46	9,64	6,41	9,58	6,45

Tabla 6: Importancia y calidad percibida de los atributos por franjas horarias

4.3 Variación espacial y temporal de la satisfacción

Por último, es posible combinar el análisis temporal con el espacial para estudiar la evolución de la satisfacción de los usuarios a lo largo del día en los distintos puntos de la red. En la Figura 5 se muestran los resultados para la satisfacción general de la línea 1 en los 6 periodos analizados. El mismo proceso podría realizarse para todas las líneas y todos los atributos, sin embargo, dicha información no se ha añadido en el artículo por mantener una extensión razonable.

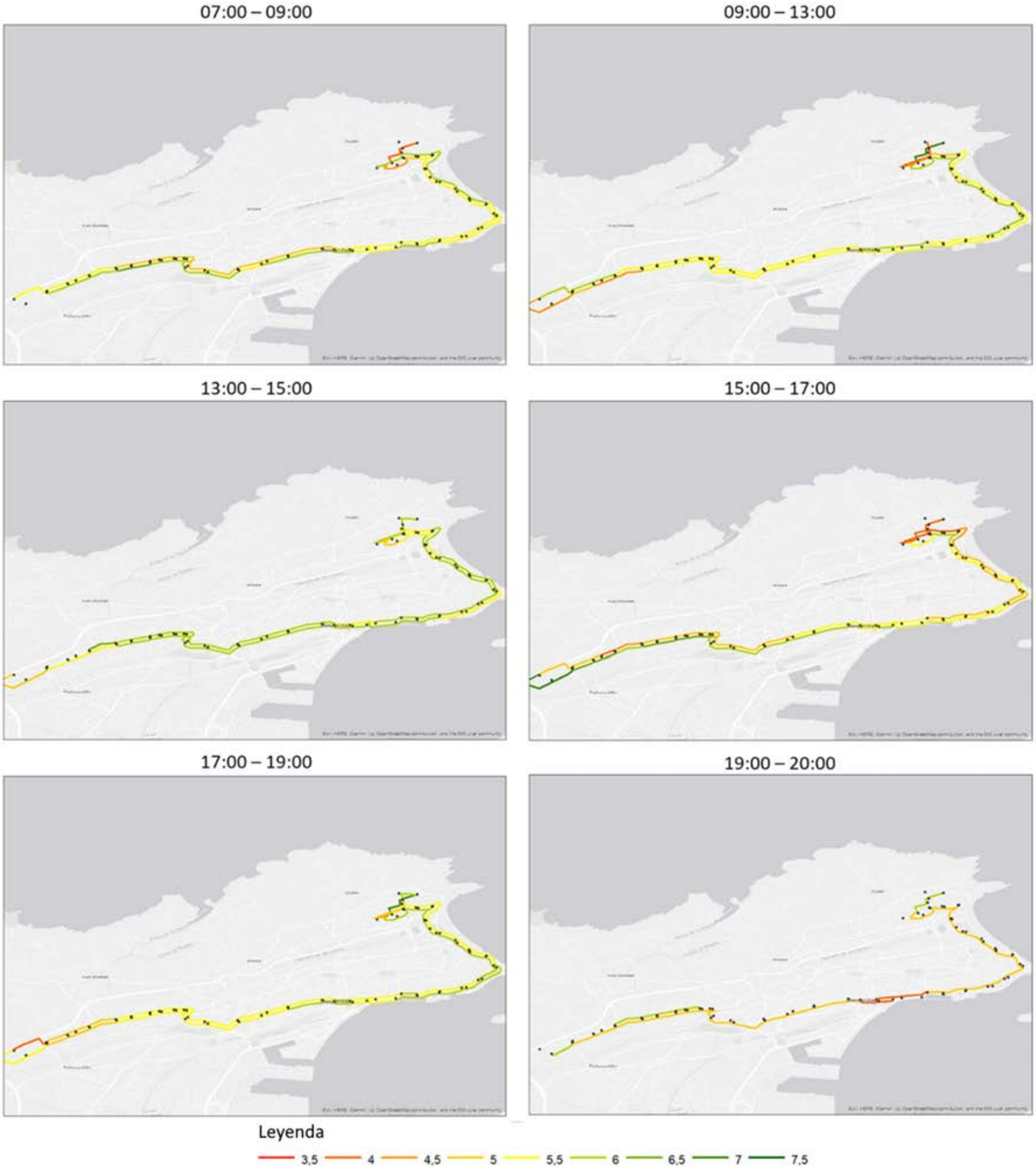

Figura 5: Variación espacial y temporal de la satisfacción general en la línea 1

Analizando las imágenes en su conjunto, se puede observar que la satisfacción cambia tanto espacialmente como temporalmente de forma simultánea, esto es, que en distintas horas del día la satisfacción es diferente en distintos puntos de la red.

Observando la hora punta de la mañana (7:00-9:00) se detecta que la satisfacción tiene un carácter claramente direccional. Los usuarios que cogen el bus para ir de la zona norte (principalmente residencial) a la zona oeste (residencial y laboral) muestran una satisfacción más negativa del servicio, mientras que en sentido contrario la satisfacción es mayor. En la hora valle de la mañana (9:00 – 13:00) el efecto es el contrario, la satisfacción es peor en dirección este, mientras que aumenta en dirección oeste. En la hora punta del mediodía la tendencia vuelve a cambiar, en este caso la direccionalidad es más homogénea, mientras que la distinción es entre la zona central de la línea y las zonas periféricas, donde se observa una menor satisfacción en estas últimas. Al comienzo de la tarde (15:00 – 17:00) la tendencia es similar a la hora punta de la mañana, observándose unas satisfacciones generales menores. El menor nivel de satisfacción se ha observado a las 15:00, al finalizar la hora punta del mediodía y empezar la hora valle de la tarde. En la hora punta de la tarde (17:00 – 19:00) la tendencia es similar a la del mediodía, donde las peores opiniones de los usuarios se perciben en los extremos de la línea. A partir de las 19:00 la satisfacción es baja de forma generalizada.

Por lo tanto, observando las variaciones diarias de la satisfacción de los usuarios, se puede decir que esta está inversamente relacionada con la direccionalidad de los viajes realizados por obligación (trabajo, estudios) en las horas punta, mientras que en las horas valle la tendencia es la contraria.

5. CONCLUSIONES

El artículo presentado desarrolla una metodología de análisis que complementa el estado del arte actual. La variación de la satisfacción entre distintas líneas de un mismo servicio ha sido analizada en diversos estudios, tal y como se ha mencionado en la introducción de este artículo. Sin embargo, la variación espacial y temporal en la satisfacción de cada línea no se ha tenido en cuenta anteriormente, habiéndose demostrado en este estudio que dicha variación existe y puede ser significativa.

El análisis espacial de las líneas ha demostrado que existe una clara distinción entre varios puntos de la red en lo referente a la percepción de la calidad. Por lo general, las zonas con una densidad de líneas de transporte público menor tienden a valorar el servicio de forma diferente que las zonas donde hay una mayor elección de líneas. Esta variación puede ser positiva o negativa dependiendo de cada zona y de cada línea, estableciéndose la necesidad de estudiar de forma específica cada caso.

Por otro lado, el análisis temporal de la satisfacción ha demostrado que la calidad percibida por los usuarios cambia a lo largo del día. Considerando al usuario medio, puede decirse que los niveles de satisfacciones menores se dan en las horas punta del día. En el caso concreto de este artículo, el peor nivel de satisfacción se ha observado en la hora punta del mediodía. Analizando la variación temporal por líneas, se ha observado que la variación es menos marcada en las líneas de mayor frecuencia y demanda (mejores prestaciones), en comparación con las líneas menos utilizadas y de menor frecuencia (peores prestaciones). Otro aspecto importante es que el tipo de usuario afecta a la localización horaria del punto de menor satisfacción, siendo este el caso de la línea 13 analizada. En esta línea el número de usuarios de edad avanzada es alto, por lo que las horas de más uso se encuentran desplazadas del resto de líneas, siendo este un factor que afecta a la variación de la satisfacción, puesto que en esta línea el peor nivel se ha observado en la hora valle de la mañana.

Los modelos BW estimados han permitido estudiar la variación de la importancia de los atributos a lo largo del día. En este aspecto, aunque sí existe una variación de los niveles de importancia entre los distintos atributos, la variabilidad a lo largo del día no es significativa en la mayoría de los casos. Algunas excepciones son la facilidad de hacer trasbordos, que gana mayor importancia para los usuarios en la hora punta de la tarde, la información en las paradas que es más importante en las horas punta del día y la amabilidad del conductor, que también es más importante en las horas punta.

Por último, el análisis en conjunto de la variación espacial y temporal ha demostrado que la satisfacción de los usuarios cambia con la hora del día y el lugar, siendo la direccionalidad del flujo un aspecto importante a considerar. Además, la satisfacción del usuario es generalmente menor en los extremos de la línea.

En resumen, el estudio presentado en este artículo ha demostrado que la satisfacción de los usuarios cambia dependiendo de la zona de la ciudad y la hora del día donde se analice. Este resultado puede servir a las empresas operadoras para mejorar los servicios de forma más específica, actuando en aquellos lugares y aquellos momentos donde la satisfacción es más baja.

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TOOLS FOR THE MONITORING, USER CHARACTERIZATION, AND THEIR APPLICATIONS TO THE PUBLIC INTEGRATED TRANSPORT SYSTEM DUE TO THE COVID 19 DISEASE EFFECTS: A CASE STUDY IN BOGOTÁ, TRANSMILENIO COMPANY

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ABSTRACT

The pandemic made the transport system administration switch the way decisions were made in topics such as the response speed, resilience to shifts in the demand, and the new policy needs. Therefore, public transport requires monitoring tools, such as dashboards, and an emphasis in user characterization, in addition to traditional modeling and supply-demand indicators historically used by TransMilenio in order to command the operation of the public transport system of Bogotá D.C.

This study employed descriptive spatial and statistical analysis to comprehend the relations among the registers of contagion waves, user polls and the boarding information on SITP. Complementarily, the article shows the shifts in the demand towards the regulatory milestones for the pandemic, and how short-term changes in bus supply were made due to these set of regulations.

The paper also provides a recap of the international discussion about the occupation, efficiency, and biosecurity of massive public transport systems. The main results for TransMilenio were some supply changes, among others.

1. INTRODUCTION

The entity in charge of planning and coordinating the public transport system of Bogotá D.C, Empresa de Transporte del Tercer Milenio – TRANSMILENIO S.A., has three different services. The first one is the worldwide known as BRT, with a fully dedicated lane, central stations, high floor buses, and payment outside the bus. The second one is a conventional bus service with validation on board that covers the demand of the zones where there are not BRT lanes, carrying people from their neighborhoods to the BRT stations, making last mile solutions or trips to remote places in Bogotá's rural zone. The third one is TransMiCable, which is a cable system included statistically in the demand of the BRT and serves the locality of Ciudad Bolívar. The TRANSMILENIO system comprises 761 articulated buses, 1,323 bi-articulated buses and 273 dual standard buses for the BRT, as well as 7,105 bus services with validation on board and 160 cabins for the cable. Fig. 1 illustrates its geographical distribution through Bogotá.

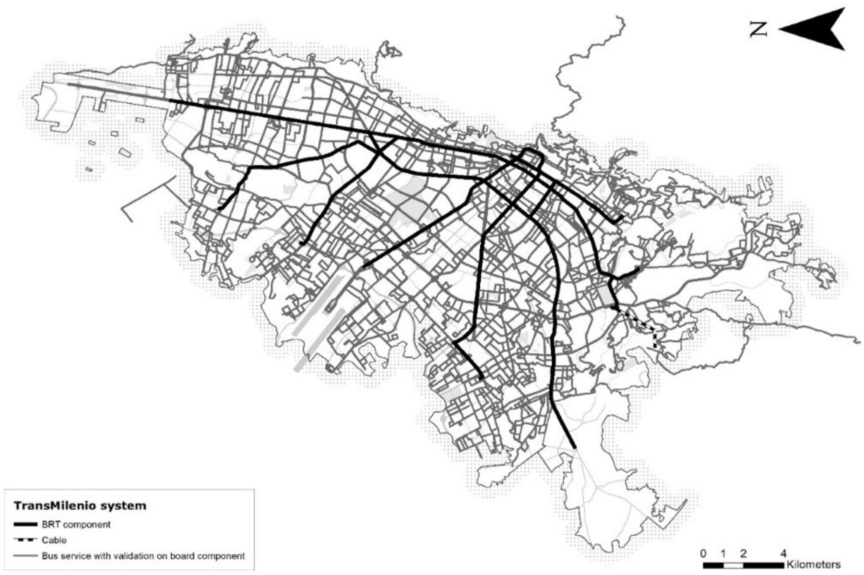

Figure 1: TRANSMILENIO: BRT system and on board validation bus service

Trying to predict the dynamism of a contagious disease is not an easy task, however, getting as close to reality as possible through models and analyses, such as those shown in this study, is an effort that can save human lives (Gomez, Prieto, Leon, & Rodríguez, 2021). For the purposes of this paper, people decide in the way described before. For a university council, it can be rational to order scaled schedules for on-campus lessons, because they want to prevent desertion and maximize learning, restricted by the capacity controls imposed due to the pandemic and the probability that an outbreak starts in the campus. For a student, the choice related to the self-care measures works in the same way. If the student considers that going to the campus is too risky for their life or for the life of people who live with them, the student will choose not to go, even if the place is open. On the other hand, if the student thinks that only by wearing mask, they will be able to protect themselves from COVID-19, they will more probably go to the campus, given the choice of the university council. In the student's example, the information and the context play a role on how they make their decisions. This mechanism of decision is similar to the one described by Przybylowski, Stelmak, & Suchanek (2021). In that way, each individual's decision plays a key role that has to be taken into account when modeling demand.

2. LITERATURE REVIEW

This chapter included three focuses: The first about de pandemic and public transport, the second on geographic information systems and their use with infectious diseases and finally, the third on changes the individual preferences and behavior.

2.1 Literature about the pandemic and public transport

The reviews and recommendations about COVID-19 and the challenges of public transportation indicate a general context about the service and the risk for users (Gutiérrez, Miravet, & Domènech, 2020). Likewise, changes in the demand for transport modes were evident, as well as the decrease in public transport systems (Le , Sheng, & Sharp, 2021) (Komla Junior Dzis, Obeng-Atuah, Ackaah, Yaw Tuffour, & Eric Aidoo, 2021) and research needs (Gkiotsalitis & Cats, 2020).

The case studies during COVID-19 about the effects on public transport show a global problem that includes analysis of supply, demand and biosecurity, in countries like Turkey (Devecí, Aydin, & Kusakci, 2021), Finland (Tiikkaja & Viri, 2021), Poland (Przybylowski, Stelmak, & Suchanek, 2021) and United Kingdom, regarding the future of public transport (Vickerman, 2021).

2.2 Literature on geographic information systems and their use with infectious diseases

In 1854, an English doctor named John Snow, through the spatial location of cholera cases in London, managed to realize a pattern that until then no one had noticed, thus discovering the source of the outbreak of the disease in a water pump of the place (Fradelos, Tsaras, Papathanasiou, & Kleisiaris, 2014). Although geographic information systems did not exist in 1854, this example makes it clear that having information on a map allows us to ask ourselves questions and solve problems, as we do with current tools.

Another investigation on the spread of hepatitis C was carried out in Connecticut (Navarro, Trooskin, & Hadler, 2005) through cluster analysis. This study was able to identify clusters in the most densely populated urban areas, which had previously been identified as areas of substantial injection drug use. Although local demographic characteristics alone do not follow a particular phenomenon, crossing them with other geographic variables helps to prevent disease transmission.

Currently, with the COVID-19 pandemic that can affect a population very quickly, it is necessary to have a solid support of spatial information for decision-making, formulation of measures and evaluation of the effectiveness of prevention and control of COVID-19 (Zhou, y otros, 2020). Considering the above, the cities with updated information day after day on dashboards, and maps on the location of infections and availability of care in medical centers for decision-making are those that have the least consequences to regret.

2.3 Changes in the individual preferences and behavior

A preference is a comparative evaluation of a set of objects and works as a cognitive marker that reminds people how to interact with the environment. The objects of preferences are not given for being organized but are those that can be perceived by a human being, whose experience allows to differentiate, and those which a human being's cognitive capacity can remember (Druckman & Lupia, 2000). In the case of the preferences for a contagious disease, as COVID-19, the preference for staying home or going out to work depends on factors such as the education received by the person related to viruses, their risk tolerance, among others. Thus, two people who receive the same information about a first case detected can react in two different ways.

The rational choice theory is an approach founded on methodological individualism (MI), from which human behavior is explained. The MI starts its analysis with the principle that social behavior reflects the choices everyone makes. For that reason, the individual behavior determines the social outcomes. In this paper, we suppose that choices made by everyone, such as deciding to work or not, or by each person with agency, e.g. a university headmaster, can impact the results in activities related to occupancy of public transport. Back into the ration choice theory, Elster (1996) says that the social behavior responds mainly to the decisions made individually, which are the consequence of a rational thought. This is an instrumental rationality, which means that people use reason to obtain something they want. In this sense, a choice is rational if it maximizes o minimizes certain objective people trace for themselves, with a given context, rules, as well as other types of restrictions, e.g. the income level or the education you received.

For example, in the case of COVID-19, your rational choice can be guided by the principle of minimizing the probability of being infected, while having to do an essential job (e.g., a nurse), or maximizing your personal income, given some restrictions to your individual behavior. Once the person identifies the rule of decision, the decisions of public health are linked with people's personality (Blagov, 2020) or a consequence of the current political discourse with which people identify (Hatcher, 2020). A rational choice explains each one's behavior as the decisions made to accomplish that rule. Therefore, the rationality, in this case, is guided by the results an individual plans to obtain.

3. SUMMARY OF THE INTERNATIONAL BENCHMARKING

This chapter is divided into two parts, the first on benchmarking of the policies of the pandemic and the second, benchmarking of the occupancy.

3.1 Benchmarking of the policies adopted in the early stages of the pandemic

The benchmarking is presented in Table 1, this includes cities of the five continents about transport system and strategies used in pandemic.

City	**Country**	**City popul.**	**Urban area of the city**	**Type of public transport system**	**Strategies used**
Sidney	Australia	5,3 millions of inhabitants (2018)	12367,7 km²	9 subway lines and one train line	There is no capacity to clean en-route buses during shifts. They requested to avoid travelling during rush hours if possible and to limit travels to those who are strictly necessary.
Lima	Peru	8,8 millions of inhabitants (2017)	2672,3 km²	2 subway lines and 5 BRT lines	Since Monday, March 16th, 2020, only BRT operates, the other systems are closed. BRT is working with the Saturday schedule with difficulties for the transport of operators. Cleaners and all employees of the system have gloves and masks.
Shenzhen	China	12.53 millions of inhabitants (2017)	1748 km²	8 subway lines and bus system	Buses are disinfected after each trip. At night, some routes are suspended. Floor markings (also adopted in Europe) are used as a guide to minimum distances between passengers for social distancing.
Madrid	Spain	3,2 millions of inhabitants (2019)	604,45 km²	13 subway lines, tramway and bus system	The transport offer must be reduced to at least 50%. The subway prioritized stations near hospitals. The use of the two lines of seats closest to the driver is prohibited.
Santiago	Chile	6,25 millions of inhabitants (2017)	837,89 km²	7 subway lines and bus system	Buses are sanitized more often. From March 22nd, 2020, they adjust and reduce the hours of operation.
Singapore	Singapore	5,6 millions of inhabitants (2017)	697 km²	6 subway lines and bus system	Two campaigns: (1) protect employees by disinfecting drivers' seats and the use of protective items such as gloves, and (2) avoid contact with employees at information points as much as possible, which includes "safe distancing".
Kuala	Malaysia	7,59 millions of inhabitants (2016)	243,65 km²	BRT system	They took temperature measurements of the drivers and the system team before starting the shift. In addition, the hygiene days of the buses and the system facilities tripled.
Jakarta	Indonesi	10,3 millions of inhabitants (2017)	750,28 km²	6 train lines and a bus system	They reduced the service of the TransJakarta system: 248 routes were reduced to only 13 with buses traveling every 20 minutes.
Buenos	Argentin	3 millions of inhabitants (2017)	203 km²	6 subway lines and a bus system	Long distance trains and buses suspended their services. Buses and trains in the Buenos Aires metropolitan area operated only with seated passengers

City	**Country**	**City popul.**	**Urban area of the city**	**Type of public transport system**	**Strategies used**
Stuttgart	Germany	634 830 inhabitants (2019)	207,36 km²	train and bus system	The trains reduced their frequency to every 30 minutes; there are no night or weekend buses. Service to and from the airport was suspended. Payment in cash was prohibited. The ascent-descent of passengers is only allowed through the farthest door from the driver.
Panama City	Panama	880 691 inhabitants (2013)	275 km²	2 subway lines and a bus system	They included maximum capacity for buses and distance marks inside the buses. The "adopt your hero" campaign was implemented to raise awareness about the drivers' work. They disabled the seats closest to the driver and the rest of the interleaved-use seats.
Curitiba	Brazil	1, 8 millions of inhabitants (2015)	412 km²	BRT system	Initially, they reduced the supply of buses but since the quarantine was not official, the system had to increase the supply again due to demand.
San	U.S.A	805.235 inhabitants (2010)	121 km²	Light train and bus system	The frequency of the service was reduced and if the buses are full they will not stop to pick up passengers. Additionally, there was a reduction in routes.
Paris	France	2,18 millions of inhabitants (2017)	105,4 km²	14 subway lines, 13 train lines, 11 tramway lines and bus system	The frequency of the routes was reduced and they generated a real-time report of the offer of each of the transport services.
London	England	9,7 millions of inhabitants (2018)	1572 km²	11 subway lines and bus system	Metro stations are closed and using the system is only recommended if essential. They suspended the subway service on Friday and Saturday nights, but the bus service continues to operate for essential workers. They suspended the service in the city center and communicate by email with registered users
Vancouver	Canada	2,2 millions of inhabitants (2016)	114,97 km²	3 skytrain lines, SeaBus (ferry) and bus system	The free service was implemented. There was a change in frequencies. In addition, the entry and exit of passengers was required only through the back door or the one furthest from the driver. They increased the disinfection of buses per day.

Table 1: Policies adopted at the beginning of the pandemic by COVID-19

3.2 Benchmarking of the occupancy

After adopting some of the decisions mentioned above, TRANSMILENIO S.A. faced a new situation, in which the economy was progressively being reactivated. At the international level, there were restrictions to the occupancy of public transport, in cities such as: Shenzhen, where the limit in place was of the 50% (Ma, 2020); Jakarta, where public transport was shut down and then, on June 8th, 2020 opened at 50% of its capacity (Widadio, 2020), or Mumbai, where the occupancy limit was also 50% (Mumbai Mirror, 2020). At the national level, the order was to have a 35% capacity limit. The main reason to do this was that the local health authorities considered that public transport could be a place where massive contagion clusters of the virus SARS-CoV-2 could appear.

However, more international evidence about the behavior of the contagion clusters started to appear and it suggested that public transport was not as risky as thought. First, discussing the recent epidemics caused by other Coronaviruses (SARS and MERS), Avineri, Musselwhite, and Susilo (2020) argued that there was no significant evidence of reduction of the contagion in the cities that closed their transport system.

Second, referring to the COVID-19 pandemic, the evidence collected from the tracking and contact tracing strategies did not suggest a statistically relevant effect of public transport on contagion. For example, Japan, at the beginning of its outbreak, followed a strategy that consisted in detecting contagion clusters. Despite its robust contact tracing strategy, no single cluster was detected in passenger trains (Normile, 2020). Likewise, in New York, from 1300 patients admitted with positive COVID-19 results, only the 4% of them affirmed to have used public transport in recent days (Shwartz, 2020). With those results, the next step was to ask why public transport seems safer than other crowded and enclosed places. Fig. 2 shows the overall map of the cities consulted.

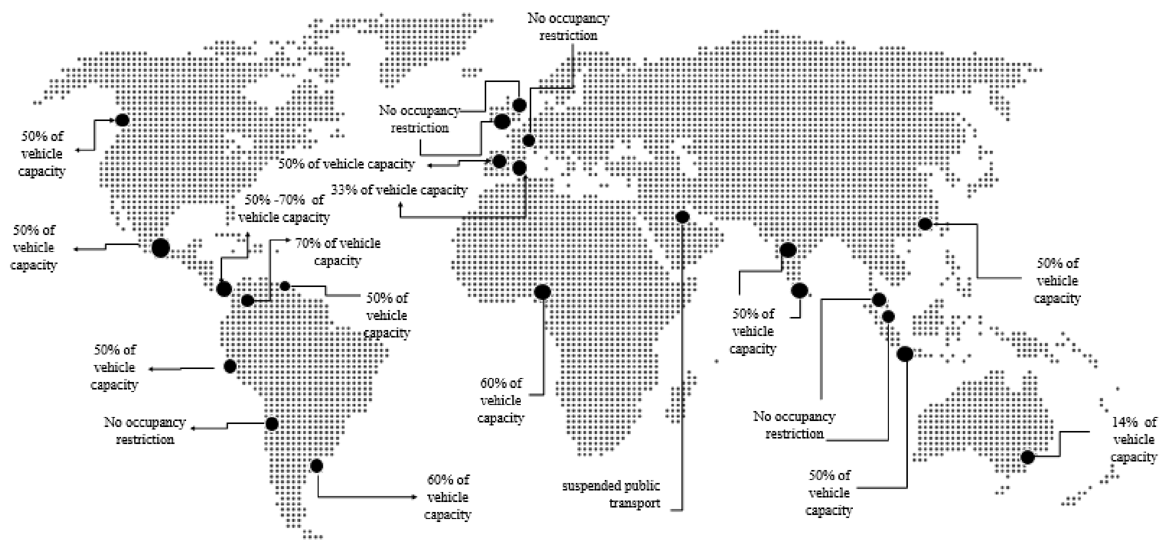

Figure 2: Map of the consulted cities

The evidence found suggested that the transmission of the virus is low, if users wear their masks in the appropriate way and if they do not talk at all during their trip, although the evidence was not yet conclusive (Tirachini & Cats, 2020). Even though inside the vehicles, that are enclosed places, there are concentrations of people who do not keep the prudent distance, but the implementation of other non-pharmaceutical measures, such as the use of mask or the prohibition of speaking (as in the case of Singapore), helps to reduce the probability of contagion (Tirachini & Cats, 2020). Attending to these data, in Colombia the occupancy limit went from 35% to 50%, while trying to ensure that people could make the appropriate decisions about the use of masks, and silence, for protecting themselves from the virus.

4. INSTITUTIONAL POLICIES ADOPTED

This section explores the different measures and strategies adopted by TRANSMILENIO S.A. in response to the pandemic, and the need of reducing the occupancy of the system. First, there were a set of sanitary measures that intended to reduce the contagion probability, as well as other that were meant to increase the supply of the system. The second section shows some demand management strategies that were implemented with other public offices.

4.1 Sanitary measures

Given the importance of mobility in a city, the district entities in this sector must face the critical impacts of the coronavirus, making a change in demand that contributes to the safety of passengers and operating personnel of the system. TRANSMILENIO S.A. focused its service on measures that promote social distancing and biosafety standards in accordance with the regulations issued by the Nation and the District. Therefore, the maximum offer of the system was modified, a monitoring tool with public access was generated and cooperation measures were agreed with other entities to characterize users, among other strategies that are detailed below. The measures were related to the resolutions issued at the national level.

On March 6th,2020, the first case of COVID-19 was diagnosed in Bogotá D.C. By March 12th, there were already 5 cases diagnosed and a yellow alert was emitted. In Bogotá, people started to diminish the use of public transport. On March 16th, an orange alert was emitted, and some temporary bike lanes were made by the city administration. Afterward, the national government announced a “national quarantine” since March 25th.

The government started to permit the opening of some economic activities since April 27th until July 13th, when the city administration made localized confinements, so that part of the city could maintain the economic activities, while the other was in a strict confinement. On August 28th, this policy ended and, on September 1st, another policy called “Nueva realidad” (New Reality) started, which limited de working days per economic sector, and assigned entrance and exit hours for each one of them. The regulations were modified slightly during the next months, until almost the whole scheme was derogated by November. Fig. 3 summarizes the policies implemented.

Decree	Expedition date	Measure applied by TRANSMILENIO S.A.
081, 2020- Sanitary measures	11th March 2020	Installation of 134 portable sinks Daily washing and disinfection of stations and buses
087, 2020- Public calamity	16th March 2020	Pedagogical prevention activities
090, 2020- Vital Drill exercise	19th March 2020	Fleet coordination Demand reduction (87% BRT component and 80% bus service with validation on board component)
457, 2020- Mandatory isolation	22nd March 2020	Creation of the public control board Control of user influx Mandatory use of face masks in the system System offer between 50% and 75% from March 20th to April 29th, 2020 Health routes
593, 2020 and 121, 2020 - Opening of economic sectors	24th April, 2020 and 26th April, 2020, respectively	User characterization New access scheme to critical stations Chair marking Offer increase to 100% Demand management app - "Full bus"

Table 2: Decrees issued by the District of Bogotá for COVID-19

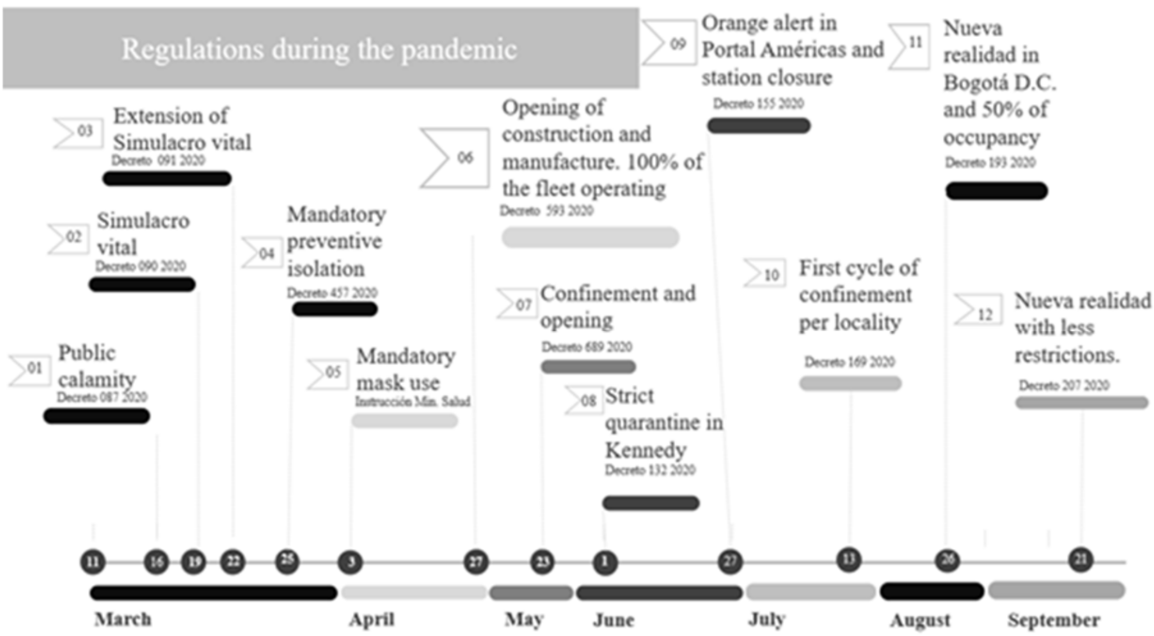

Figure 3: Timeline of the general policies implemented

4.2 Demand management: Public officers' demand management and Universities

An additional policy implemented by TRANSMILENIO S.A. and Bogotá D.C. was to organize public employee's schedules in different turns, as well as pilot schedules for some universities. Due to the occupancy limit of 35% (and then 50%), if activities were to be made in person once again, the transport system would not have been able to maintain a low occupancy, especially in some points of the city and during rush hours.

The most important schedule was developed with the Departamento Administrativo del Servicio Civil, the entity that regulates the exercise of public employees in Bogotá D.C. They designed a survey which asked, first, basic data, such as the institution they worked for, their municipality and department of residence, and, if the place of residence was Bogotá, their locality, and the planning unit they lived in. Second, there were some questions about the days of the week they worked and the mean of transport they used. On the following lines, there is a brief illustration of the descriptive statistics relevant for TRANSMILENIO S.A. As of June 23rd, there were 12.329 observations of the survey, but the size of the sample was different, according to the institutions where the instrument was applied. Fig. 4 represents the day of the week in which the public servers work, according to this survey.

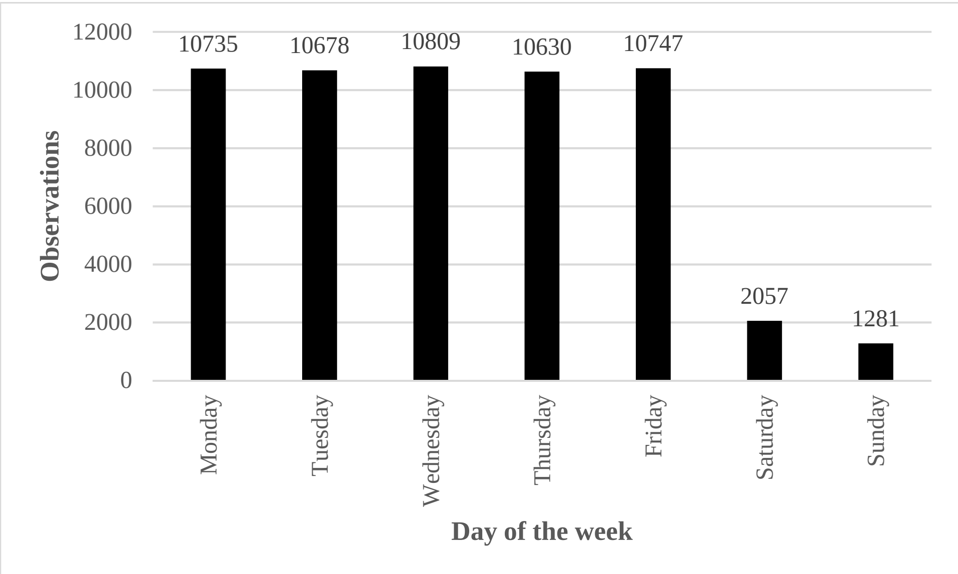

Figure 4: Day of the week in which the officer works

In general, it was observed that most public servers worked from Monday to Friday. Most of the records corresponding to Saturdays and Sundays belonged to health sector workers. This pattern indicated that some of the district servers could work during the weekends, without adding extra pressure to the system occupancy. This aspect depended on how they made their risk-benefit balance and took the most rational decision to maximize that benefit, while minimizing the risk of contagion, given the restrictions that could be held at that time.

However, to obtain internal validity, these analyses need to be representative of the level of the entities and must provide information about the number of people that could use the system. In this way, it could be possible to make projections and formulate alternatives for schedules and labor days, according to the impact of the demand generated by public servers on punctual zones of the city, close to their workplaces. Assuming that the collected sample was representative and using the data that belongs to the Departamento Administrativo del Servicio Civil of the number of public servers per entity in Bogota, an expansion factor was generated from the sample of the institution. With the obtained data, the analyses that required orders of magnitude were performed.

The first graph on Fig. 5 represents the percentage of district servers who answered if they used the on board validation bus service, at least, one business day of the week, to transport themselves. A percentage of 39% of them answered that they did use it.

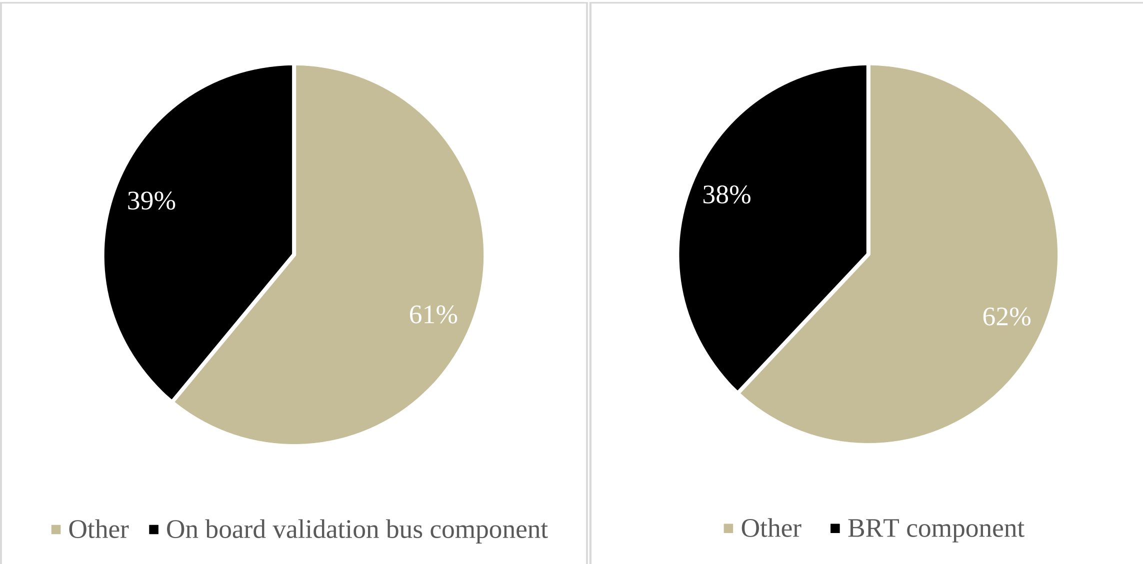

Figure 5: Use of the on board validation bus component and the BRT component

Since the public employees could answer with more than one means of transportation per week, it is not possible to distinguish either if someone used both system components or if they had a main mode of transportation. This means that the data of both components should be analyzed separately. The second graph on Fig. 5 represents the percentage of district servers that answered if they used the BRT, at least, one business day of the weekend, to transport themselves. A 38% of them answered they did use it.

These preliminary data indicated that the expanded sample of public employees of Bogotá D.C. could be subjects of interest for TRANSMILENIO S.A. Initially, these possible trips were used to identify the zones with more density of district employees who made trips in the transport system. This is the most relevant geographic information used to build the maps shown below.

Fig. 6 shows the spatial distribution, and the magnitude of the trip attraction zones. They are in the same spots where there is a big concentration of public employees, or public hospitals.

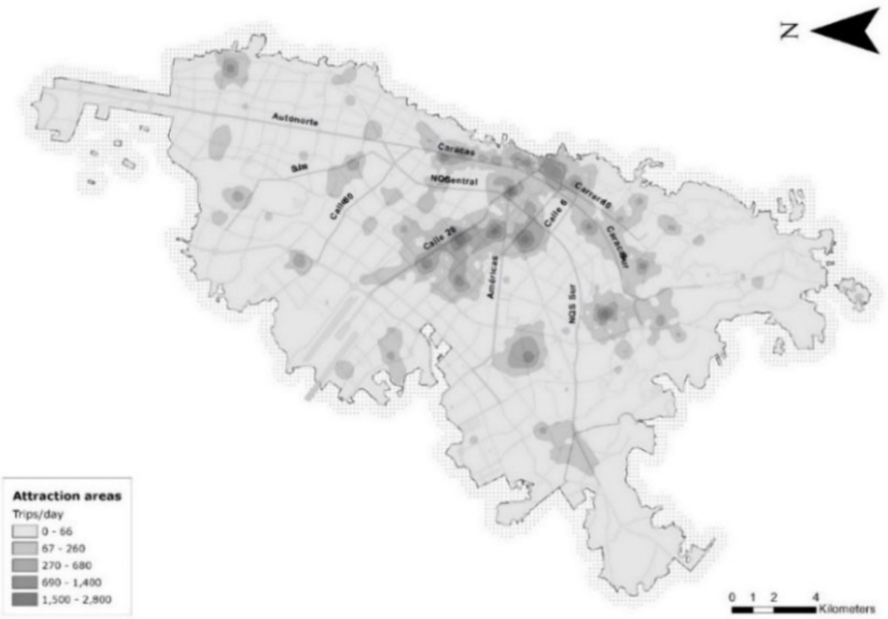

Figure 6: Geographic distribution of public officers

Afterward, the team assigned the expanded observations of the survey to the nearest bus stop, for the Bus Rapid Transit (BRT), or bus stops for on board validation bus service, of the surrounding area. If there were two or more nearby bus stops or stations, it was supposed that their demand was distributed in the same way as the demand of a normal day, punctually, March 11th/2020. For example, A and B are two stations, and on March 11th/2020 the demand of A+B was of 100 passengers. A total of 60 of them went to A, while 40 of them went to B. This means that, for entity E, which is in between A and B, the team assigned 60% of the demand entity E generated to A, and 40% to B. Fig. 7 illustrates this process with the BRT.

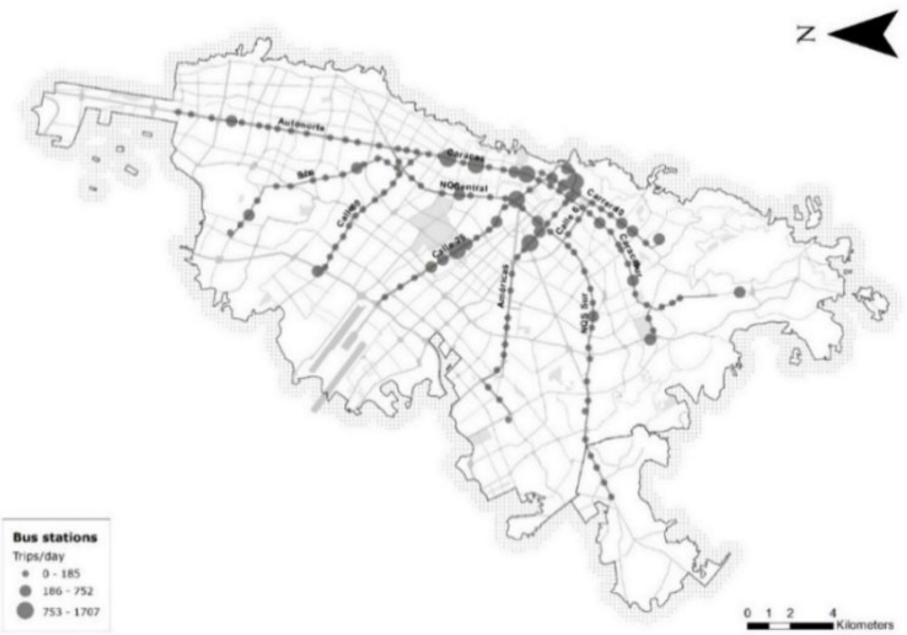

Figure 7: Geographic distribution of public officers. Trunk component.

The stations that would probably receive more demand from public servers were Museo del Oro, Calle 34, CAD, Concejo de Bogotá, Salitre-El Greco, and El Tiempo-Maloka. The process was repeated with the bus stops of the on board validation bus service, and the results are shown on Fig. 8.

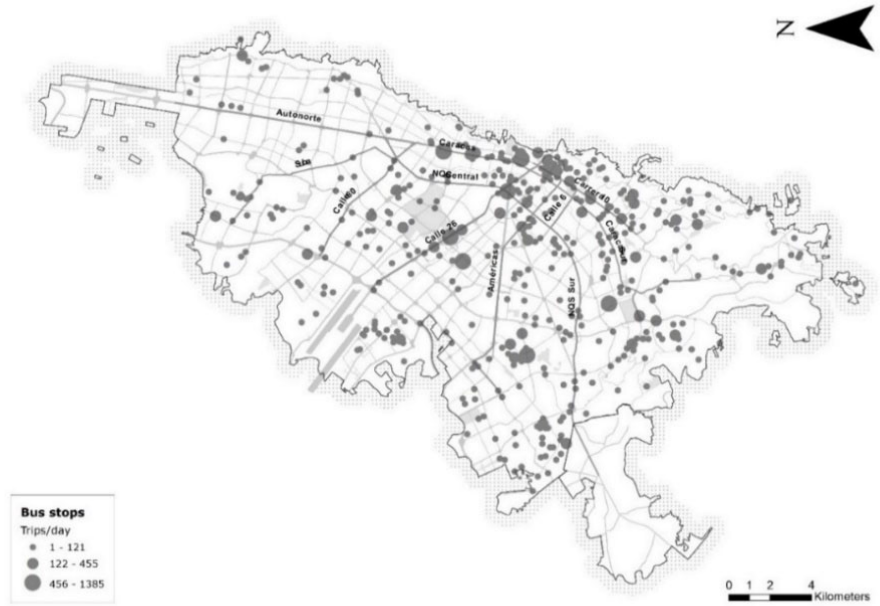

Figure 8: Geographic distribution of public officers. Zonal component

However, the analysis of the on board validation bus service was not considered, because it was close to surpass the current threshold set by the local government, that is, the 35% of the occupancy. For the BRT, the team made a projection of the maximum additional demand that the public employees could represent, given that 38% of the public servers, in average, would rather choose to use it. The value obtained was added to the demand profile observed recently, for visualizing at what times of the day the demand could get over the 35% limit. Fig. 9 represents the results obtained for the CAD station.

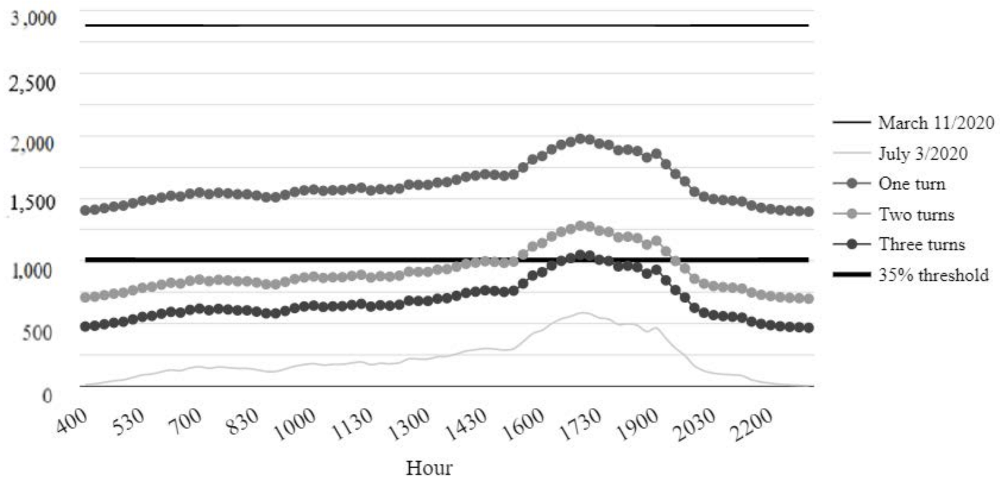

Figure 9: Scenarios for the CAD Station

The uppermost or first horizontal line represents the maximum number of ticket validations observed during an hour on March 11th /2020, day in which the system reached its highest demand on the year. The second line represents its 35%, which was the threshold in July. The light gray line shows the volume of ticket validations observed on July 3rd, which was the day when the maximum demand was observed after the first confinement. The first dotted line represents the biggest extra demand that the station could receive during an hour if all public employees in Bogotá D.C, registered in the Departamento Administrativo del Servicio Civil, went out at the same time. The second and third dotted lines expose how much variation on the hourly demand could be observed if these people went out of their jobs in two or three different, but equal in the number of employees, turns, etc.

The second profile can be interpreted as public employees who worked close to the CAD station and divided into three equal groups at the end of their working day. In this case, the station could surpass the 35% threshold at, about, 17:00. Consequently, TRANSMILENIO S.A. recommended that the institutions located near CAD returned to in person activities in two or three turns, but avoiding the station rush hours (15:30 to 19:30 for two turns, or 16:30 to 17:30 for three turns). This process was repeated with the other stations selected.

The analysis for the universities was made in a similar way. First, the team took data from the Encuesta de Movilidad 2019, which is a survey made by the mobility authority (Secretaría Distrital del Movilidad-SDM) and contains information about the purpose of the trips and the zones that attract them, among other aspects. Two simulation scenarios were formulated. In the first of them, the total trips with going to study as main purpose were considered to add them to the observed hourly demand profile on July 3rd/2021. The objective was to predict the best and the worst hours of the day for planning massive trips, according to the decisions of the universities, which would probably aim to maintain a low occupancy of their campus, with the rationale mentioned in the literature review. This occupation was supposed to be of about 50%, 30%, or even 10% of the normal occupancy. That extra demand was added to the observed profile, thus representing again a threshold of the 35% of the demand observed on the maximum demand hour of March 11th/2020. Fig. 10 represents the main scenarios.

The line marked with Univ_50 represents the scenario in which the universities restrict their occupancy to the 50% of their campus' capacity, supposing that all students who assist go out at the same time of the day. The reader can observe that, during rush hours, the demand ff the whole system could surpass the 35% occupancy limit, when adding linearly the extra demand to the observed demand profile of July 3rd. The other lines show that, if the campus capacities were lowered, the impact on the whole system would be small enough for it to respect the imposed threshold. But the question about what could happen to the stations located close to the campuses remained.

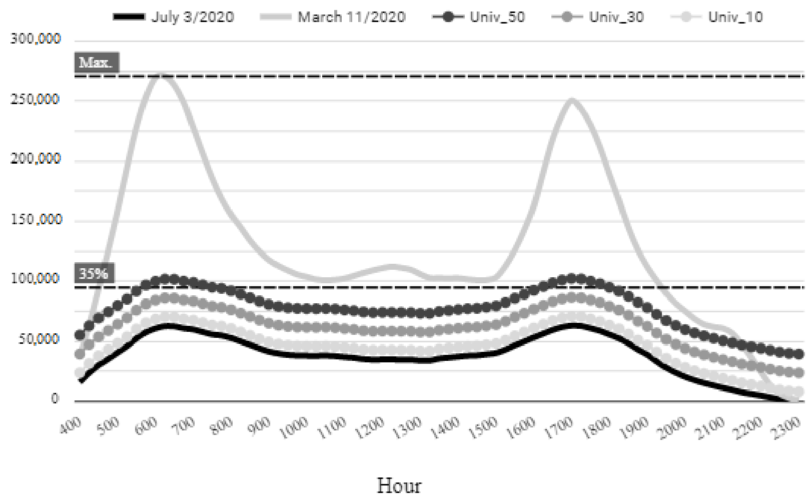

Figure 10: Potential extra demand due to the return to presential activities universities

The second scenario tried to answer it. The database provided by the SDM had also information disaggregated by Zona de Análisis de Transporte (ZAT), which are geographic demarcations of the territory that contain trips of people with similar conditions. The ZAT located downtown, in the historic center, were eligible for the analysis, because that zone concentrates most of the private universities. For each one of them, the team calculated the percentage of trips per purpose, and chose those ZAT where the trips that had "education" as their purpose were predominant. Then, we took the sum of the expansion factor of the observations that had education as their purpose and assigned them to three stations located in the area. (Museo del Oro, Las Aguas and Universidades), with the same three occupancy restrictions. Fig. 11 shows the result, with the same 35% threshold.

It can be observed that, although the scenario with the 30% of the normal occupancy of the campus do not exceed the threshold imposed to the system, the limit is surpassed in the stations that attend the ZATs analyzed. So, as in the case of the public employees, the recommendations had to seek to change people's behavior in a sectorized way

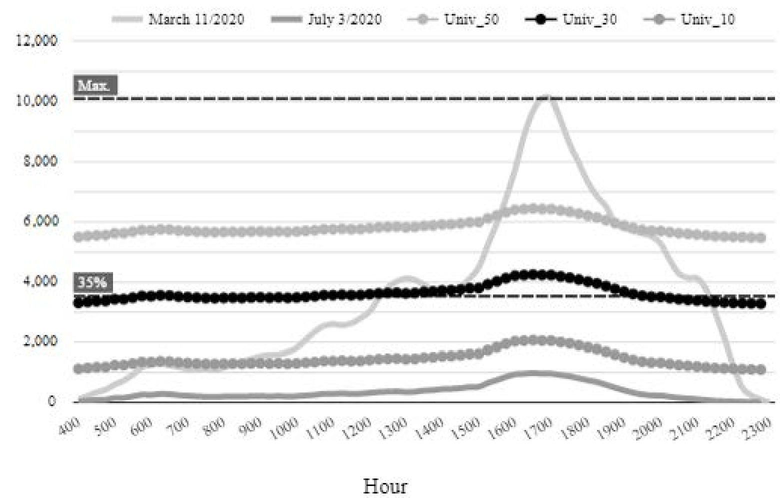

Figure 11: Change in the demand if universities return to presential activities

5. RESPONSE OF THE DEMAND

This chapter has three sections, the first is about the context in which this study identifies the variation of demand, the second is about vulnerability to COVID-19 for the transport system and finally, the third is the main section in this paper about demand graphical analysis.

5.1 Context

The transport demand was heavily affected by the collective and administrative response to the COVID-19 pandemic. Fig. 12 illustrates the daily behavior of the demand from March 1st/20 through March 26th/2021.

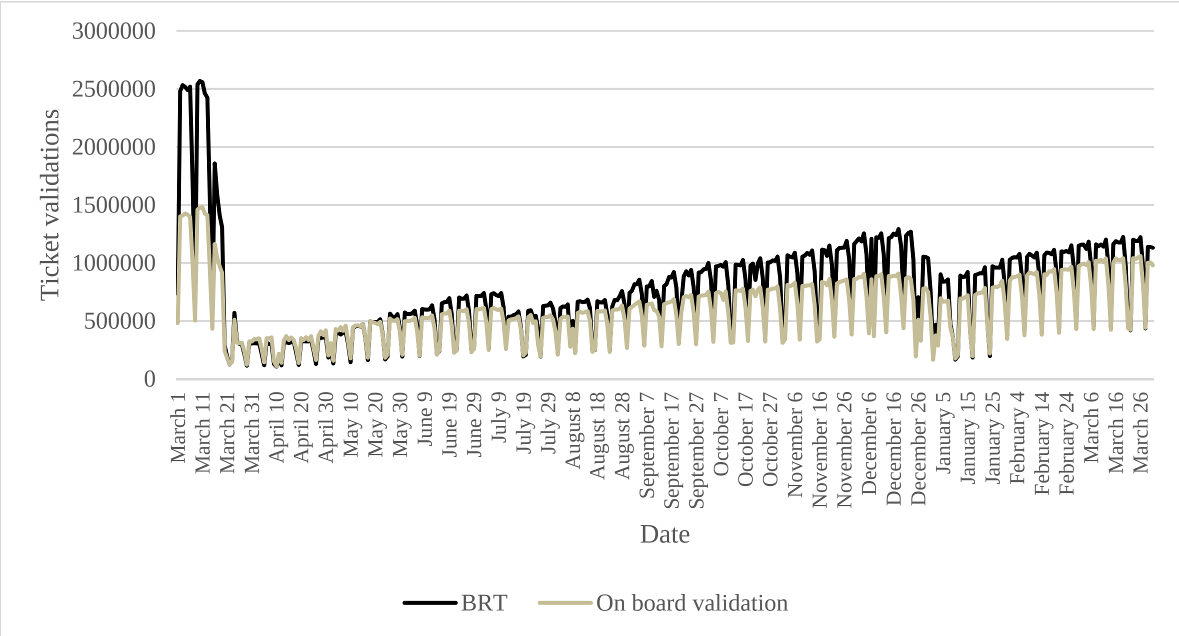

Figure 12: Comparison of the demand of the BRT and on board validation bus service.

It is possible to observe a reduction of the demand since March 12th/2020 y until March 19th/2020, which reflect a modification in the behavior due to the announces of the pandemic. On March 6th/2020, the first case of COVID-19 was diagnosed in Bogotá D.C. During those days, the demand maintained stable, and reached its annual peak on March 11th/2020. But, by March 12th there were already 5 cases diagnosed and a yellow alert was emitted. In Bogotá, people started to diminish the use of public transport. But the tendency went steeper when, on March 16th, an orange alert was emitted, and some temporary bike lanes were made by the city administration. We assume that, during those days, the reduction of the demand was caused more by the announces made by the authorities, rather than by impositions. It was rational for Bogota´s habitants to avoid the crowded places and the contact with other human beings, so they started to make choices to protect themselves. The steep decline of the demand was followed by the enforcement of a “simulation of isolation”, which was meant to prepare the citizenship for a prospective confinement There is a small peak of demand on March 24th, because it was the last normal workday of the year. The national government had announced a “national quarantine” since March 25th.

The demand dropped to previously unsuspected levels but started recovering even before the government started to permit the opening of some economic activities (April 27th), but then is when demand started increasing progressively. This tendency was maintained until July 13th, when the peak first wave of the pandemic was taking place. The policy adopted by the city administration was to do localized confinements in some localities, in a way in which part of the city could maintain the economic activities, while the other was in a strict confinement. The demand dropped initially but recovered in a small proportion during the next day. On August 28th, this policy ended, and, on September 1st, it started another one called “Nueva realidad” (New Reality), which limited de working days per economic sector, and assigned entrance and exit hours for each one. The regulations were modified slightly during the next months, until almost the whole scheme was derogated by November. The demand increased in a steeper manner than the one observed previously, and kept doing it until December 18th, when the Christmas celebrations had started. That is a normal seasonal change observed in year by TRANSMILENIO S.A. Then, from January 5th to January 28th, there was another cycle of localized confinements, but the demand grew during all the time, until March, when the increasing tendency started to stabilize.

5.2 Vulnerability to COVID-19 and the transport system

The entity responsible for the planning, collection, processing, analysis and dissemination of official statistics of Colombia, Departamento Administrativo Nacional de Estadística” ((DANE), 2020), carried out an analysis in which an index of vulnerability to COVID-19 considering demographic characteristics such as age and population density, as well as their previous health conditions. Fig. 13 illustrates this indicator.

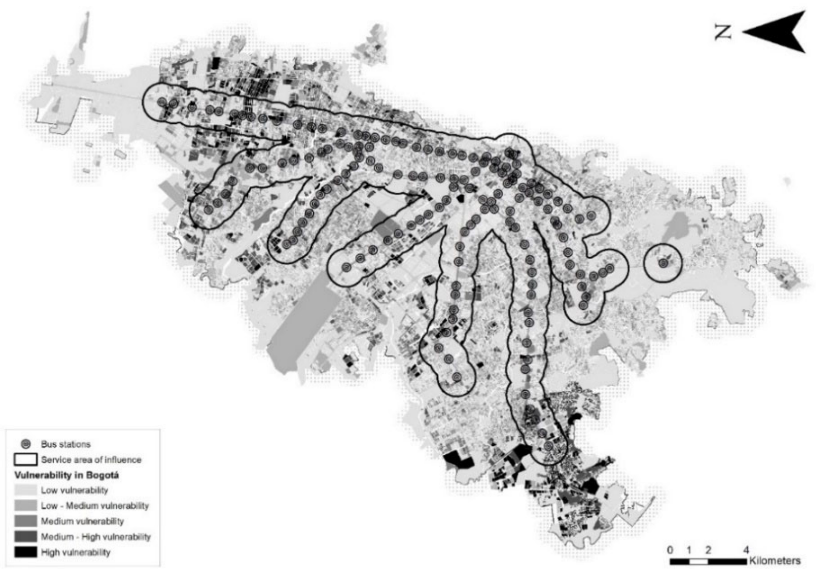

Figure 13: Vulnerability to COVID 19. Source: Own elaboration based on data from ((DANE), 2020)

Based on the previous study, it was possible to know the risk that the main users of the BRT have. The analysis using ArcGIS included the population that is 1km away or the so-called last mile and consisted of identifying the level of vulnerability our users are in the highest proportion. As shown in the following table, the highest proportion of vulnerability is found in the range of low and medium-low vulnerability with 41% and 36% respectively.

Vulnerability category	Percentage
Low vulnerability	41%
Medium - Low vulnerability	36%
Medium vulnerability	15%
Medium - High vulnerability	5%
High vulnerability	2%

Table 3: Vulnerability proportion

Vulnerability could be a factor that explains people's behavior related to the interaction with public transport. People would probably use more public transport if their risk perception due to the vulnerability of their home was low, and if they did not coexist with relatives with previous health conditions.

5.3 A brief graphical analysis

We are going to present some descriptive analysis of statistics, that can be explained by the influence of political decisions (which work as restrictions to people's behavior). The first one of them is Fig. 14, a graph that relates the percentage of decrease in the demand of both, BRT and on board validation bus service, with the COVID-19 cases identified, by the date in which the results of the tests were given. The focus of the analysis will be the two waves of cases that can be identified, particularly bnentetween July 11th/2020 to August 28th/2020 and from December 14th/2020 and January 31st/2021, and the time after they took place.

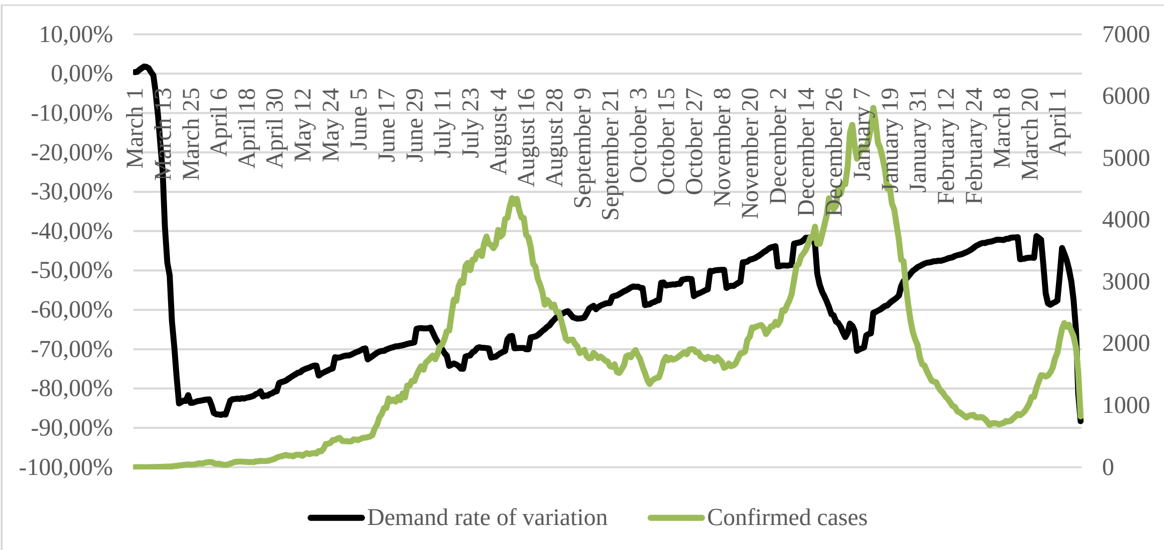

Figure 14: Change in the demand and cases by diagnose date

On the first interval, it is observed that, as the cases start to rise, the administration takes restrictive measures to prevent the effective contacts between people. This reflects in the transport system as a strong decline on the daily demand. Then, the demand of the system starts growing slowly, while cases continue increasing. After that, the ticket validations keep growing even when the diagnosed cases start dropping. Once the wave passed, the demand of the system continued to grow in a quicker way, but the number of confirmed cases kept stable during most of the "valley" observed.

On the second interval, the pattern is similar. The growth of cases can be observed since November 21st, day in which the anniversary of the national strike was commemorated. This was followed by a decrease on the demand of the system since December 18th, not due to the policies chose by the administration anymore, but because of the Christmas celebrations. As the demand of the system decreased, reaching its lowest point on January 5th (which was the first day of the second cycle of localized confinements), the confirmed cases grew onto the peak of the second wave of the pandemic. When the cases started to decline, the demand was already growing. This can be evidence of the uncorrelatedness of COVID-19 cases with the use of public transport.

A counterargument can be that the effect of the confinements or the dropping of the demand can be lagged. One way in which this can be observed is by taking the cases by the date on which the first symptoms appeared. However, this data is incomplete in the Health Department (Secretaría Distrital de Salud - SDS) dashboard's downloadable data because there are 203.211 (of 713.559, by April 9th/2021) observations without any date assigned. The tendencies described above do not change, as shown in Fig. 15 .

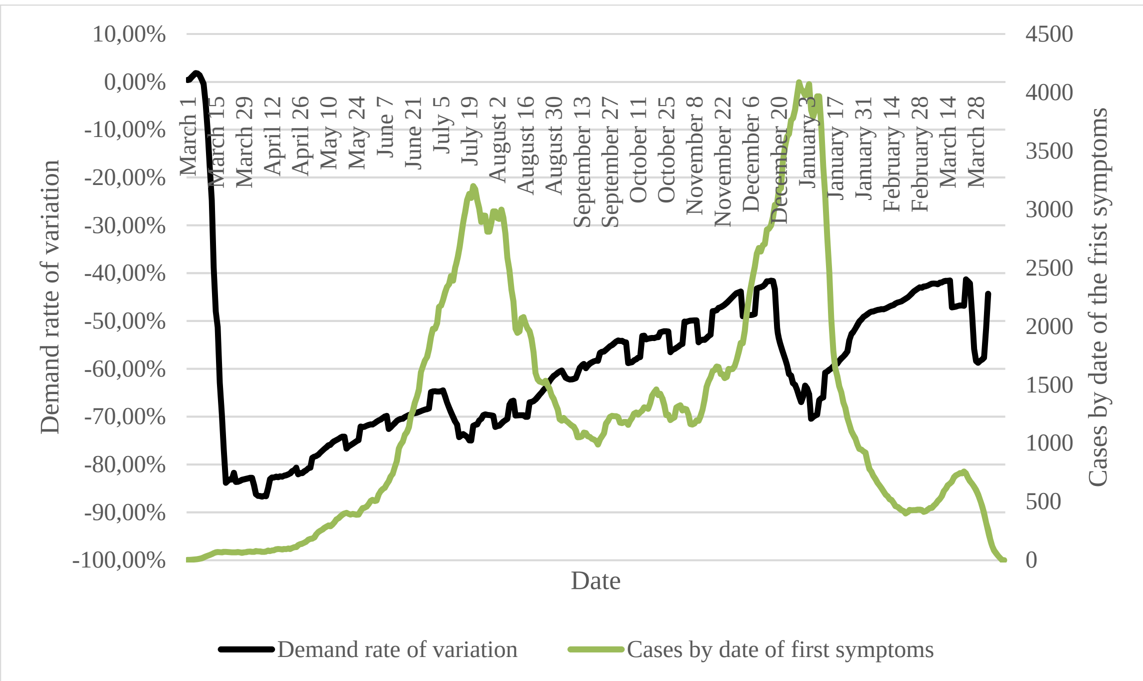

Figure 15: Change in the demand and daily confirmed case by date of symptoms

Furthermore, the decisions taken during the peak of the first contagion wave seem to coincide with the stabilization and start of decline of the cases, while, during the second wave, the new symptoms observed rose just as the demand of the public transport declined. An objection for the second analysis is that, on average, the symptoms start to appear some days after the contagion occurs. That can be answered with another indicator generated by the SDS: the effective reproduction number, which is calculated subtracting five days to the date in which the symptoms were initiated, with a time window that may vary through time. We use the latest boundary of the window. Fig. 16 illustrates this indicator:

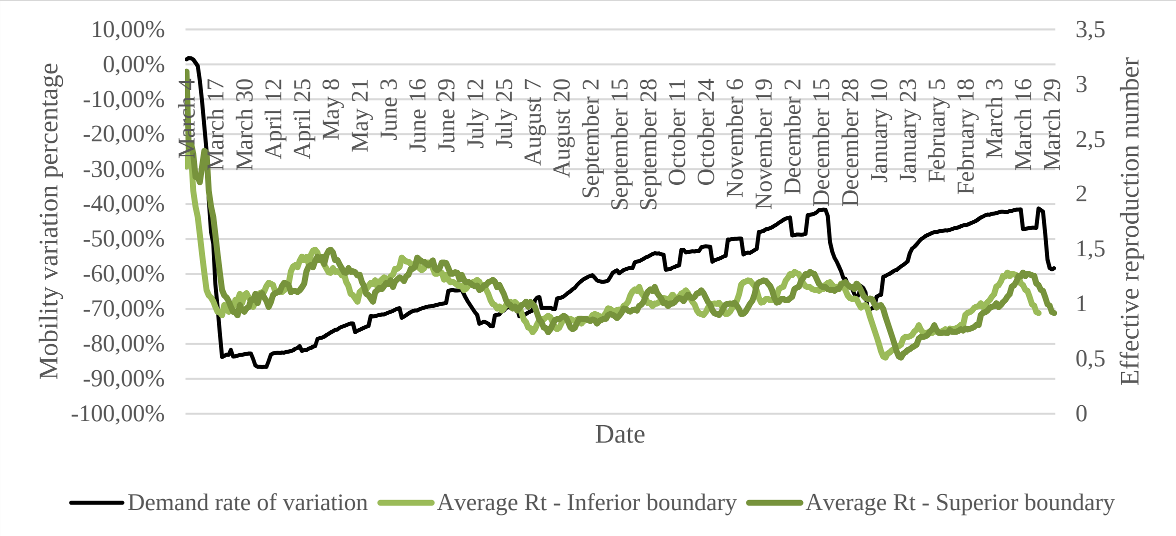

Figure 16: Daily effective reproduction number and demand rate of variation

The patterns do not reflect the behavior of each other. For example, after December 15th the demand drops two weeks earlier than the effective reproduction number or even three weeks superior boundary is used. The last figures indicate that the big changes in the relevant variables of the pandemic depend on factors that are different from the decisions taken with respect of the transport system. So, there is not a direct relationship between the evaluated variables and the contagion could be explained by other social interaction patterns, as well as by the natural behavior of the virus.

6. CONCLUSIONS AND POLICY LESSONS

The use of geographic information tools helps public transport systems to manage the demand variations, caused by the response to the state of the COVID - 19 pandemic, to make informed and focused decisions to prevent and mitigate the contagion on each of the areas of the city.

Analyzing the data of one year of the pandemic, during the time lapses when there was a progressive increase in demand for the TRANSMILENIO system, this slow growth does not appear to have a direct relationship with the number of infections or the reproduction rate of COVID - 19.

It was possible to show that the policies of the decrees implemented in Bogotá are reflected in the changes in the demand of public transport which shows that most of the population effectively complies with social isolation and biosafety measures.

For the next research, this study suggests analyzing the possible causal or non-causal link between the contagion and the public transport system.

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IMPROVING BRT ROUTE DESIGN THROUGH CODE: THE CASE OF BOGOTÁ'S BRT SYSTEM, TRANSMILENIO

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ABSTRACT

This study presents the methodology used by TRANSMILENIO S.A. –the company in charge of managing the BRT lines in Bogotá, Colombia– to renew its operational design. TRANSMILENIO S.A. is increasing its bus fleet by acquiring higher capacity bi-articulated buses. This process demanded a redefinition of the frequencies, stops, and type of bus for all routes in the system. Therefore, a line scheme was selected based on the number of trips between corridors. A non-linear optimization model was then used to establish an initial route design that could satisfy passenger demand in the morning rush hour.

Five algorithms were implemented to adjust the initial route design to the actual restrictions, namely, fleet and bus capacity at stops. The algorithms modified the type of bus employed, the defined stops of routes, and eliminated low demand routes. Different alternatives were tested for the execution order of algorithms. The alternative to implement was selected based on compliance of the defined restrictions. Algorithms were iteratively run. Between iterations, a trip assignment model was used to adjust route frequencies based on demand.

The execution order of algorithms, its impact on the level of service indicators, and compliance of restrictions are part of this study's discussion. Particular relevance and effects of each algorithm are also analyzed. Both methodology and results might be tested, adapted, and improved in further studies by other BRT systems as a reference or input for their own route design process.

1. INTRODUCTION

Bus Rapid Transit systems have proven to be a sustainable solution for cities' mobility and economic development. This means of transport based on segregated lanes for bus circulation reduces the use of private cars, improves air quality, mitigates traffic accident rates, and generates employability (WRI, 2013). For its part, the city of Bogotá is responsible for 30% of the Colombian PIB and is one of the principal population center in the country (Hernández, 2020). TransMilenio is the name of Bogotá´s BRT system, one of the largest BRT systems in the world (WRI Brasil Ross, 2021). This system is managed by TRANSMILENIO S.A. a company owned by several public authorities of the city and is in charge of planning and managing the public transport system in Bogotá (which also includes regular bus routes and cable cars). Furthermore, this company does not own or operate buses but assigns routes to private transport operators.

Transport operators are privately-owned companies that own the buses and manage the hiring of drivers, and the maintenance, repair, washing, and operation of the buses. Transport operators are typically selected through a bidding process (including price per traveled kilometer and other factors) and awarded term-limited concessions to operate. City administration is currently making considerations to create a public-owned Transport operator.

Within the bidding process, a collection operator is also selected whose duty lies in the ticket purchase and the required hiring and maintenance for box-office operations. Tickets are sold in the form of electronic cards which are purchased by users in box-offices and “loaded” with a balance in currency.

The ticket value is then subtracted from the balance at the entrance of BRT stations or at non-BRT bus doors. The collection operator is also in charge of providing and maintaining the required electronic equipment in buses and stations, and the databases of user’s balance.

On the other hand, the city administration oversees the construction and maintenance of the infrastructure. Some infrastructure (e.g., parking lots, maintenance, washing, and facilities) is given to the operators to use and maintain during concessions. The city administration also provides capital to subsidize the system reducing the fare paid by users. Some financial institutions are also involved in saving resources and distributing them among the involved parties.

1.1 Operational Design

Bogotá city requires basic infrastructure and resilience services able to face the emerging challenge of growth. Hence, TRANSMILENIO S.A. performed two priority public bids (TMSA, 2018) which incremented the number of buses in the system.

The new fleet was divided into 67% bi-articulated and 33% articulated buses. The entity set off the design of a renovated operational design which apart from establishing the operable conditions for the new fleet, must guarantee general attention of Bogotá's BRT demanded trips. Likewise, BRT systems, unlike rail schemes, have a set of operational parameters that must be defined for service coverage. Particularly, BRT system has higher flexibility since its infrastructure can be adapted to the existing needs of a given space (CEPAL, 2012) and is not tied to rail infrastructure. Therefore, when planning the scheme of routes for this type of system, the followed variables must be considered:

- The number of routes offered per corridor or line.
- The defined path for each route.
- The stops within those routes.
- The frequencies with which of the routes to attend the trip demand.
- The type of bus to be used for each route.

These variables highlight the requirement to generate a process in which all are analyzed in a holistic and coordinated methodology. A methodology that leads to the execution of the process called Operational Design.

2. INITIAL SOLUTION

2.1 Existing methodologies

Planning public transport has been widely analyzed in the literature. In this section, two types of methodologies are presented: the first one related to a regular bus routes design, and general guidelines specifically for a BRT system.

In the first case, the principal process to evaluate a design is based on three main steps according to (Ceder, 2007): Initially, a feasible solution is proposed based on the different OD pairs with higher demand.This will result in a first approximation of the model.
Then, these groups of routes are evaluated based on the attended demand. Subsequently, an evaluation of frequencies and network performance is executed according to selected indicators such as fleet size, rules for insertion or elimination of nodes in existing routes, among others. Finally, it is obtained an improved solution after removing, dividing, or interchanging the routes.

The second one comprises a BRT Planning guide (ITDP, 2017) which shows the guidelines for executing the service planning. In the document, mainly in chapter 6, the different indicators and considerations for basic service planning are presented. Some of these are saturation, speed, travel time, service frequency and headways, direct and express services. However, these guidelines are presented from a general strategic perspective. In the present document, it is presented a combination of both methodologies.

2.2 Lines selection

One of the main objectives with the accomplishment of the new operational design was to migrate from one current system divided into trunk lines to one with lines, similar to urban rail transport systems like metros. Since Bogotá's BRT system currently has eleven trunk lines, analyzing all the possible lines becomes an unfeasible task because of communication to users, design complexity, and efficiency (not all the lines would have a significant number of travels).

To generate an initial approximation of this design, the first duty was to analyse the trip demand between all the origin-destination pairs in the possible lines to retain the most important ones, as mentioned by Ceder (2007). The trip demand used was the morning peak hour (6:30 to 7:30) estimated in a study for the integral structuring of the trunk component operation of TransMilenio System (Temporary Union SDG-PHR-KPMG, 2018).

Furthermore, in this contract, the lines with a demand of 6.000 trips per day and up to 9.000 trips were kept as "main lines", a step that was followed in this evaluation. Nevertheless, this process left some original trunk lines outside the proposed principal lines. To circumvent this issue, the lines with higher demand among the ones including the left-behind trunk lines were added to the "principal lines" set. At the end of the process, 22 lines were considered as main lines.

2.3 Optimization model and preliminary design

For each of the major lines selected a simple optimization model was developed in Excel to create a set of "seed routes" implemented within the following steps.

All the models constrained the maximum number of resulting routes to five (except for two lines for which the demand was too high and hence the number of routes was greater), all with a similar frequency (between nine and twenty bus/hour) while maximizing the number of biarticulated buses and avoiding leaving any station with no service. To define the objective function, all the origin-destination pairs in the line were ranked following the number of trips, and the pairs with more trips than the percentile 95, were marked. The objective function was defined as a maximization of the number of principal O-D pairs covered with no need for transfers.

3. ADITIONAL RESTRICTIONS

The preliminary design, which resulted from the initial optimization model required to be adjusted to the existing restrictions to be implemented successfully. These restrictions are described below.

3.1 Available buses

The resulting operational design should require no more buses than the available in the system. This parameter is given by the total amount of buses in the system minus a percentage of buses which is receiving maintenance or are kept in reserve to attend emergencies during operations. In TRANSMILENIO S.A. 2% of the total fleet is reserved for these purposes. This led to 736 articulated and 1263 bi-articulated buses available to operate.

3.2 Bus type restrictions at stations

After the acquisition of the new bi-articulated buses, this type of vehicle will constitute the majority in Bogotá's BRT system. However, a bi-articulated bus commands larger stations, stop points, and doors. However, not every station in the system is adequate to operate with this vehicle type. The resulting design must ensure that there are no bi-articulated bus routes designed to stop in stations without the adequations required.

3.3 Bus station capacity

TransMilenio stations have one or more gates (stop points) for buses to stop in each direction. The number of buses that can stop at the same gate in a period is limited. When the number of buses increases above this limit, queues might form with a higher frequency, which can cause delays. Using traffic simulations and field observations TRANSMILENIO S.A. had previously defined capacity values for each station (buses per hour per direction). This was the greater restriction, and after consulting with the company team responsible for this data, a station was considered to comply if the number of buses was within 110% of the defined capacity value, otherwise, the station is considered to be saturated.

3.4 Headway restrictions

Headway between buses on the same route has a direct impact on user waiting time, and therefore, on the perceived level of service. To avoid long waiting times, TRANSMILENIO S.A. has established a seven (7) minute limit for the maximum headway allowed. This limit must be observed even when route demand could be served with a higher headway, therefore, complying with this condition might require more buses. A limit of two (2) minutes for the minimum headway allowed has also been established to avoid bus bunching.

4. DEVELOPED ALGORITHMS

To adjust the preliminary operational design to the current restrictions, four algorithms were developed that iteratively modified the initial scenario. A transit assignment model was used for the evaluation of the different supply scenarios. The model used was previously developed for TRANSMILENIO S.A. as part of the consultancy by Temporary Union SDG-PHR-KPMG (2018) and uses EMME transport planning software. Algorithms were implemented using python scripts. For more information on transit assignment models refer to Ortúzar and Willumsen (2011), chapter 10.6.

4.1 Relevant OD pairs inclusion

Although the initial optimization model sought to maximize the number of DO pairs that were directly connected, the solution obtained did not directly connect (that is, by the same route and without the need for transfers) all the pairs. In particular, some of the OD pairs with high trip numbers were not directly connected. Consequently, the first algorithm seeks for the OD pairs with the highest number of trips in the origin-destination matrix and connects them. OD pairs with several trips within a percentile that is received as a parameter are searched for.

Finally, once the largest OD pairs have been found, those that are not directly connected, a route is searched that passes through the corresponding origin and destination stations, and the mentioned route is used to connect the OD pair. In case of finding several routes, the route with the lowest volume of passengers at the station of origin is used. If no routes are found, the OD pair remains without direct connection. This algorithm is executed once (not iterative).

4.2 Capacity adjustment in stations

This algorithm was developed to reduce the formation of queues in the stations of the system and adjust to the measured capacity of the stations. The algorithm takes the current design, and searches for stations that are saturated (as defined in section 3.3) in any of the two directions, then eliminates the stop of the route with the least number of total movements (ascents and descents in both directions). Therefore, the selected route will no longer stop at this station.

After eliminating a route stop for each of the saturated stations, an assignment and headway adjustment (as described in 4.5) is carried out. The stop elimination process is repeated, continuing iteratively. The algorithm ends when the percentage of saturated stations falls below a defined threshold or is 0 (when there are no saturated stations), or when the maximum iteration defined number is reached.

4.3 Change to biarticulated type

Followed by the execution of any of the algorithms, it might result that the obtained operational design does not comply with the available fleet restriction. A particular case is that the design required more articulated buses than those available, and less bi-articulated than those available.

It is also possible that highly demanded routes that are candidates for using bi-articulated buses (for their higher passenger capacity) could not be initially designed with this vehicle type. This is caused now that the restriction of infrastructure. Hence, after executing the algorithm for capacity adjustment in stations, those routes were debugged to suspend stop in stations with biarticulated restrictions.

With those cases in mind, an algorithm was designed to seek those routes that are being served by articulated buses and stops only in stations equipped for bi-articulated buses. The algorithm modifies the type of bus of all the routes found from articulated to bi-articulated and performs a frequency adjustment and assignment process. This is not an iterative process, and all the routes found are modified at once.

4.4 Fleet adjustment

For the other cases in which the available fleet restriction is breached (even after executing the algorithm for changing to bi-articulated bus type), two algorithms were developed. These algorithms are designed to be executed consecutively.

4.5 Change to articulated type

The first algorithm seeks to comply with the restriction of bi-articulated buses and is executed when the current operational design requires more bi-articulated buses than those available. In each iteration, it looks for the route of bi-articulated buses with the lowest demand (fewer total boardings) and modifies it to articulated bus type. After each iteration, an assignment and headway adjustment (as described in 4.5) is carried out. The algorithm continues to iterate until the design meets the available fleet of bi-articulated buses.

4.6 Routes Elimination

After completing the first algorithm, and if the available articulated bus fleet restriction unfulfilled, the second algorithm will search for the articulated bus route with the least demand (least number of total boardings) and eliminate it. The algorithm continues to iterate until the design meets the available fleet of articulated buses. After each iteration, an assignment and headway adjustment (as described in 4.5) is carried out.

4.7 Assignment and headway adjustment

As stated above, between the iterations of the algorithms a process or assignment and headway adjustment was executed. This process was implemented to improve transit assignment results and adjust route frequencies to actual demand conditions. It consisted of three steps, as described below:

- The first step was to equal the headway from all routes. This was done in preparation for a transit assignment process, to equalize the perceived waiting time for the user. The subsequent transit assignment was therefore reliant on in-vehicle time and transfers, and less dependent on headway results from previous iterations.
- The second step consisted of a transit assignment using EMME’s optimal strategies (Spiess and Florian 1989) extended transit assignment algorithm, followed by a headway adjustment which was the third step. Headway adjustment consisted of calculating the frequency required for each route to be able to transport the passenger demand at the segment with the higher load; this was done by dividing hourly passenger demand at the highest loaded segment between bus passenger capacity.

> The resulting value was the required route frequency (in buses per hour) from which headway in minutes could be obtained. Capacity values used for articulated and biarticulated types were 160 and 260 passengers, respectively.

A relatively simple methodology for transit assignment was used, as the effects of vehicle capacity, parallel lines, and overlapping routes were not addressed. An alternative for the future improvement of this methodology is the use of more sophisticated assignment models, such as those developed by Verbas and Mahmassani (2016), or Schmöcker and Fonzone (2011).

4.8 Special route protection

In addition to all system routes, it exists a set of routes that stop in all stations along their path. These are known in the city as “easy” routes. There’s typically one of these routes for each main line in the system.

Due to their low speed, these routes often have a lower demand, and therefore relatively high headways. The existence of these routes usually ensures that all stations are interconnected, and helps new or occasional users to easily use the system.

Likewise, to prevent any of the algorithms to erase or modify these routes, a functionality was implemented to “protect routes” by marking them using a dummy variable in the software. Marked routes could be subjected to changes in the type of bus used, and their frequencies were adjusted to demand in every iteration (section 4.5) but were ignored by algorithms that eliminated routes or route stops.

Initially, only “easy” routes were protected. However, as planning process progressed, this functionality proved to be useful and was extended to other routes. The reason is briefly explained in section 7.

5. PERFORMANCE INDICATORS

To evaluate the performance of the developed algorithms, the overall design, and the resulting routes, were based on six indicators previously selected. Indicators were calculated between every iteration. These variables cover different parameters as bus fleet, waiting times in stations, and time in vehicles, among others. A description of each indicator will be shown below.

5.1 Bus fleet

After the renovation of the bus fleet, the quantity of articulated and bi-articulated buses available to operate is limited: 736 and 1263 respectively. These are target values as described in section 3.1.

5.2 In-vehicle time

In the transit assignment process (INRO, 2020), a time in vehicle is generated for each iteration. This is obtained by multiplying the transit times by a perception factor. These values were compared with the actual values corresponding to the base scenario.

5.3 Waiting time

Like in-vehicle time indicator, this indicator is obtained through the transit assignment algorithm by INRO (2020). This corresponds to the weighted average of passengers waiting times. These values were also compared with the actual values corresponding to the base scenario.

5.4 Average boardings

Indicates the average number of boardings passengers have to make to reach their destinations, including transfers. Values close to one indicate a low number of transfers in the system. Similar to the time in vehicle indicator, this variable is obtained by the transit assignment algorithm. These values were also compared with the actual values corresponding to the base scenario.

5.5 Saturated stations

This indicator shows the number of saturated stations (as defined in section 3.3) in relation to the total stations in the system. The indicator is presented as a percentage.

5.6 Generalized cost

This corresponds to the impedance function in the EMME algorithm. The total impedance is the sum of perceived time and cost components (total waiting times, total boarding times/costs, in-vehicle times/costs, auxiliary transit times/costs) where the perceived component is the actual component multiplied by the corresponding perception factor (INRO, 2020).

6. DEVELOPMENT PROCESS AND EXECUTION ORDER

Initially, only Fleet Adjustment (FA) algorithm (section 4.4) and Capacity Adjustment in Stations (CAS) algorithm (section 4.2) were developed. FA was intended to precede CAS, but this intended execution order proved inadequate. As a result, the execution order was inverted and further issues were identified, which lead to the development of the other two algorithms.

Scenarios 351 and 361 were both built using the preliminary design as the starting point (section 2.2). For scenario 351 FA was executed before CAS. When issues with scenario 351 were identified, scenario 361 was created with the execution order inverted. Issues with the first scenario are evident when compared to the second one, as is shown below.

For scenario 351, Change to Articulated Type (CAT) algorithm (section 4.4.1) was performed from iterations 1 to 8, when the bi-articulated fleet restriction was fulfilled. Route elimination (RE) algorithm (section 4.4.2) was subsequently performed until iteration 22, and CAS was then executed until iteration 42. At iteration 42 CAS maximum iteration number was reached without achieving convergence.

For scenario 361, CAS was executed from iterations 1 to 21, when the desired convergence was reached (5% of stations saturated). CAT was performed until iteration 30 when the bi-articulated fleet restriction was fulfilled. RE was then executed until iteration 50 when the maximum iteration number was reached (20 iterations).

Figure 1 shows the required number of bi-articulated buses along algorithm execution. This figure shows that CAT had the desired effect by reducing the number of required bi-articulated buses. However, required buses also vary when CAS is executed.

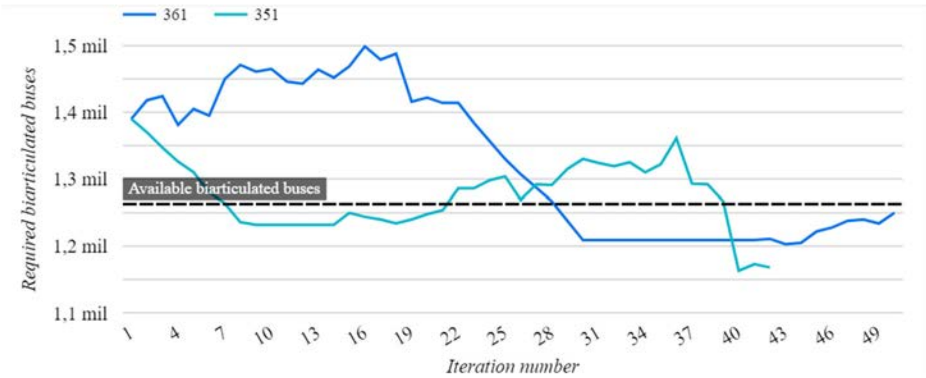

Figure 1: Required number of biarticulated buses throughout algorithm execution, scenarios 361 and 351

Figure 2 shows the required number of articulated buses along algorithm execution. This figure also shows the desired effect of RE algorithm in reducing the number of required articulated buses. It can be observed that required articulated buses also vary when CAS is executed.

Figure 2: Required number of articulated buses throughout algorithm execution, scenarios 361 and 351

By comparing both scenarios it was clear that progress obtained by FA algorithm could easily be undone by CAS. On the other hand, the inverse relation was not true. As shown in figure 3, the Percentage of saturated stations was effectively reduced by CAS and it was not significantly increased when executing FA. It was then decided to execute FA after CAS.

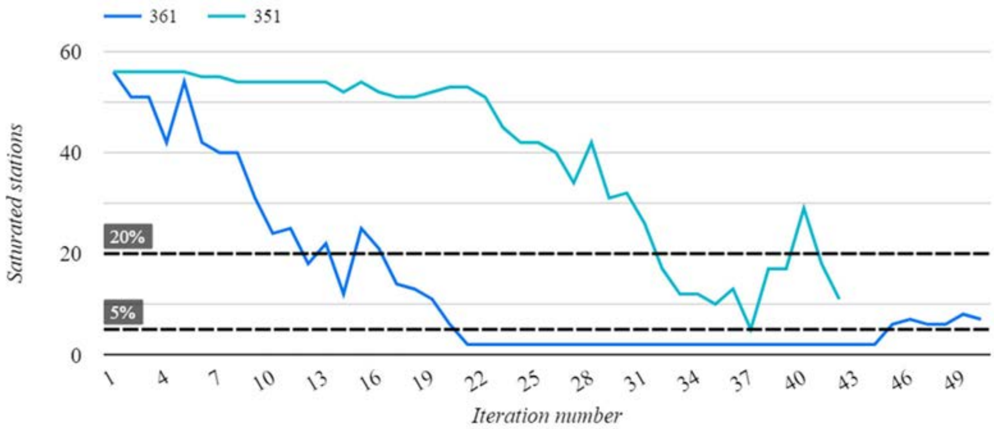

Figure 3: Percentage of saturated stations throughout algorithm execution, scenarios 361 and 351

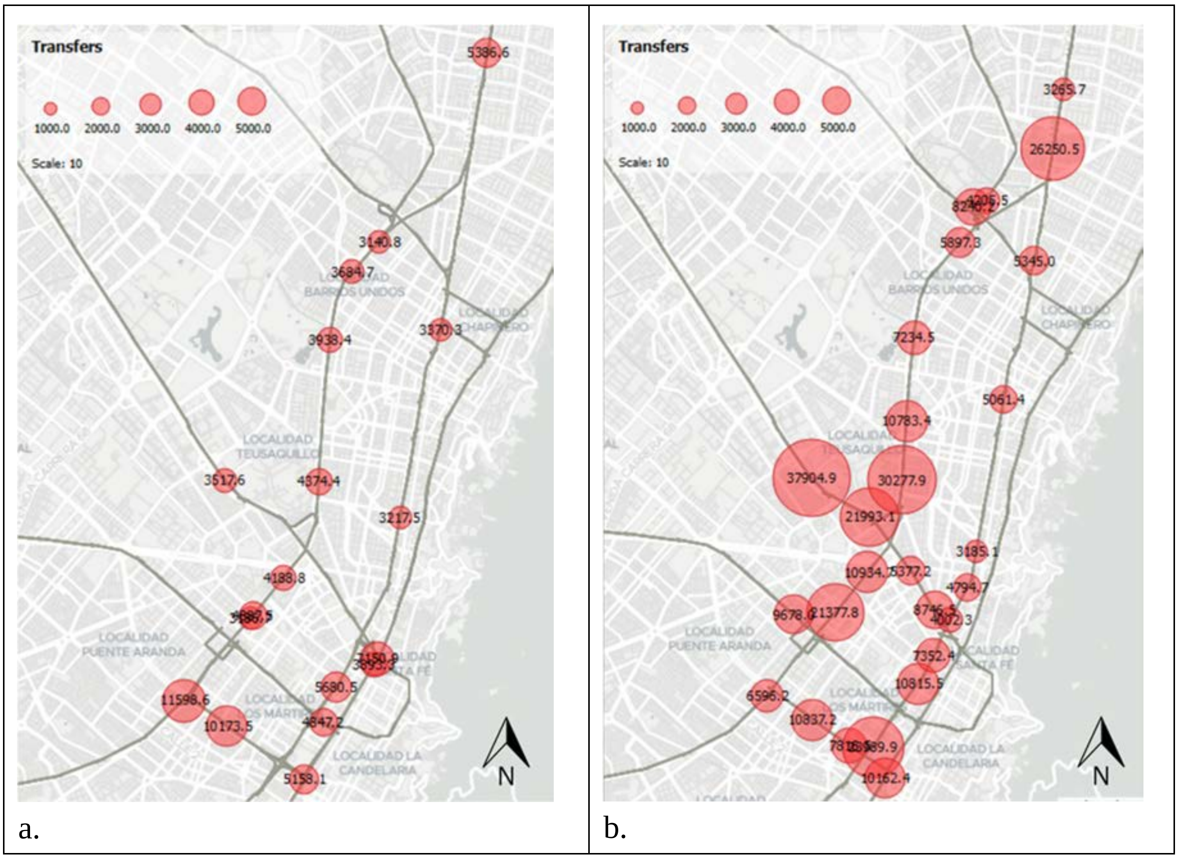

Figure 4: Stations with more than 1000 transfers base scen. (a) and scen. 361 (b)

FA and CAS algorithms were effective at complying with system restrictions. However, since both eliminated routes and routes stops, more transfers were required in the system. Even though for some stations the number of transfers diminished, for others, it augmented dramatically. “Calle 100” station, for example, went from nearly 2.350 transfers to 26.250; more than 11 times the initial value.

To address this problem, Relevant OD Pairs Inclusion (RPI), and Change to Biarticulated Type (CBT) algorithms (sections 4.1 and 4.3) were developed. CBT was executed between CAS and FA and two options were evaluated for the execution of RPI. RPI was run immediately after CAS in scenario 403, and before CAS (at the beginning of the whole process) in scenario 413.

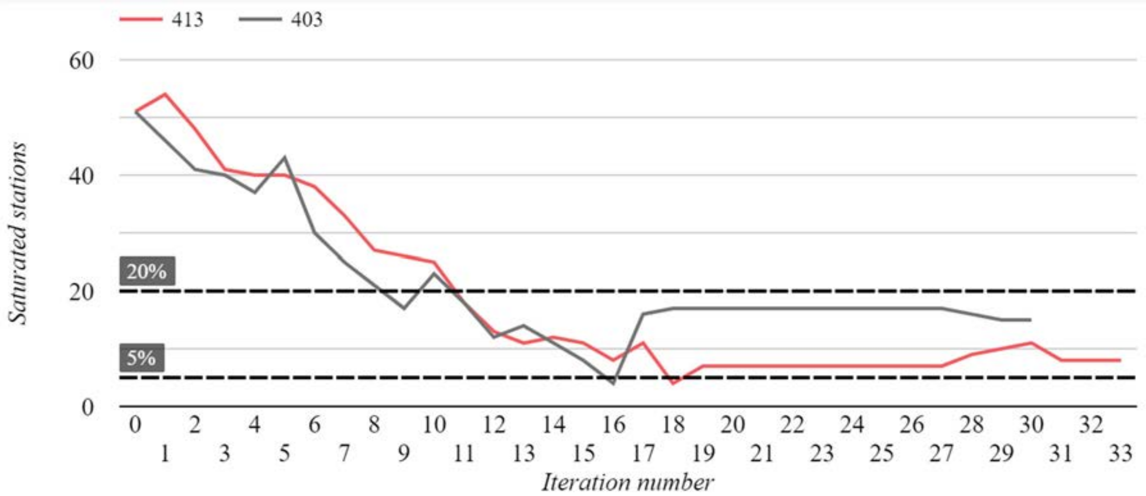

Figure 5: Percentage of saturated stations throughout algorithm execution, scenarios 413 and 403.

Except for the percentage of saturated stations, there were no significant differences in performance indicators between scenarios 403 and 413. Figure 5 shows that some of the progress achieved by CAS was undone by RPI in scenario 403 (Iteration 16 to 17). It was then decided to execute RPI before CAS.

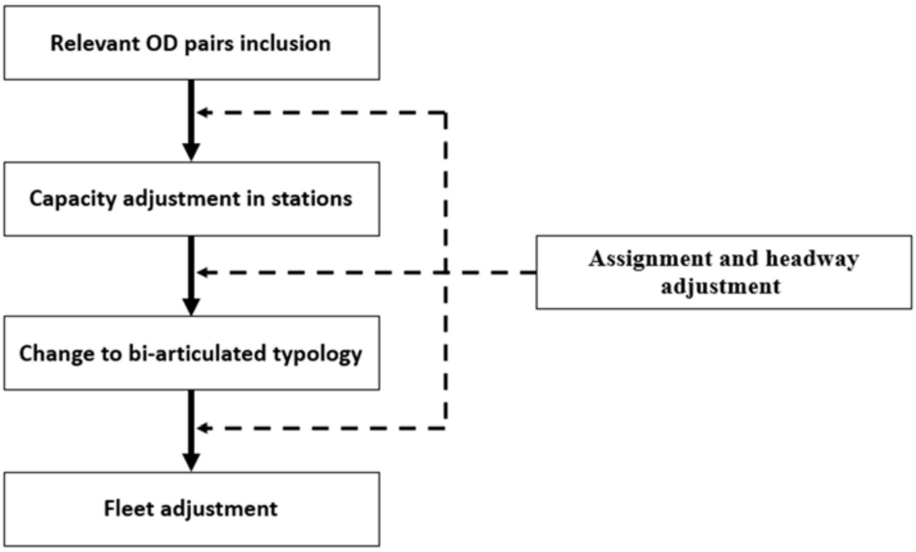

Figure 6: Selected algorithm execution order

Figure 6 shows the selected order of execution for the algorithms. Note that the assignment and headway adjustment (section 4.5) was not only performed between each of the algorithms, but also in every iteration.

6.1 Capacity adjustment in stations algorithm convergence

As stated above, the execution of CAS algorithm was completed when the percentage of saturated stations was 5% or less. This value was selected as a convergence threshold because complete compliance of station capacity restriction (0% saturated stations) could not be achieved though the continued execution of the algorithm.

Furthermore, in the scenarios when CAS was executed beyond reaching 5% of saturated stations, it continued to eliminate route stops increasing the number of transfers therefore deteriorating the overall route design.

7. RESULTS

CAS and FA algorithms were designed to achieve target values in saturated stations and bus fleets. The two are effective in this matter. A negative effect in the use of these algorithms is the increase of transfers at one or more stations, usually caused by the elimination of a route or a route stop that was the only direct alternative for a particular group of users.

To reduce transfers in a particular station, relevant origins and destinations were identified for the users performing such transfers. A stop or route that eliminated the need for transfers was then added to the preliminary design, and the algorithm was again executed. If necessary, some routes were protected from deletion as described in section 4.6.

This process was repeated iteratively for all stations with more than 4000 transfers/hour generating several scenarios until a stable point was reached. Consequently, this section presents the results for scenario 744, which satisfied system restrictions and had reasonable amounts of transfers at most stations.

CAS algorithm ran from iteration 1 to 15, and stopped when the proportion of saturated stations was under 5%. As shown in figure 7, this percentage was relatively stable for the remaining of the process, never exceeding 10%.

After CAS and CBT were completed, CAT algorithm was initiated at iteration 16. Figure 8 shows a drop in the required number of bi-articulated buses during CAT, and figure 9 shows an increase in the required number of articulated buses. CAT ended at iteration 28 when the target value was met.

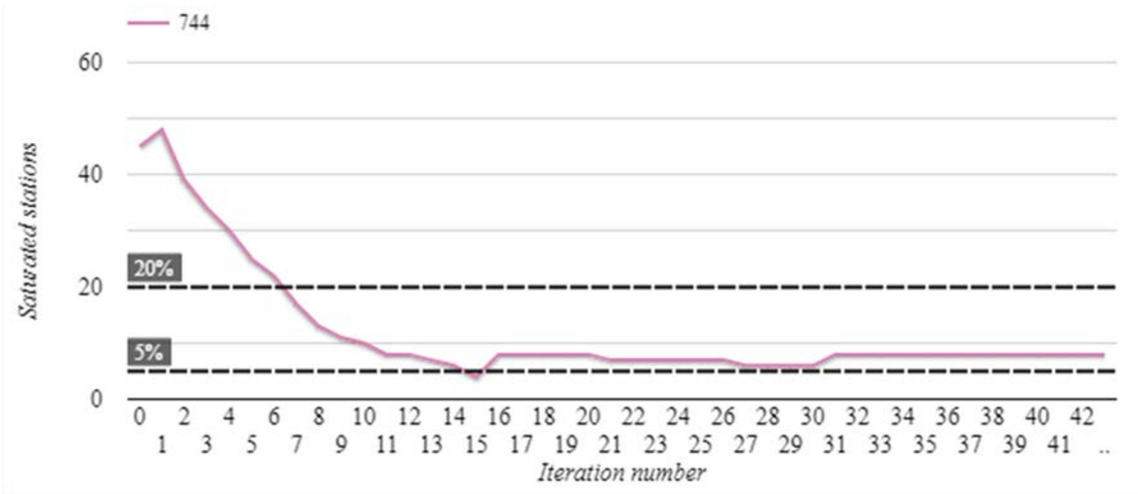

Figure 7: Percentage of saturated stations throughout algorithm execution, scenario 744

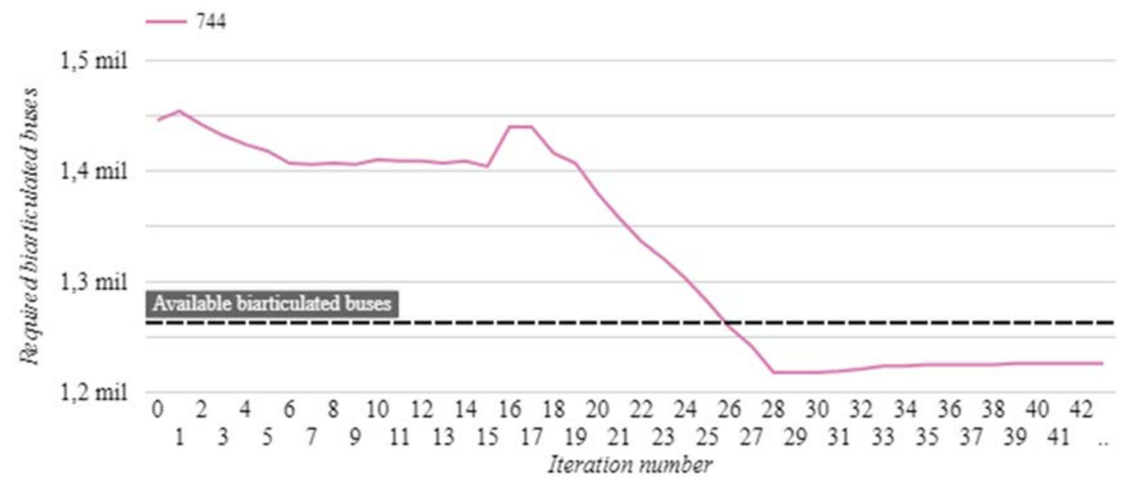

Figure 8: Required number of articulated buses throughout algorithm execution, scenario 744.

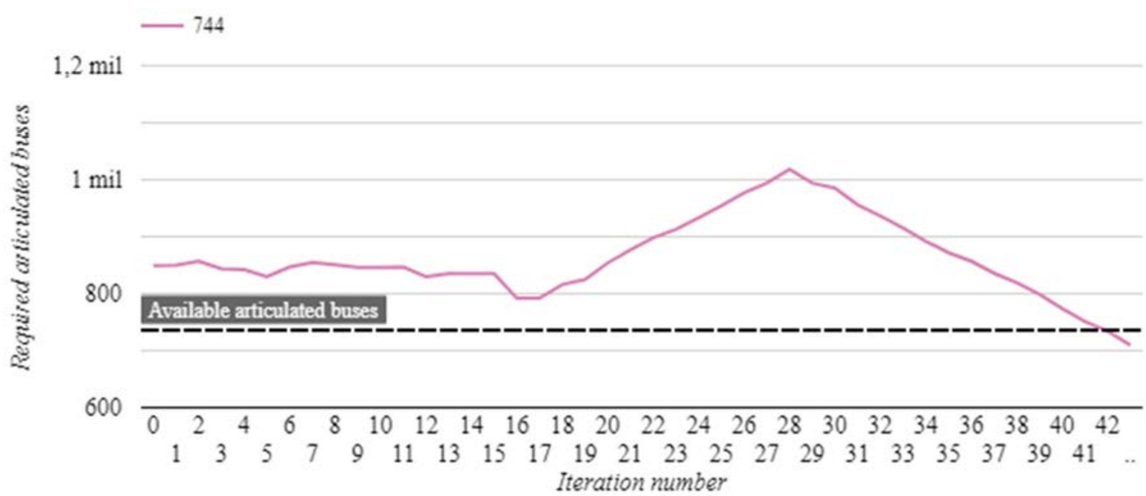

Figure 9: Required number of articulated buses throughout algorithm execution, scenario 744.

Figure 9 shows that the required number of articulated buses decreased as RE algorithm ran from iterations 28 to 43. The required number of bi-articulated buses and the percentage of saturated stations remained under acceptable ranges.

For the other indicators described in section 5, their value improved **between** base scenario and the preliminary design, but there were no significant variations when the algorithm was executed.

8. CONCLUSIONS

Process automation aids to create an operational route design proposal for a BRT system by considering a broader set of restrictions when compared with traditional methodologies.

It is possible to develop algorithms that adjust an initial route proposal for a BRT system to existing restrictions of station capacity and available bus fleet. However, the developed algorithms have an impact on system direct connectivity. In this case, planners had to manually resolve high transfer rates at some stations.

The execution of the described algorithms was not sufficient to achieve a fully applicable operational design. In the case studied, the attained percentage of saturated stations was 8%, meaning that 12 stations were to be analyzed manually to avoid sending more buses than their capacity.

Based on the iterations carried out with the CAS algorithm, it was reasonable to infer that a convergence scenario with 0% of saturated stations was not reliable, regarding the current conditions of the system. Since the saturation values in stations did not exceed the threshold of 5% in the iterations process, regardless of the elimination of service stops. Thus, in this research, it was necessary to manually restrict the algorithm to avoid undesired exclusion of several routes per station that can bring detrimental effects (stations or OD pairs not attended) so it must stop once the threshold is reached.

Despite the existence of international methodologies to generate an operational design for BRT systems, these methodologies are not definitive and do not include specific guidelines for addressing the station capacity and available fleet restrictions. The planning process for a BRT system is still open for improvement and debate.

Vehicle capacity, parallel lines, and overlapping routes can affect the results of transit assignment. Using an assignment model that takes these factors into account could improve the assignment results, and therefore the overall operational design.

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METRO SYSTEMS IN LATIN AMERICA, COMPARISON OF PLANNING AND DEVELOPMENT MODELS VERSUS OTHER REGIONS IN THE WORLD

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ABSTRACT

The population growth in cities pushes to seek solutions for the mobility of people, one of the most efficient but at the same time more expensive solution is a rapid transport system, commonly known as metro systems. In last 50 years, Latin America has seen how many of its cities have grown to have populations of several million inhabitants and therefore they have considered the development of a first metro line or if they already had existing lines, expand the metro network. This study seeks to understand the planning and development models of metros in Latin America and analyze the traits of these systems, compared to metros in other regions of the world. The conclusions of this study will not only be useful for local planners, but also for development banks and other international organizations in a way that they can understand and adapt their processes to local conditions. The research uses statistical information from benchmarking groups of metro systems throughout the world, as well as information presented in annual reports of companies operating metro systems. Academic documents are also used, as well as reviews and analytical studies by experts from international organizations and multilateral banks. In the first section of the paper, planning models to develop a metro project are analyzed, then a comparison is made between levels of demand or passenger flows and economic-financial variables and finally the operation models are studied. Conclusions are presented with the most relevant factors to consider when planning and developing a metro system in Latin America.

1. INTRODUCTION

1.1 The Latin American context: the demographic explosion and the construction of metro systems

During the last century and a half, the Latin American region has experienced explosive demographic growth, going from a population of 75 million in 1900 to 165 million inhabitants by 1950, continuing growing to 510 million inhabitants by 2000 and it is estimated that in 2025, the population will reach 783 million inhabitants (Ortiz Álvarez et al., 2003), this means an increase of more than 1000% in the period stated. But not only the population grew, but it has also become more urban, going from an urbanization level of 25% in 1925 to a percentage of urban population of 75,3% in 2000, and its projected urban population will reach 82,2% in2025, also being the region of the planet with the greatest changes in population growth and levels of urbanization (Lattes, 2001). As for the most populous cities in Latin America in 1900, none exceeded the figure of one million inhabitants, by 1950 six cities in the region had exceeded one million inhabitants, and by 1995 39 cities within the region had exceeded that population, including three cities that had more than ten million inhabitants (Ortiz Álvarez et al., 2003).

At a global level, the phenomena of population growth and urbanization have led to public transport having a substantial weight in the dynamics of large cities and urban metropolitan railways, commonly called “metros” which are among the most implemented solutions in large cities. Studies cite that the 10 largest metro systems in the world transported more than 22,000 million passengers in 2013, equivalent to three times the world population (Brage-Ardao et al., 2015). In Latin America the trend towards the construction of metro systems has not been different from the rest of the world. Throughout the 20th century, metros had been built in thirteen cities in Latin America, but in just two decades of the new millennium ten new cities in the region joined the club of cities that have metro systems (Clemente, 2013).

1.2 The particularities of Latin America in transportation investments

Latin America is in a construction boom of metro systems, but this region has its own conditions that are not necessarily similar to other regions of the world where many metro systems have been built, such as in Europe, North America, and Asia.

Latin America is a developing region, with a series of social challenges, including considerable levels of poverty, political instability in its governments, and difficulties in state finances that lead to limitations on public investment. The region has been involved in successive financial crises, which has influenced the capacity of state or local governments to make investments, which has been reflected in the fact that it is the region of the planet with the lowest level of investment in infrastructure, just 1.8 % of GDP, which has led it in recent years to focus on different types of concessions or public-private participation (PPP) (Vassallo Magro, 2015). It is essential to study the planning and management models of transport infrastructures in the region, addressed in section number two of this document. Although the population's transportation needs are high since the region is very populous and with high levels of urban concentration in large cities; on the other hand, the aforementioned financial limitations at the level of investment in infrastructure lead to unique phenomena in terms of demand levels and use of metro systems in the region. These phenomena will be explored later in a comparison by regions. Finally, the permanent tension due to financial issues in the region prompts a search for financing sources of various origins and that many metro systems in the region have a vocation for financial self-sustainability.

Given the nature of this research, the main method of gathering information will be by bibliographic sources, including scientific articles, reports from operators or concessionaires of metro lines, comparative reports from benchmark associations of comparative analysis and by studies, reports and reports of multilateral development and investment banking

2. LITERATURE REVIEW

Due to their nature of large-scale works, metro systems have been inserted in urban spaces and with constructions that require underground works or viaducts, present construction complexities and high investment costs. According to an analysis of 40 metro lines in the world, their construction costs range from US $ 50 million to US $ 150 million per kilometer of construction (Flyvbjerg et al., 2008), and a study by the same author shows that the presence of cost overruns are on average 45% above the original budget (Flyvbjerg, 2007). Other authors have studied the causes of cost overruns, finding in 75% of the cases incomplete or low-quality designs, work delays and administrative problems between the parties involved (Cantarelli et al., 2010). The problems in the metro systems do not end with their construction, since their operation also involves great challenges, both in terms of demand coverage and financial sustainability. Flyvbjerg reports that worldwide 9 out of 10 projects do not meet expectations for passenger demand ranges, with three-quarters of those projects falling below 40% of forecast demand (Flyvbjerg, 2007); moreover metro projects are the most inaccurate at the level of demand forecasts in the field of transport, which has been maintained for several decades (Siemiatycki & Friedman, 2012). Lastly, financial sustainability is a critical factor in metro systems worldwide, and it is thus that in benchmark reports comparing metro systems in various continents, very few operators achieve a degree of cost coverage equal to operating revenues, commonly called the “coverage index” (ALAMYS, 2013; Condry, 2013). This inability to achieve financial equilibrium at cost level and operating income indeed leads metro operators to demand high levels of subsidies from central or regional governments. Given the fact of presence of various levels of risks in terms of: design, construction, demand forecast, and political, some mechanisms have been found at international level in order to transfer this risks to private parties, under various administrative modalities of operation contracts, concessions and public-private participations (PPP) that allow transferring the risk from the infrastructure developer to the private sector (Siemiatycki & Friedman, 2012), existing a diverse variety of models ranging from the traditional model where the project developer is responsible for all phases, to complex and varied alternatives where one or more phases of the Design (D), Build (B), Operate (O), Finance (F) stages are transferred to the private party and - if applicable - the Transfer (T) or Property (O) of the project. Hence, progressive models of involvement of the private sector as a concessionaire are described. Each acronym described represents the commitment that the private sector acquires in the PPP such as: DB, DBO, BOT, BOO, until reaching the broader risk transference model the DBFOT, also called “turn key”, here, the project developer leaves everything in the hands of the private company that takes action in all activities from design, through construction, to long-term operation (Clemente, 2013; Delmon, 2010; Wojewnik- Filipkowska, 2012).

There are other factors that influence metro systems, beyond the development models of the projects. On the one hand, studies show that there are particularities or conditions both in favor and against for those "greenfield" type projects that correspond to absolutely new infrastructures for the environments where they are implanted, compared to "brownfield" type projects, which are those that are an extension or are very similar to an existing project (Amos, 2004; Gago De Santos, 2014) and the literature consulted agrees that among the advantages of greenfield projects are the high degrees of freedom to start a project without previous conditioning factors, meanwhile among the disadvantages is the lack of experience in these projects. And finally, another major issue that influences metro projects is the approach to receive technical support and financing from multilateral entities ,or development banks compared to new technical and financial parties such as Asian governments. In this sense, multilateral financial entities not only act as lending banks, but there is also a strong focus on developing internal capacity of project operators by improving institutional capacities and technical and knowledge transfer (Sagasti & Prada, 2002). Faced with this alternative, in the last two decades, there has been a strong influence of new actors such as the case of China, a new infrastructure lender in the region (Gallagher et al., 2013; Slipak, 2014), although these credits are linked to obligations to contract Chinese companies and under the conditions that their government requires, according to Gallagher and Slipak.

3. COMPARISON OF LATIN AMERICA METROS VS. OTHER REGIONS OF THE PLANET

Obtaining data from all metro systems in the world is an extremely complex task, not only due to the high number of existing metro systems, which by 2018 were 182 cities (UITP, 2018), but also because many of those systems do not carry complete statistics on their operations; moreover, even if they have statistics, they do not have standardized indicators that allow comparisons between equivalent parameters. Therefore, in order to be able to compare Latin America’s metro systems with metros in other regions of the world, the data and information have been taken from some metro systems that are representative of each region and for which there are sufficient data and harmonics with one another. The information come from public use of benchmarking metro associations such as reports from the Asociación Latinoamericana de Metros y Subterráneos (Latin American Association of Metros and Subways) (ALAMYS, 2014), Community of Metros Benchmarking Group (Anderson, 2006; Anderson, Findlay and Allport, 2010; Condry, 2013) and the Union Internationale des Transports Publics (UITP, 2012, 2016, 2018) as well as annual reports or official reports from metro operators (Azienda Trasporti Milanesi, 2015; Taipei Rapid Transit Corporation, 2015; Transport for London, 2015; CRTM, 2015; Delhi Metro Rail Corporation Ltd., 2015; Metro Sao Paulo, 2015; Metropolitan Transportation Authority - MTA, 2015; MTR, 2015; SMRT, 2015; BVG, 2016; Washington Metropolitan Area Transit Authority, 2016; San Francisco Bay Area Rapid Transit, 2016; Metro Rio, 2017) and of multilateral entities or investment and development banks from consultants or analysts of these institutions (Rebelo, 2006; Mitric, 2013; Ardila-Gomez and Ortegon-Sanchez, 2015; World Bank et al., 2015; European PPP Expertise Center, 2016; Pulido, 2016; Pulido et al., 2018)

3.1 Demand level versus the size of the metro network

The first feature which has been found particularity in metro systems in Latin America compared to other regions, is the high demand they have in relation to the size of those metro networks. To carry out the analysis, it is necessary to compare the variables "number of annual travelers" expressed in millions of passengers (MMpax) with "network size" expressed in kilometers. Some metro systems have been selected from each region among the most representative operations. These data are observed in table 1, and in graph 1.

City - Operator	**Region**	**Network Length (km)**	**Annual passengers (MMPax)**	**Passengers by Network Length (MMPax/km)**
New York City Subway	North America	485	1751	3,61
Washington Metro	North America	171	209	1,22
Montreal Metro	North America	71	280	3,94
San Francisco BART	North America	197	128	0,65
Average metros selected North America		**231**	**592**	**2,56**
London Underground	Europe	402	1265	3,15
Metro de Madrid	Europe	294	561	1,91
Berlin U-Bahn	Europe	175	500	2,86
Metro de Milan	Europe	97	350	3,61
Metro de Valencia	Europe	147	60	0,41
Average metros selected Europe		**223**	**547**	**2,45**
Hong Kong MTR	Asia	185	1578	8,53
Shanghai Metro	Asia	613	2500	4,08
Singapore MRT	Asia	142	1200	8,45
Delhi Metro	Asia	212	780	3,68
Taipei Metro	Asia	129	680	5,27
Average metros selected Asia		**256**	**1348**	**5,26**
Mexico City Metro	Latin America	200	1580	7,90
Metro Sao Paulo	Latin America	75	800	10,67
Metro de Santiago	Latin America	105	650	6,19
Subte de Buenos Aires	Latin America	45	380	8,44
Metro Rio	Latin America	45	200	4,44
Metro de Medellín	Latin America	35	201	5,74
Average metros selected Latin America		**84**	**635**	**7,55**

Table 1: Passengers by Network Length (MMPax/km)

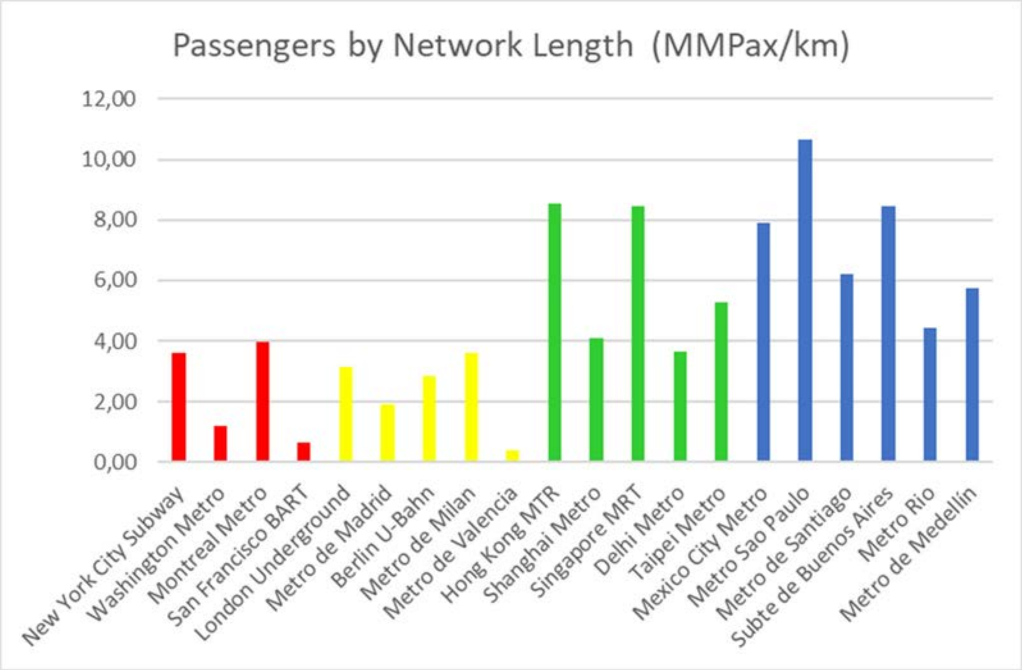

Figure 1: Passengers by Network Length (MMPax/km)

The calculation of the average of the selected metro systems shows that the metro systems in both Latin America (7.55 MMpax / km) and Asia (5.26 MMPax / km) have higher levels of demand for the lengths of the metro networks than their counterparts in North America (2.56 MM / km) and Europe (2.45 MM / km). Actually, passenger load per km in Latin America is the highest in the world.

3.2 Financial Sustainability

In order to evaluate this parameter, two variables will be analyzed; on the one hand, the quotient called "recovery ratio" which represents a relationship between operating income versus operating costs, in such a way that a recovery ratio greater than 1 represents that all the operating costs are paid with operating income received and therefore the operation of the metro system is financially sustainable, and a ratio lower than 1 represents that the operation does not cover its costs and will permanently need government subsidies. The second variable used is “additional or non-tariff income”, which corresponds to all commercial activities that are not related to transport activities but generate income in a metro system. Among these are commercial advertising in stations or on trains, businesses related to telecommunications within the metro network including mobile telephony, the rental of store places within metro stations and even activities outside the metro system like real estate activities related to administration of residential buildings and shopping centers in areas near metro stations. The comparative data of the two mentioned variables can be seen in Table 2.

City - Operator	**Region**	**Recovery Ratio**	**Percentage of revenues not related to transport**
New York City Subway	North America	50,3%	7,3%
Washington Metro	North America	36,5%	5,0%
Montreal Metro	North America	64,0%	6,0%
San Francisco BART	North America	67,0%	9,9%
Average metros selected North America		**54,5%**	**7,1%**
London Underground	Europe	100,6%	16,0%
Metro de Madrid	Europe	73,9%	6,2%
Berlin U-Bahn	Europe	57,6%	12,9%
Metro de Milan	Europe	91,9%	8,6%
Metro de Valencia	Europe	52,5%	4,2%
Average metros selected Europe		**75,3%**	**9,6%**
Hong Kong MTR	Asia	183,8%	29,3%
Singapore MRT	Asia	128,1%	26,8%
Delhi Metro	Asia	149,7%	7,7%
Taipei Metro	Asia	118,5%	16,1%
Average metros selected Asia		**145,0%**	**17,9%**
Mexico City Metro	Latin America	41,7%	4,6%
Metro Sao Paulo	Latin America	102,7%	11,5%
Metro de Santiago	Latin America	103,3%	19,8%
Metro Rio	Latin America	170,9%	8,1%
Metro de Medellín	Latin America	153,1%	5,4%
Average metros selected Latin America		**114,3%**	**9,9%**

Table 2: Recovery ratio and Percentage of revenues not related to transport

It is notable that in terms of the recovery ratio, very few operations in Europe and North America manage to cover all their costs with operating income, while in the case of the metro systems in Asia and Latin America, several of them exceed the recovery ratio of 100%. In fact, when evaluating all the systems in Latin America and Europe, there are 5 metro systems that are financially self-sustainable and a similar number that approach recovery ratios equal to or greater than 100% in Latin America, whereas in Europe there is only one metro with a ratio of recovery greater than 100%. By comparing averages of the recovery ratio for the metro systems selected, it is observed that Asia has a recovery ratio of 145% and Latin America 114.3%, while Europe has 75.3% and North America 54.5%.

A similar situation occurs with incomes that does not come from transport activities, and looking to the average of the metros selected, it is noticeable that the Asian metro systems lead in obtaining this type of non-tariff income with a 17,9% average of in revenues not related to transport, followed by the metro systems of Latin America (9.9%) and Europe (9.6%), and at a greater distance those of North America (7.1%).

Considering the two variables, it can be concluded that in Asia and Latin America there is a strong effort to obtain financial sustainability, while in North America and Europe there is no high interest in achieving it. This goes hand in hand with the social perspective existing in most European countries, where transport systems are a service and a fundamental citizens' right.

3.3 Greenfield projects, degrees of freedom and technical experience

As mentioned above, there are brownfield-type metro projects that are extensions of previous projects (such as a new metro line in an existing system or the extension of a line) and greenfield-type projects where there are no pre-existing metro lines in the same city or even in many cases, within the same country. Greenfield projects have advantages and disadvantages. One of the advantages is the possibility of working with a greater degree of freedom, since there are no conditions for following the standards of previous or existing metro lines that force the use of technical specifications such as platform size, voltage levels, train width, among others; which for the project developer and the builders is favorable since it allows greater freedom for the designs and construction. In contrast, the biggest disadvantage of a greenfield project is that there is no prior technical experience; therefore, there are no local engineers knowledgeable about these systems and acquiring that experience has considerable costs.

In Latin America, with the exception of Brazil, which has several metro systems and extensive metro construction experience, for the rest of the countries the metro systems development processes have fallen into the typology of greenfield projects, and for their developers this has demanded strong learning and costs associated with this need to learn and to acquire urban rail technology. Statistics show that in eight Latin American countries there is only one city that has a metro system: Argentina, Colombia, Chile, Ecuador, Panama, Peru, Puerto Rico and the Dominican Republic (Clemente, 2013). In other words, for those eight countries, the metro systems have been greenfield projects. And even more, given the low regional integration of Latin America, the developments of new metro systems in other countries of this region will also fall into the greenfield typology, unlike Europe or North America where there is high regional integration and railway experts can relocate labor very easily from one country to another.

3.4 Public Operation and Public-Private Participations

Several studies confirm that unlike in Europe, Asia and North America, where Public-Private Partnerships (PPP) are frequently used in the operations of metro systems, in Latin America PPPs have not been used frequently, or instead, these concessional models are fairly recent or appear as a result of a continuity crisis due to poor performance (Leipziger and Lefevre, no date; Schwartz, Corbacho and Funke, 2008; Chang, 2013; Carpintero and Helby Petersen, 2014; Gago De Santos, 2014; World Bank, 2014).

In Latin America, there are currently PPPs in Brazil in the cities of São Paulo and Rio de Janeiro; Argentina in the city of Buenos Aires (Rebelo, 2006), and Lima in Peru (Ositran, 2017), all these PPPs have appropriate financial and operational results for cities and their users, according to the sources cited above. But besides these mentioned cases, in the rest of the 22 metro systems in the region, the operation by themselves is imposed at the level of public sector equity companies. Furthermore, in the case of Rio de Janeiro and Buenos Aires, these concessions are from recent times and in the case of São Paulo, they only correspond to one line of the entire system. This shows that despite PPP models attempts have been introduced in the region, they still do not have strong acceptance by local or national governments that are the owners of the metro systems.

4. CONCLUSIONS

The comparisons that have been presented allow us to find some particular characteristics of the metro systems in Latin America in terms of high levels of passenger demand, a permanent concern for the financial sustainability of metro operations, the preeminence of greenfield type projects in the region and, finally the little acceptance that PPPs have had in the region's metro systems.

Understanding the particularities of the metro systems in the region and making good use of this information will be very useful for transport planners, development bank executives, railway constructors, metro operators and finally for politicians and policy makers in general, who will be able to better adapt their vision on how metro lines are developed and built in Latin America.

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GENERAL GUIDELINES FOR THE DESIGN OF BRT ROUTES IN THE PUBLIC TRANSPORT INTEGRATED SYSTEM OF BOGOTÁ

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ABSTRACT

The objective was to establish general guidelines for the design of the BRT route network in Bogotá's Public Transport Integrated System – SITP – in terms of geographical layouts, stop points, and frequencies. The demand for the morning rush hour in a typical business day before COVID-19 was contemplated.

The research methodology had three phases. 1) Establish several sets of preliminary guidelines for route network design in the Bogotá BRT System – TransMilenio –. 2) Development of a methodology – based on a transport model implemented in PTV-Visum – to assess different routes scenarios designed following those sets of preliminary guidelines. 3) Application of this assessment methodology to quantify the impact of each set of preliminary guidelines for route network design, thus choosing the best alternatives.

The outputs can be divided into two categories. 1) Heuristic processes for the systematic design of routes in the BRT system. 2) Selected guidelines for the design of route network in TransMilenio. This report will be focused on the second category of outputs. Among the conclusions, the BRT services in Bogotá should be designed with a multi-criteria approach, which implies a relatively complex route network. A very simplified route network has proven to be inconvenient. On the other hand, in the short term, it is recommended to maintain diametrical routes to avoid the collapse of central stations due to increased transfers. However, in the medium term, the paradigm must evolve to radial routes design. This approach would make it possible to significantly reduce the minimum required fleet, improving headways, increasing comfort within buses, and/or reducing investment in rolling stock. Furthermore, it has been shown that the radial routes approach would require four new central interchange stations in Bogotá.

1. INTRODUCTION

Bogotá's BRT - TransMilenio - constitutes the backbone of mobility in the city (TransMilenio, 2019). Beyond its qualities or problems, the sustainability of this transport system is essential to guarantee the correct development of urban activities on a day-to-day basis. This sustainability is the result of a combination of many factors related to various areas of knowledge, and among them, transportation planning is one of the branches that can contribute the most to the success of a transit system.

1.1 Background

The design of the route network in transit systems, as part of the transportation planning process, is a problem whose solution can significantly affect some aspects of the service (Ceder, 2001). In this way, the research problem to be solved was the determination of guidelines for route network design in BRT systems, specifically for TransMilenio in Bogotá.

The main objective of the research was "To establish general guidelines for the design of the BRT route network in the Integrated Public Transport System -SITP- of Bogotá, at least in terms of geographical layouts, stop points, and frequencies." Its importance lies in the fact that it is necessary to seek innovative solutions that optimize, even more, the use of available resources to improve the service level offered to the user. This becomes even more relevant considering that, before the COVID-19 pandemic, TransMilenio supported over 45,000 passengers per hour in a single direction (TransMilenio, 2020), and therefore, historically high levels of overcrowding have been notorious.

1.2 State of the art

As defined in the main objective, this research has covered three aspects of the route network design in a BRT system: the design of geographical layouts, the choice of stop points, and the assignment of frequencies. Thus, in this review, literature has been grouped according to its relevance in each of these three items.

According to Kepaptsoglou and Karlaftis (2009), the literature on geographical layouts for route network design can be classified into three levels:

- Design objectives: maximization of the benefit to the user (Lee and Vuchic, 2005; Zhao and Zeng, 2006); minimization of operating cost (Ceder and Israeli, 1997); maximization of total well-being (Fan and Machemehl, 2006); maximization of transport capacity (Morlok and Viton, 1984); energy conservation / environmental protection (Delle and Filippi, 2001).
- Operational parameters: priority decision variables (Van Nes, 2003); network structure (Chang and Schonfeld, 1993); demand patterns and characteristics (Zhao and Zeng, 2007; Tom and Mohan, 2003; Chakroborty and Dwivedi, 2002).
- Methodology used: conventional methods vs. heuristic methods.

As regards methodologies, it is worth digging a little deeper. Conventional methods (Morlok and Viton, 1984; Van Nes et al., 1988; Delle and Filippi, 2001; Chang and Schonfeld, 1993; Van Nes, 2003) include analytical methods and those that involve some type of mathematical programming. However, due to their high complexity and combinatorial and multi-objective nature, these methods are only suitable for problems where it is necessary to generate general policies but not complete detailed designs. In general, they are only theoretical interests, according to Kepaptsoglou and Karlaftis (2009).

Thus, the heuristic approach becomes the dominant methodology for dealing with real-life problems using reasonable computational power. There are at least two heuristic paths to be followed. The main of these, and that has been adopted in this research, consists of the following steps:

- Previous processes for consolidating demand data, road network information, and setting restrictions.
- Generation of a set of candidate routes through heuristic processes based on algorithms. (Lee and Vuchic, 2005; Ceder and Israeli, 1997; Tom and Mohan, 2003; Chakroborty and Dwivedi, 2002).
- Configuration of routes through processes in which frequencies are iteratively determined and demand is assigned, the best routes are selected according to previously defined indicators, these selected routes are improved, and the iterative cycle is resumed. (Zhao and Zeng, 2007; Fan and Machemehl, 2006; Cipriani et al., 2005).
- Final selection of the optimal set of routes and their associated frequencies.

The other possible path starts with the direct construction of the set of routes through a heuristic process that considers operational restrictions and that can be based on geographical considerations, and travel demand flows (Carrese and Gori, 2002). It can also be based on "ant colony algorithms" (Hu et al., 2005; Yu and Yang, 2006; Yang et al., 2007).

Turning to the literature on the choice of stop points, a problem that has received a little more attention than geographic layouts design, it is possible to cite studies based on mathematical optimization models on the design of express services in corridors with capacity restrictions (Leiva et al., 2010; Larraín et al., 2010; Larraín and Muñoz, 2019). Likewise, also notable publications are Scorcia (2010), with a work of design and evaluation of BRT express services in Chicago. Hart (2016) with a methodology to evaluate the potential of express services in corridors where regular services also operate. Ghaderi et al. (2017), which method focused on reducing users’ travel times through the spatial analysis of the stop points and their locations. Luo et al. (2017) with a heuristic for the design of express services at rush hour with a fixed-size fleet; and (García and Jaramillo, 2019) where it has been sought to maximize the users' comfort within buses through an improvement of express services.

Regarding the literature on the assignment of frequencies to services, Campos (2016) proposes a "Lego" type heuristic that would allow obtaining a reasonable frequency assignment for the BRT system in Bogotá. Meanwhile, Peña et al. (2016) present a mathematical model adapted to TransMilenio's case to optimize its operation by adjusting frequencies and variations in the scheduled departure times for the different routes. Additionally, a heuristic methodology based on an evolutionary algorithm to simultaneously undertake the design of routes and the assignment of their frequencies is developed by Martínez et al. (2017), with a case of theoretical application to various BRT systems in Colombia.

Finally, two books have been vital to the development of this research. One of these books (Ceder, 2007) constitutes a whole compendium that anyone designing and operating public transport systems should review. The other reference text (Norambuena, 2002) has as its main objective the formulation of a heuristic that allows obtaining an efficient route structure for a public transport system, with application case for transit corridors in Santiago, Chile.

From the above, it has been possible to conclude that although there is a certain amount of literature that addresses the route network design problem from a theoretical perspective, it is not so common to find studies applied to real-life transport systems, particularly regarding the sup-topic of geographical layouts. It is even less frequent to find works that covers simultaneously all the relevant sub-topics – geographical layouts, stop points and frequencies – related to route design in BRT systems. Thus, the present research aims to fill this gap, offering comprehensive guidelines for route network design in BRT systems, with an application case focused on TransMilenio.

2. METHODOLOGY

The methodology implemented was of the hypothetical-deductive type, as shown in the diagram in Figure 1:

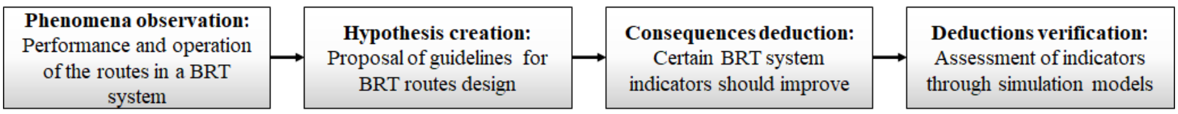

Figure 1: Hypothetical-deductive scheme of the research.

2.1 Experimental design

The phases of the research methodology are shown in Figure 2. In its first phase, the research had a qualitative design. Through a review of the existing literature, international study cases, and interviews with experts in the area, several candidate sets of guidelines for route network design were established. This process will not be covered in this document, but it can be consulted here (Moreno, Unpublished results).

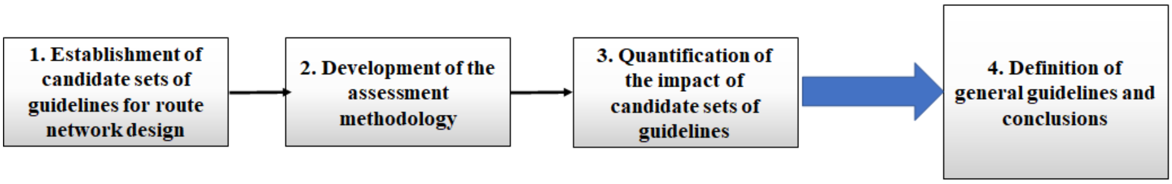

Figure 2: Phases of the research methodology.

Once the candidate sets were established, a quantitative approach was adopted: the impact of the various sets of proposed guidelines was quantified numerically to select the best solution alternatives to the research problem. All this through experimentation with a PTV-Visum simulation model.

2.1.1 Population and sample

The object of the study is to create design guidelines for Bogotá's BRT route network and their impact. However, as these guidelines have an intrinsically abstract nature, it is necessary to generate a transport model that simulates the behaviour of different variables that adequately describe the system's performance. Regarding the population and sample data for this transport model, the demand of internal trips in the BRT system has been considered:

- Population: trips, or trip segments, of the morning rush hour on Bogotá's BRT, establishing their origin and destination as stations in the system.
- Sample: a statistically representative collection of trips belonging to the previously defined population and presented in the form of a travel matrix.

The 2019 Bogotá Mobility Survey (SDM, 2020), the input and output records from the stations' turnstiles (TransMilenio, 2020), the seed matrix – calibrated to 2019 – of internal trips of the BRT system, and the study with the evasion baseline in TransMilenio (UNAL, 2019) have been used for the elaboration of the travel matrix.

The aforementioned data sources have been combined to generate a travel matrix updated to February 2020 – before the pandemic – by implementing a generation and attraction sub-model, and a distribution sub-model by Fratar. The final matrix estimated for the morning peak hour - 06:15 to 07:15 - contains 265,000 internal trips - for Bogotá's BRT. Additional details on the construction of the travel matrix can be found in (Moreno, Unpublished results).

2.1.2 Operational variables and objective function

These are the operational variables defined to characterize the transport model:

- t_{wait}: first boarding wait time (min)
- t_{travel}: onboard travel time (min)
- t_{trans}: transfer time (min)

- $\boldsymbol{N_{seats}}$: total number of seats (size of the minimum required fleet – bus seats)

The access time has not been considered since it has been assumed that users are already inside the stations in the internal transport model. The user fare cost has not been taken into account either because there is a flat fee to access any of the stations in Bogotá's BRT. Thus, the total fare does not depend on the number of transfers within the BRT system, or the distance travelled: it is the same for every individual in the BRT system.

Based on the first 3 operational variables, the objective function that allowed the assessment of the candidate sets of guidelines has been defined as the sum of perceived travel times for **n** trips:

$$F_U = a_{wait} \sum_{i=0}^{n} t_{wait} + a_{travel} \sum_{i=0}^{n} t_{travel} + \sum_{i=0}^{n} t_{trans} \quad (1)$$

For the first two time-weighting coefficients, these values were used (Ortuza and Willumsen, 2001):

$$a_{wait} = 2 \quad (2)$$

$$a_{travel} = 1 \quad (3)$$

Meanwhile, the transfer time was broken down into three components, as allowed by PTV-Visum:

$$t_{trans} = a_{walk\ trans} * t_{walk\ trans} + a_{wait\ trans} * t_{wait\ trans} + P_{trans} * N_{trans} \quad (4)$$

where:

- $\boldsymbol{t_{walk\ trans}}$: walking time during transfers (min)
- $\boldsymbol{t_{wait\ trans}}$: waiting time during transfers (min)
- $\boldsymbol{P_{trans}}$: penalty for each transfer (min)
- $\boldsymbol{N_{trans}}$: total number of transfers (dimensionless)

For the coefficient of walking time during transfers, again a classic value suggested by the literature is taken (Ortuza and Willumsen, 2001):

$$\boldsymbol{a_{walk\ trans} = 2} \quad (5)$$

On the other hand, for the two remaining coefficients, three simulation cases were defined:

- Low penalty transfers:

$$a_{wait\ trans} = 2 \cap P_{trans} = 2{,}5_{min/trans} \tag{6}$$

- Medium penalty transfers:

$$a_{wait\ trans} = 3 \cap P_{trans} = 5_{min/trans} \tag{7}$$

- High penalty transfers:

$$a_{wait\ trans} = 4 \cap P_{trans} = 7{,}5_{min/trans} \tag{8}$$

Additionally, for the assessment of the various scenarios, the minimum fleet required was also taken into account, estimated as the total number of seats:

$$N_{seats} = N_{f\ dual} * 80 + N_{f\ art} * 160 + N_{f\ biart} * 240 \tag{9}$$

where:

- $\boldsymbol{N_{f\ dual}}$ corresponds to the required number of 80-seats dual buses.
- $\boldsymbol{N_{f\ art}}$ corresponds to the required number of 160-seats articulated buses.
- $\boldsymbol{N_{f\ biart}}$ corresponds to the required number of 240-seats bi-articulated buses.

2.2 Assessment methodology

From the elaboration of state of the art, four groups of guidelines were defined. Namely:

- Simple design: this group of guidelines refers to the design of the route network must be as simple as possible.
- Multi-criteria design: this group of guidelines seeks that the route network design adopts multiple strategies and criteria that are necessary to optimize transport operation, even if this implies generating a complex route network.
- Radial design: this group of guidelines refers to the geometry of the routes layouts. Specifically, it is suggested that the routes should start from trip-generating areas, travel to a trip-attracting zone in the downtown, and then return to the initial point of origin.
- Diametrical design: in this case, it is suggested that the routes should start from a trip generating area and make their tour to another trip generating area, at the opposite side of the city, passing through the downtown.

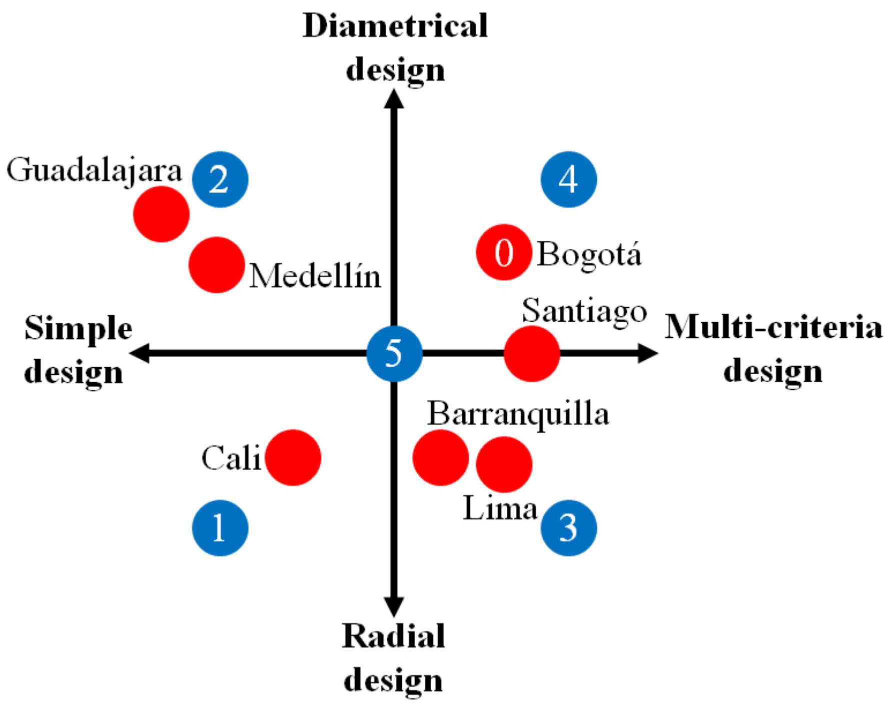

Figure 3: Cartesian plane of candidate sets of guidelines for route network design.

Combining these guidelines groups, as shown in Figure 3, five candidate sets of guidelines were obtained for the route network design. From each of these candidate sets, a route network scenario was generated by implementing a heuristic process. A route network scenario 0 (zero) was added, containing the actual services – February 2020 – of Bogotá's BRT. Therefore, it was possible to compare the solution given by the current route network vs. the solutions given by the new candidate sets of guidelines. The following are the route network scenarios generated:

- Scenario 0: 2020 route network.
- Scenario 1: radial routes with a simple design approach.
- Scenario 2: diametrical routes with a simple design approach.
- Scenario 3: radial routes with a multi-criteria design approach.
- Scenario 4: diametrical routes with a multi-criteria design approach.
- Scenario 5: routes based on different guidelines sets (radial + diametrical + multi-criteria design approach).

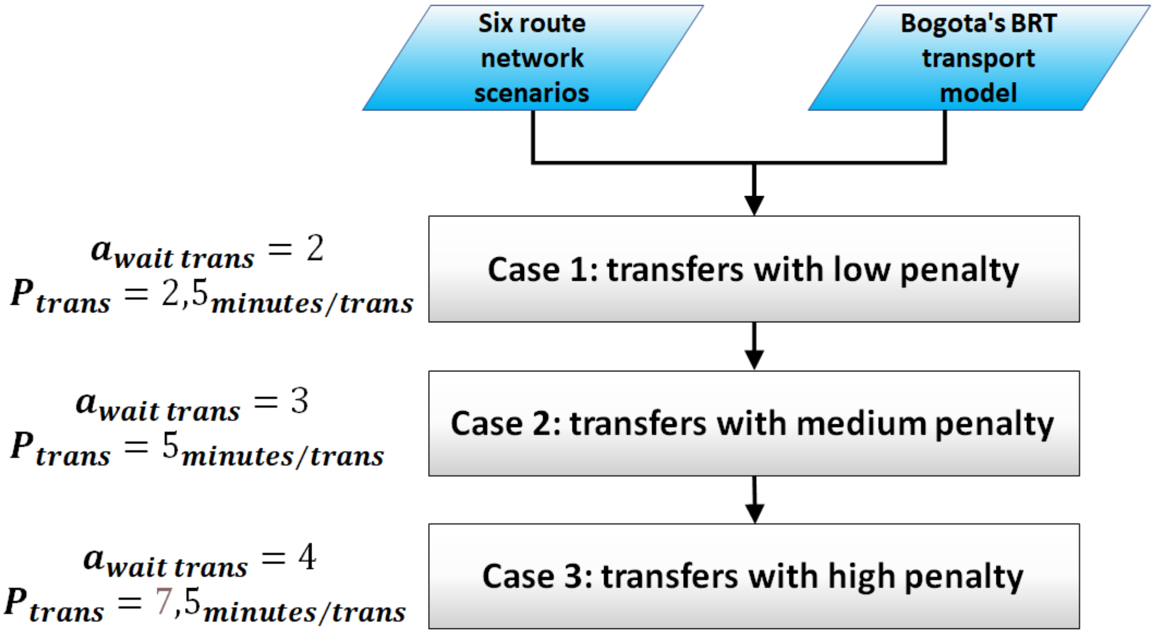

Figure 4: Structure of simulation cases.

Details of the heuristic processes developed for the generation of the route network for each candidate set of guidelines will not be covered in this document. They are widely explained in the thesis book generated for this research (Moreno, Unpublished results). Meanwhile, Figure 4 illustrates the simulation cases that were run to assess the different route network scenarios.

3. RESULTS

Table 1 summarizes the route network scenarios that were generated. In this table, the corresponding roundtrip services are counted as a single route. The total number of routes per scenario corresponds to the sum of its number of radial and diametrical routes.

Esc.	Geographical Guidelines	Design Approach	# Radial Routes	# Diametrical Routes	# Regular Routes	# Express Routes	# Super Express Routes	# Partial Routes
0	Actual	Actual	27	38	9	50	6	8
1	Radial	Simple	46	0	9	37	0	0
2	Diametrical	Simple	5	20	6	19	0	0
3	Radial	Multi-criteria	85	0	9	54	22	14
4	Diametrical	Multi-criteria	9	45	6	32	16	10
5	Rad/Diam.	Multi-criteria	34	32	6	40	20	11

Table 1: Synthesis of the six simulated route network scenarios.

Furthermore, Table 2 shows the results obtained for the six route network scenarios in each of the three simulation cases.

Scenario		Typology (Seats/Bus)			Fleet Size		F_U = Travel Time (min)		% Trips by required transfers			
Caso	**Esc.**	**80**	**160**	**240**	**Buses**	**Seats**	**Perc.**	**Net**	**0**	**1**	**2**	**3**
1	**0**	422	678	1245	2345	441040	46,7	41,7	14,1%	38,6%	33,2%	14,0%
1	**1**	330	554	1321	2205	432080	48,3	41,9	6,2%	21,5%	30,4%	42,0%
1	**2**	743	620	1369	2732	487200	47,8	41,8	6,6%	21,7%	31,5%	40,1%
1	**3**	367	644	1164	2175	411760	47,9	41,9	9,6%	31,6%	35,4%	23,5%
1	**4**	511	766	1157	2434	441120	46,9	41,5	11,6%	36,9%	34,0%	17,5%
1	**5**	361	617	1249	2227	427360	47,0	41,6	10,5%	37,2%	34,6%	17,7%
2	**0**	341	755	1182	2278	431760	48,2	42,2	29,1%	48,7%	19,8%	2,4%
2	**1**	264	625	1219	2108	413680	50,6	42,3	12,2%	39,5%	36,3%	12,0%
2	**2**	585	587	1289	2461	450080	49,4	42,2	15,6%	43,0%	32,7%	8,7%
2	**3**	334	654	1083	2071	391280	50,7	42,5	16,5%	46,5%	31,1%	5,8%
2	**4**	446	644	1116	2206	406560	48,8	42,0	22,8%	49,9%	24,2%	3,2%
2	**5**	311	614	1117	2042	391300	49,4	42,3	20,6%	52,9%	23,9%	2,5%
3	**0**	343	683	1223	2249	430240	49,2	42,6	39,5%	48,4%	11,4%	0,7%
3	**1**	264	624	1190	2078	406560	52,6	42,7	16,5%	48,7%	30,7%	4,0%
3	**2**	544	574	1254	2372	436320	50,8	42,7	23,0%	52,1%	22,8%	2,1%
3	**3**	341	555	1117	2013	384160	52,9	43,1	21,4%	57,3%	20,5%	0,8%
3	**4**	426	642	1070	2138	393600	50,3	42,5	32,4%	54,7%	12,3%	0,5%
3	**5**	304	614	1128	2046	393280	50,9	42,7	28,0%	59,3%	12,4%	0,3%

Table 2: Quantified results of the simulation cases per scenario.

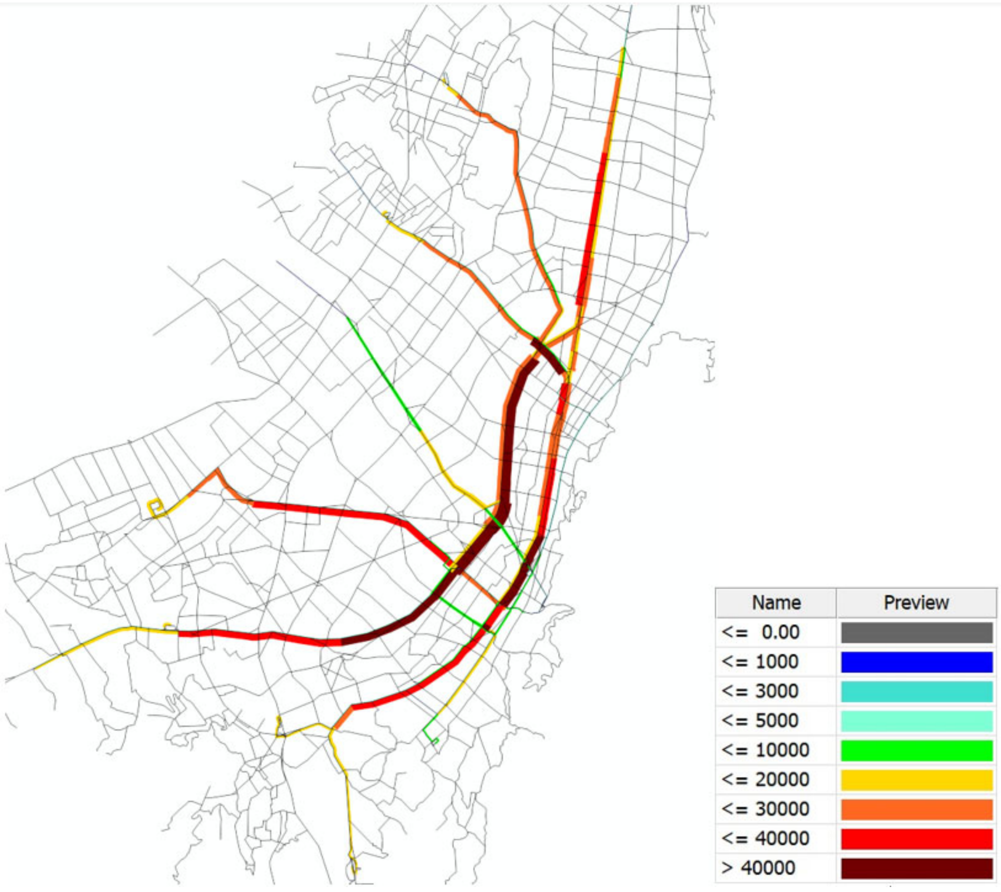

Figure 5: Passenger volume per arc in Case 2, Scenario 0 - Route network 2020 -.

Meanwhile, Figure 5 shows an example of the result of a trip assignment process. This example corresponds to Case 2: medium transfer penalty – Scenario 0: 2020 route network. In the whole exercise, a total of 18 trip-assignment processes were executed: 3 simulation cases x 6 route network scenarios.

4. DISCUSSION

Figures 6 and 7 show the results related to the average perceived travel time ($\boldsymbol{F_U}$) and the total number of seats ($\boldsymbol{N_{seats}}$). The figures compare the data obtained for the real route network (in gray tones), route networks with simple design (green tones), and route networks with multi-criteria design (in golden tones). These tones get darker as the transfers are penalized more in the transport model.

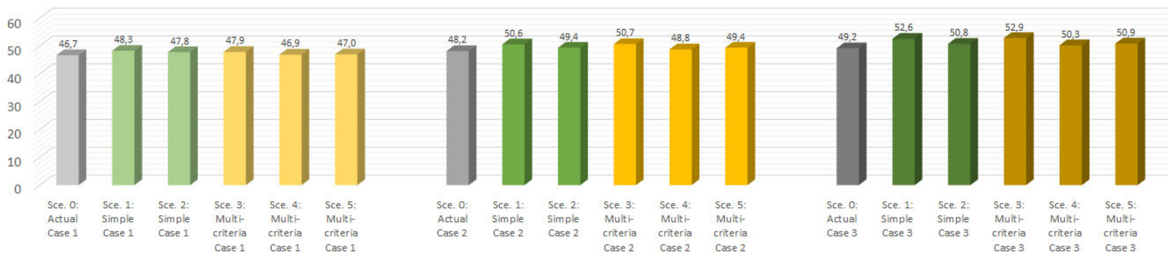

Figure 6: Average perceived travel times – F_U – per case and scenario (min).

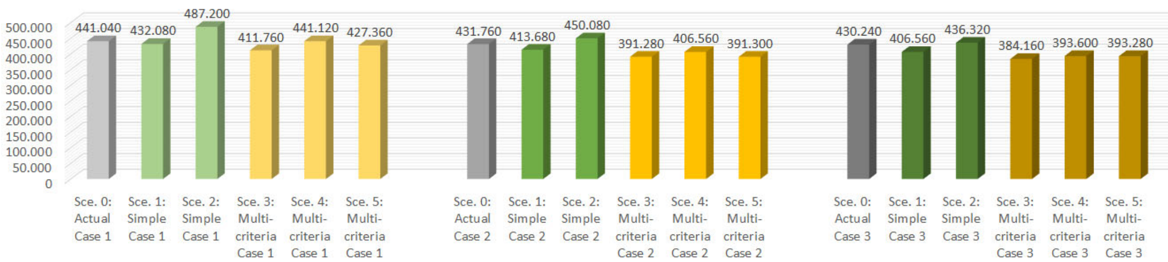

Figure 7: Minimum Required Fleet – N_{seats} – per case and scenario (seats).

At this point, it is convenient to explain that the reason why three simulation cases with different transfer penalties - low, medium, and high - have been defined is that the weighting of the transfer time from the users point of view depends, to a great extent measure, of the installed infrastructure: it is not the same to make a transfer within a comfortable station, with shops and restaurants, than to do it in a station in the most dangerous zone of the city, without a roof that covers the head and under unfavourable weather conditions. Thus, the proposed scheme of the three simulation cases allows to analyse the results for different infrastructure situations.

4.1 Simple design vs. multi-criteria design

There is no appreciable difference between route networks designed with a simple approach and those designed with a multi-criteria approach in terms of perceived travel times.

The difference is only 1.0% on average in favour of the multi-criteria approach, which is negligible.

On the side of the minimum required fleet, the differences are noticeable. It is noteworthy that route networks designed with a multi-criteria approach require fewer seats than the real route network (-7.4% on average) and fewer seats than route networks with a simple design approach (-8.2% on average). In terms of investment or user comfort level, this savings in required fleet is highly important.

The percentages provided in this comparison exercise correspond to the average of all simulation cases - low, medium, and high penalty for transfers - assessing the modelled indicators of real routes, simple approach, or multi-criteria approach scenarios, grouped according to their type.

4.2 Radial design vs. diametrical design

From the previous discussion, it is possible to conclude that the multi-criteria design approach is desirable over the simple design approach. Therefore, the performance of radial routes vs. diametrical routes will be compared, considering only the multi-criteria route network scenarios 3 and 4. The visualization of the modelled indicators from real route network is maintained, to have an additional point of comparison.

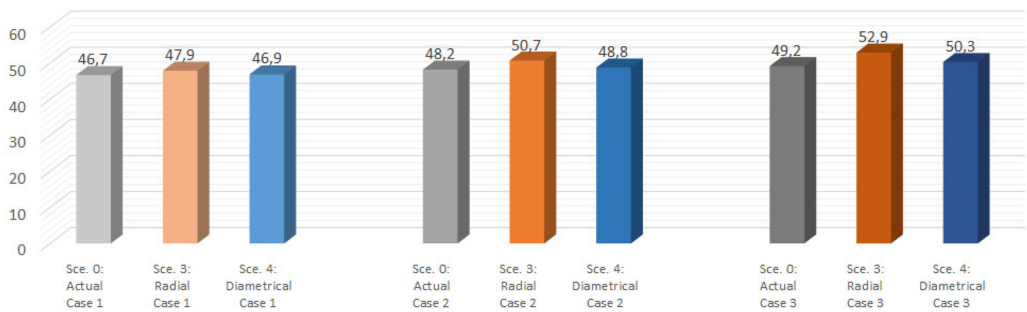

Figure 8: Average perceived travel times – F_U – per case and scenario (min).

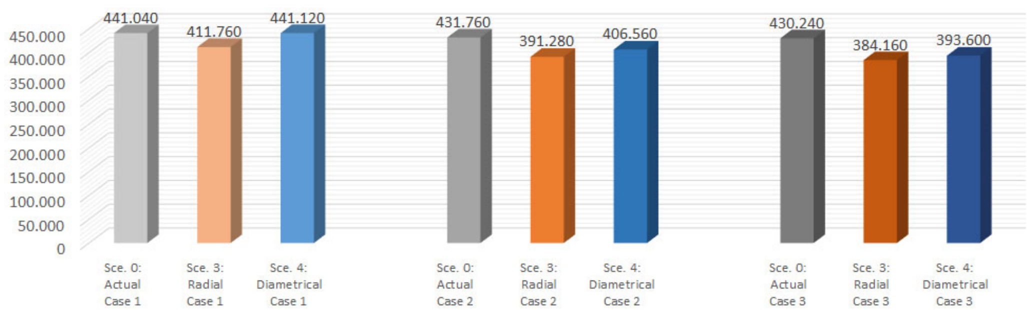

Figure 9: Minimum Required Fleet – N_{seats} – per case and scenario (Seats).

Figures 8 and 9 show the results for scenarios 0, 3, and 4, related to the average perceived travel time ($\boldsymbol{F}_{\boldsymbol{U}}$) and the total number of seats ($\boldsymbol{N_{seats}}$). Note that real routes scenarios are kept in gray tones, while the radial routes scenarios are shown in orange tones, and the diametrical routes scenarios are depicted in blue tones. Again, these tones get darker as transfers are more penalized.

Regarding perceived travel times, the route network with radial multi-criteria design has perceived travel times 5.2% greater than those of the real route network, on average. While the increase is 3.8%, on average, when compared to the route network with diametrical multi-criteria design. This is undoubtedly a product of the increase in the number of required transfers in a radial route scheme, in which a significant number of people are expected to make additional transfers at central interchange stations. Nevertheless, if the general results in Table 2 are considered, and if the net travel times are compared (net travel times without time weighting coefficients), the differences between the three assessed scenarios are reduced to the order of 1,0%. In other words, radial routes implementation does not significantly impact the net travel times, but it does on the times perceived by the user.

On the side of the minimum required fleet, the radial route network offers a savings of 8.9% in the number of seats concerning the real route network and 4.4% of savings compared to the network of diametrical routes. Again, this is highly significant in terms of investments in rolling stock, as fewer buses are required to meet demand; or in terms of user comfort, as it would be possible to schedule services with higher frequencies.

5. GUIDELINES FOR ROUTES DESIGN IN TRANSMILENIO

The foregoing discussion leads to the conclusion that the most recommended approach is to implement routes with radial and multi-criteria design guidelines: scenario 3. To give an explicit answer to the research question, the specific guidelines - radial and multi-criteria - that were applied to the design of the selected scenario are listed below:

- Geographical layouts:
    - Taking into account the current infrastructure of TransMilenio, today's day it is recommended to maintain a route network in which the diametrical design predominates. This is because the current infrastructure would not support the higher number of transfers at the central stations in the case of implementing radial routes, there is not enough space.
    - In the short term, a broader implementation of partial routes – routes starting and ending at intermediate stations, other than main portals – is recommended.

  - In the medium term, Bogotá's BRT system should migrate towards a radial route network that allows reducing the minimum required fleet to serve demand. This will require the construction of central interchange stations.

- Stop points:

  - In the medium term, central interchange stations must be implemented in certain geographical locations identified in this research. These stations must have capacity enough to serve passengers who make a transfer and allow buses operational return, in the case of implementing radial routes. Figure 10, on the next page, shows the identified places for this central stations and their passengers demand.
  - In the short term, it is recommended to expand the implementation of super-express services, both from main portals and from the intermediate stations with the highest demand.
  - In the short term, it is suggested to implement routes with asymmetric stop points for each direction, according to actual passenger flows.
  - In the short term, it would be convenient to test routes whose stops points are assigned to serve specific destination areas in the central corridors.

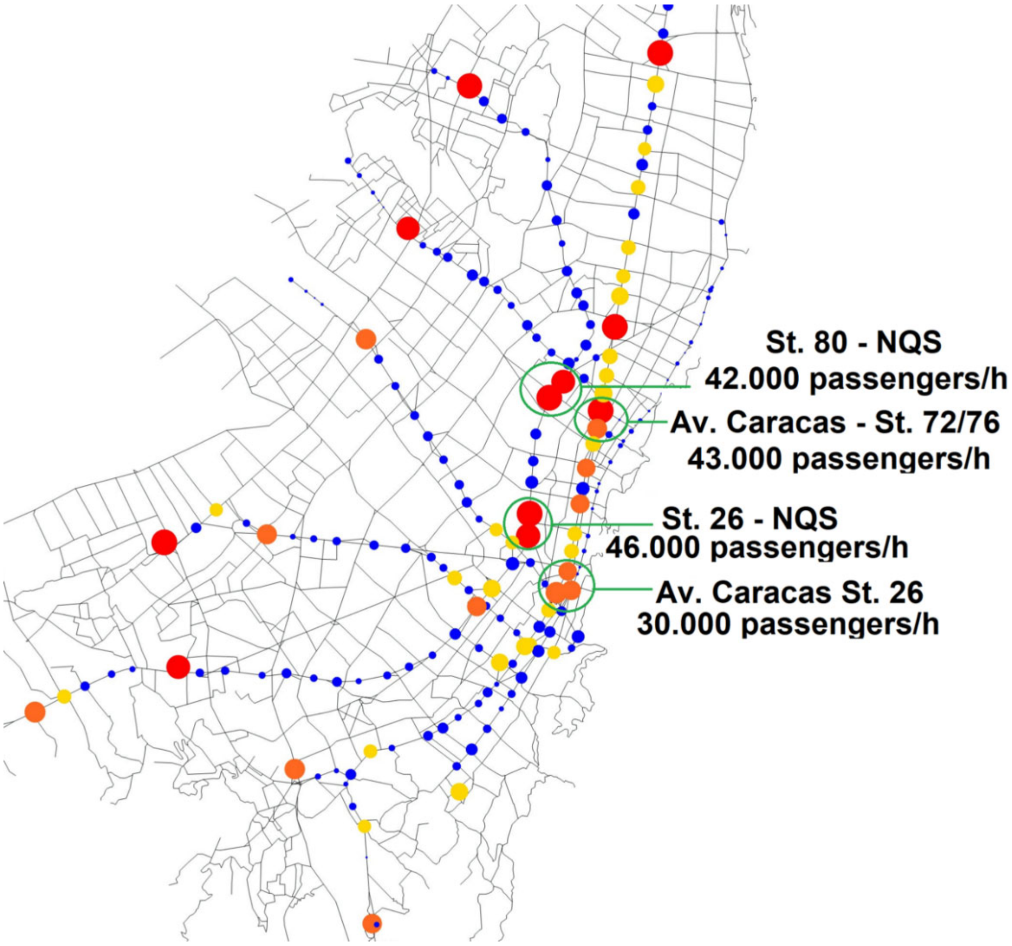

Figure 10: Location and stopping passengers of proposed central interchange stations.

- Frequencies:
    - It is not recommended to implement a route network that is too simple in Bogotá's BRT, since this would imply too short step intervals for the services, with its consequent effects on convoys formation and long lines of buses waiting at the stations. Scheduled intervals shorter than two minutes may be not suitable for actual operation.
    - The implementation of route networks designed with multi-criteria guidelines is recommended, so that the scheduled intervals are within reasonable limits – 2 to 7,5 minutes – for the rush hour operation of a BRT system such as TransMilenio. See Figure 11 at the end of the next page.

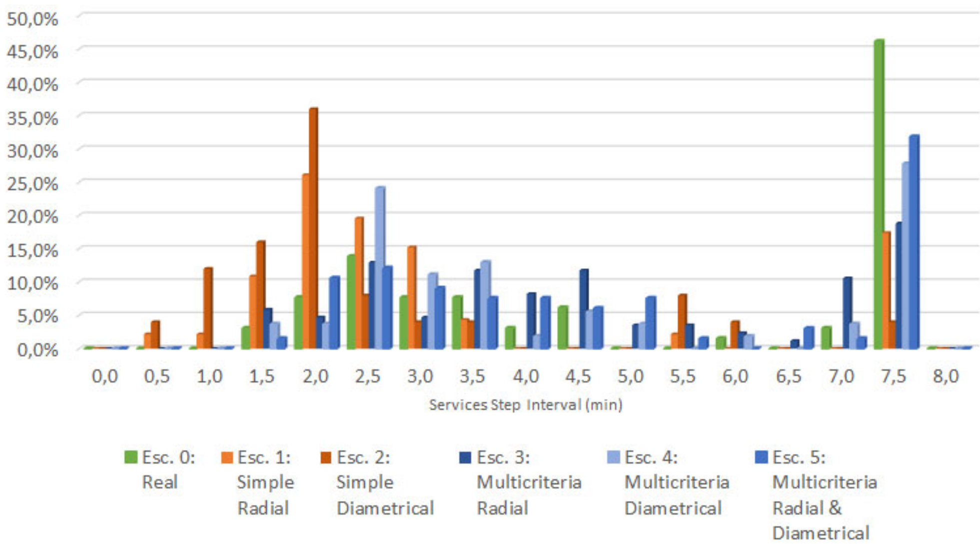

Figure 11: Percentual distribution of services scheduled intervals per scenario.

Finally, and as a reference, Figure 12 shows the route network scenario 3, which would be the most recommended: radial routes plus a multi-criteria design approach.

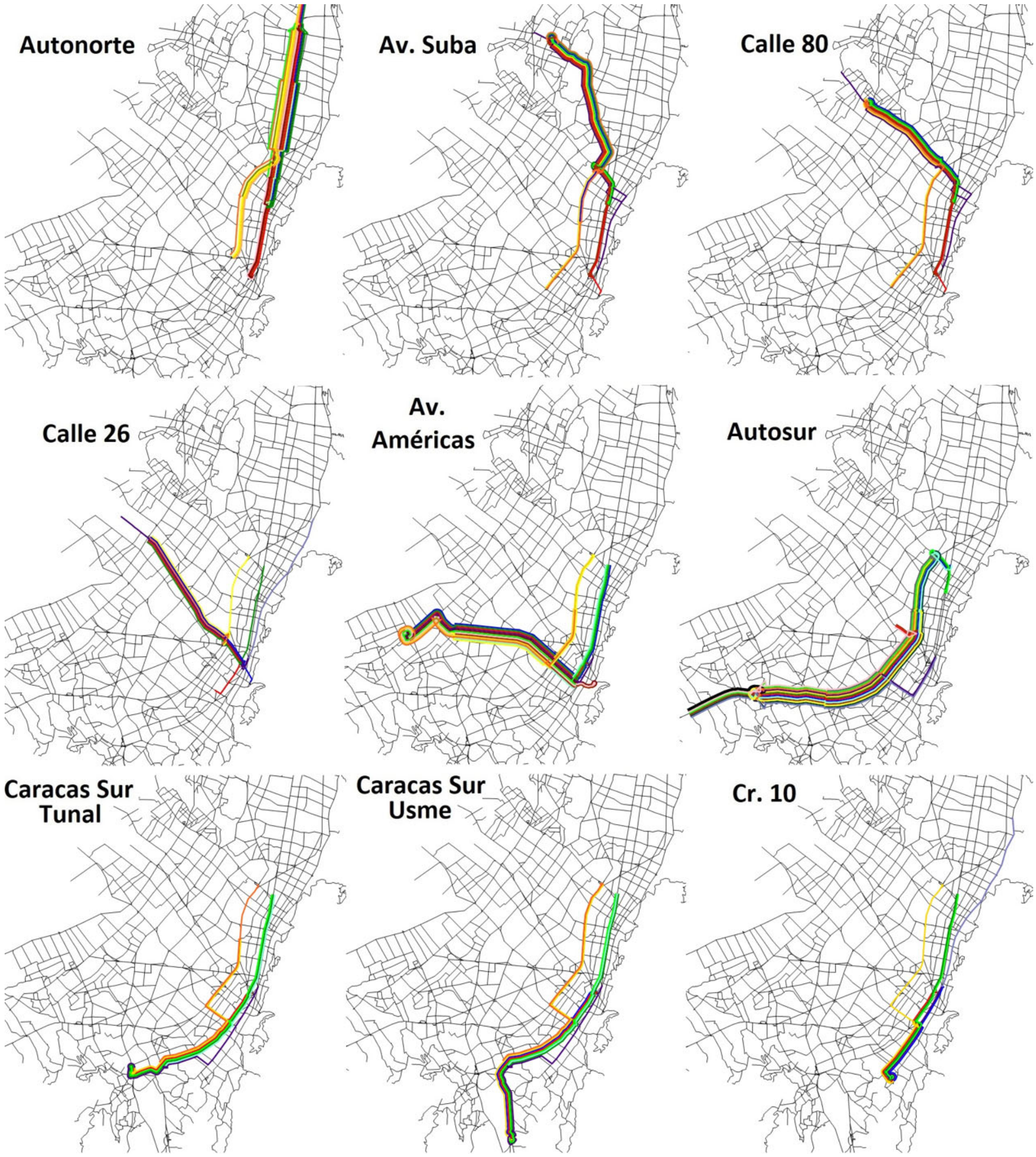

Figure 12: Scenario 3: radial route network with multi-criteria design approach.

6. CONCLUSIONS

Regarding the average perceived travel times, it has been shown that the multi-criteria design approach does not present significant advantages over the simple design approach. However, if the minimum required fleet is considered, the difference is more noticeable, with the multi-criteria approach achieving valuable seats savings. Compared to the scenario of the real route network of Bogotá's BRT, the multi-criteria approach results in slightly higher average perceived travel times. However, in terms of the average net travel times (without time weighting coefficients) the difference is negligible. As for the required fleet, the multi-criteria approach would allow, according to the simulations, significant savings in the number of seats compared to the real routes.

On the side of the comparison between multi-criteria radial routes vs. multi-criteria diametrical routes, the latter provide a slight improvement in average perceived travel times compared to their radial equivalents. However, the real route network would have slightly shorter perceived travel times than those on the multi-criteria diametrical route network. In any case, if the average net travel times are compared, again the difference between the real, radial multi-criteria, and diametrical multi-criteria route network scenarios is negligible. In addition, if the minimum required fleet is considered, the radial routes with a multi-criteria approach offer seats savings of 8.9% with respect to TransMilenio real routes, and 4.4% compared to the scenario of diametrical multi-criteria routes.

Considering the above, the main conclusion is that the scenario of radial multi-criteria routes would offer the best response to TransMilenio's needs. However, today's day it would not be possible to implement these radial routes without first building four central interchange stations that allow handling the higher flows of transferring passengers and returning buses in the expanded centre of the city.

6.1 Scope, limitations, and next steps

With respect to the research scope, these results are valid for Bogotá's BRT and its passengers demand before the pandemic. However, the developed methodology can be reproduced in any other BRT system around the world and can be scaled to cover the entire transportation system of Bogotá metropolitan area.

Among research limitations and next steps is the fact that possibly, once the pandemic ends, it will be necessary to re-evaluate the route network scenarios according to the new passenger demand after COVID-19. In addition, given that research results have been obtained through transport model simulations, these results are subject to the possible deviations of a model that merely emulates the real world. Thus, a real-life pilot in some BRT corridor would be convenient. It is also necessary to say that the transport model developed does not consider micro-simulation details of a traffic model, which development would be too helpful to assess the impact on BRT traffic due to the proposed guidelines.

AKNOWLEDGEMENTS

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ADAPTACIÓN DE SERVICIOS DE MOVILIDAD AL NUEVO ESCENARIO DE LA COVID-19: LA EXPERIENCIA DEL GRUPO ALSA CON EL PROGRAMA "ALSA MOVILIDAD SEGURA"

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RESUMEN

Uno de los retos más importantes para administraciones y operadores de transporte público de viajeros está siendo abordar los efectos de la Covid-19 y adaptar la oferta de servicios y su financiación a una realidad de movilidad muy distinta a la conocida hasta 2019.

Las expectativas de los viajeros han cambiado y los transportes colectivos están muy penalizados frente al coche privado por la percepción del viaje seguro.

En 2020 el Grupo ALSA desarrolló el programa “Alsa Movilidad Segura”, diseñado e implementado en plena pandemia. Este programa ha ido más allá de cumplir normas y recomendaciones sanitarias, y se orienta a ofrecer una experiencia de viaje segura, para los clientes y los empleados. El programa es objeto de mejora continua, con iniciativas que se van incorporando semana a semana a partir de los insights de clientes y el benchmarking de otros modos y sectores.

“Alsa Movilidad Segura” tiene como objetivo convertir el autobús en un espacio seguro para viajar, mitigar los riesgos derivados de la Covid-19 y ofrecer las máximas garantías y confianza a los clientes en todos los servicios.

La recuperación de la movilidad del transporte público va a ser un proceso lento y progresivo en el tiempo. Con umbrales de mercado inciertos y que dependerán de factores exógenos a los propios operadores y a las administraciones, como pueden ser la recuperación económica y del turismo, la consolidación del teletrabajo a medio y largo plazo, el comercio on-line, la enseñanza a distancia, etc.

La experiencia del programa “Alsa Movilidad Segura” nos está permitiendo identificar cambios en las percepciones y hábitos de viaje de nuestros clientes, y en base a estos insights adaptar en lo posible nuestra oferta de servicios de movilidad.

1. SITUACIÓN DE PARTIDA Y CONTEXTO DEL PROYECTO

ALSA es la mayor empresa operadora de servicios de transporte público de viajeros en España. En 2019, año inmediatamente anterior a la pandemia, transportó 393 M de viajeros/año, con 15.487 empleados, 4.446 vehículos y una facturación de 941 M€.

La compañía está presente en todo el territorio nacional, gestionando más de 150 contratos de servicios públicos de movilidad. Además, ALSA aborda un importante proceso de internacionalización, con presencia consolidada (entre otros países) en mercados de Marruecos, Suiza, Portugal, Francia y Puerto Rico.

Al igual que otros operadores de movilidad, esta compañía se vio impactada súbitamente desde marzo de 2020 por el impacto de la Covid-19. La afección ha sido gravísima (cierre 2020) con una caída del -62% en la demanda de las líneas interurbanas de la compañía y más de 100 M€ de pérdidas en el ejercicio. Los siguientes datos publicados por el Instituto Nacional de Estadística (INE) evidencian la gravedad de las caídas de movilidad interior en el transporte público, afectando a todos los modos y segmentos de viajes. Es especialmente significativa la caída de los viajes interurbanos (y la movilidad no obligada en general).

	Viajeros transportados (miles)	% de variación Año 2020
TOTAL	2.691.617	-46,7
Transporte urbano	1.680.181	-45,8
Metro	672.741	-47,3
Autobús	1.007.440	-44,8
Transporte interurbano	754.786	-46,9
Autobús	397.327	-45,5
Cercanías	288.675	-44,9
Media distancia	102.616	-46,0
Larga distancia	6.036	-61,4
Ferrocarril	334.896	-47,4
Cercanías	308.328	-45,8
Media distancia	14.748	-55,6
Larga distancia	11.888	-65,6
AVE	7.603	-66,0
Resto Larga Distancia	4.285	-64,8
Aéreo (interior)	16.910	-60,5
Peninsular	5.507	-67,7
Peninsular-Resto territorio	8.360	-58,5
Interinsular	3.043	-46,1
Marítimo (cabotaje)	5.611	-52,1
Transporte especial y discrecional	256.649	-51,6
Especial	204.053	-35,8
Discrecional	52.596	-75,2

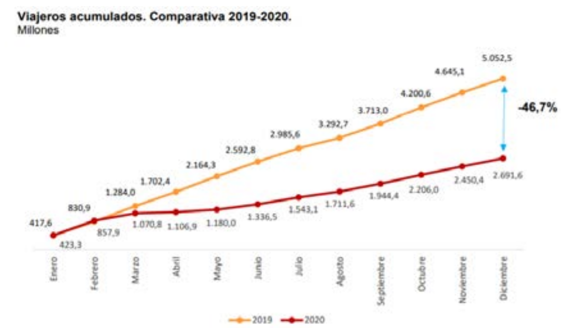

Figura 1: Datos de evolución de la demanda de los transportes públicos en España, cierre 2020 (INE).

El impacto negativo continúa 2021. Es previsible que la incidencia perdure todavía muchos meses y los umbrales de recuperación efectiva a conseguir son todavía muy inciertos.

Es significativo que la Covid-19 está afectando muy distinto a los transportes públicos y al vehículo privado. Los estudios e indicadores de movilidad publicados durante la pandemia, en muchos casos basados en técnicas de big-data con telefonía móvil (MITMA, INE Experimental, Ayuntamientos), coinciden en señalar que la movilidad general se recupera a tasas comparativamente más altas que la recuperación de los transportes colectivos (autobús, tren, metro). Esto evidencia un desajuste a la baja en la cuota de mercado del transporte público, que de continuar en el corto y medio plazo puede poner en riesgo los objetivos globales de sostenibilidad y minoración de emisiones.

Subyace un problema de falta de confianza de los usuarios hacia los transportes colectivos, lo cual ha podido constatar el Grupo ALSA en las investigaciones de mercado realizadas en el marco del programa “Alsa Movilidad Segura”.

2. OBJETIVOS Y METODOLOGÍA DE TRABAJO

El objetivo principal de este programa es convertir el autobús en un espacio seguro para viajar, mitigando los riesgos derivados de la Covid-19 y ofreciendo las máximas garantías y confianza a los clientes y empleados en todos los servicios.

Para el diseño e implementación de “Alsa Movilidad Segura”, especialmente en los primeros meses de la pandemia, el Grupo ALSA siguió las normas y recomendaciones de las autoridades sanitarias, laborales y de transporte, así como buenas prácticas observadas en otros sectores a través de la realización de un benchmarking nacional e internacional.

Una característica diferencial de “Alsa Movilidad Segura” ha sido ir más allá de estas normas y recomendaciones. Una vez cumplidas éstas, a modo de mínimos, la prioridad es ir más allá y definir una experiencia de viaje nueva, basada en el viaje seguro y confiable.

Sobre esta premisa, el programa “Alsa Movilidad Segura” se diseñó a partir del Pasillo del Cliente de ALSA (customer journey), herramienta desarrollada e implantada desde hace años en la compañía y que tiene en cuenta todos los momentos de interacción con los clientes (antes, durante y una vez finalizado el viaje). Con la intención de transformar y mejorar el Pasillo del Cliente al nuevo contexto de la Covid-19. Ofreciendo para ello garantías y compromisos de viaje seguro en todas las fases del servicio, y sobre la base del conocimiento del cliente de que dispone la compañía (insights de encuestas y otras técnicas de investigación de mercados) en las fases del Pasillo.

El Pasillo del Cliente es una representación de las fases por las que atraviesa un cliente en su proceso de concienciación, información, elección, compra, uso y valoración de cualquier bien o servicio. Es una herramienta que racionaliza el proceso mental subjetivo de las personas a la hora de consumir, identificando sus preferencias y necesidades, y detectando los puntos más importantes en el proceso, sobre los que actuar para conseguir una mejora efectiva en las ratios de compra y satisfacción con el consumo realizado.

La siguiente imagen representa el Pasillo del Cliente de ALSA para servicios interurbanos. La compañía aplica además esta metodología para servicios urbanos y metropolitanos. Su desarrollo es fruto de un importante esfuerzo de estudio y conocimiento de clientes, a través de encuestas (presenciales y on-line), dinámicas de grupo, literales de clientes (sugerencias, reclamaciones) y auditorías visión cliente. El Grupo ALSA trabaja con métricas e indicadores de calidad percibida, siendo los principales el "Customer Satisfaction Index" (ISC), "Net Promoter Score" (NPS), "Value for Money" (VFM") y "Net Emotional Value" (NEV).

Figura 2: Pasillo del Cliente del Grupo Alsa (servicios interurbanos).

El programa "Alsa Movilidad Segura" partió del Pasillo del Cliente, y sobre esta base se trabajan (mejora continua) iniciativas para mejorar la percepción del viaje seguro en todas las fases, siempre desde la perspectiva del viajero: información y venta, tránsito en estaciones y dársenas, embarque en el vehículo, cartelería y señalética, ventilación interior, limpieza y desinfección, medidas de protección de empleados, por citar las más significativas.

El programa se diseñó y comenzó a implantarse a través de 15 áreas de trabajo, que resumimos a continuación y que actualmente siguen vigentes:

Alsa Movilidad Segura		
Nuevos estándares de servicio	Protocolos y procedimientos	Equipos de Protección
Adecuación de flota	Adecuación de instalaciones	Servicios a bordo y estaciones
Canales de compra	Información a los clientes	Comunicación y marketing
Limpieza y desinfección	Formación y concienciación	Comunicación con Reguladores
Garantías de ejecución efectiva	Certificación y homologación	Insights de los clientes

Figura 3: Áreas de trabajo del programa "Alsa Movilidad Segura".

Para su desarrollo se ha creado un equipo de trabajo transversal, que afecta a todos los departamentos de la compañía, empleando metodologías colaborativas de design thinking y co-creación. En el proyecto están implicadas más de cien personas de forma directa, en el diseño e implantación de las medidas, a los que se añade la totalidad del personal operativo (incluyendo más de 5.000 conductores y personas con trato directo al cliente) en su aplicación final al servicio. El proyecto se ha llevado a cabo gracias al alineamiento de toda la compañía, siendo una iniciativa liderada por la alta dirección de ALSA (CEO, DG España y Direcciones de Negocio) desde sus inicios. La coordinación del programa se asume desde la dirección de Estudios y Licitaciones de ALSA, en la que se integran las áreas funcionales de insights de clientes, experiencia de viaje y mejora de servicios. Este planteamiento asegura la orientación del programa a la satisfacción de necesidades de los viajeros y a la mejora continua de la oferta de servicios.

Las metodologías aplicadas de design thinking y trabajo colaborativo permiten que, una vez identificada una posible mejora o actuación en cada área, el equipo responsable la evalúa y prioriza, poniendo en marcha su implantación en el menor tiempo posible.

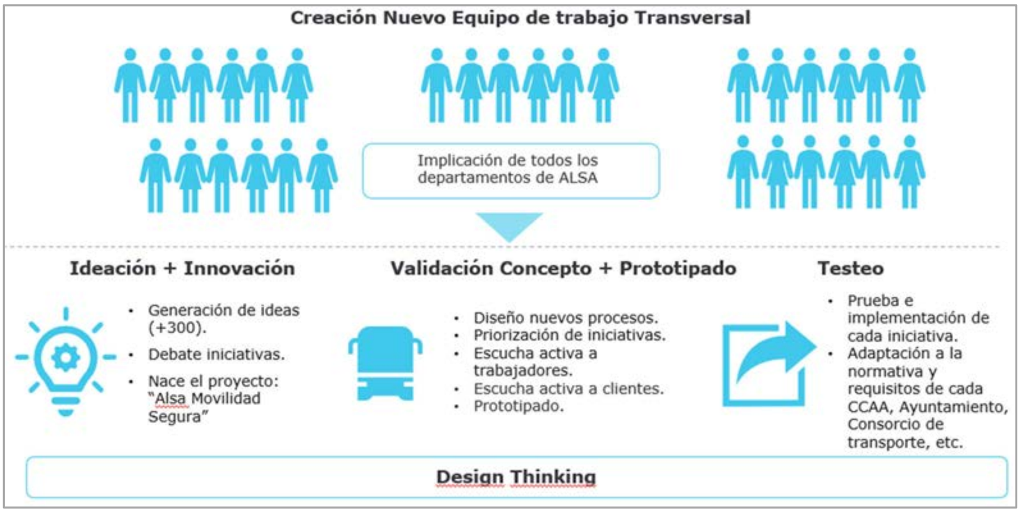

Figura 4: Proceso de diseño y validación de las mejoras.

3. DESARROLLO DEL PROYECTO

El programa "Alsa Movilidad Segura" se traduce en la definición de cinco estándares específicos, para cada una de las tipologías de servicios de la compañía: "urbano-metropolitano", "regional", "larga distancia", "discrecional" y "turísticos". Estos estándares son normas de aplicación obligada y están implantados ya al 100%.

Hasta la fecha se han introducido más de cien iniciativas de mejora a lo largo del Pasillo del Cliente, relacionadas todas ellas con el viaje seguro (mejora de la seguridad de clientes y empleados) y afectando no sólo a la operativa si no, también, a la información y comunicación de los servicios.

A continuación, se muestra el desglose de las 114 iniciativas implantadas en el marco del programa a fecha de elaboración de esta ponencia. Para su comprensión, se presentan diferenciadas para cada una de las fases del Pasillo del Cliente ("decisión y compra", "gestión previa", "estación/parada", el "viaje" y el "post-viaje"); y en función de la dimensión afectada por la iniciativa ("comunicación", "clientes", "empleados", "procesos").

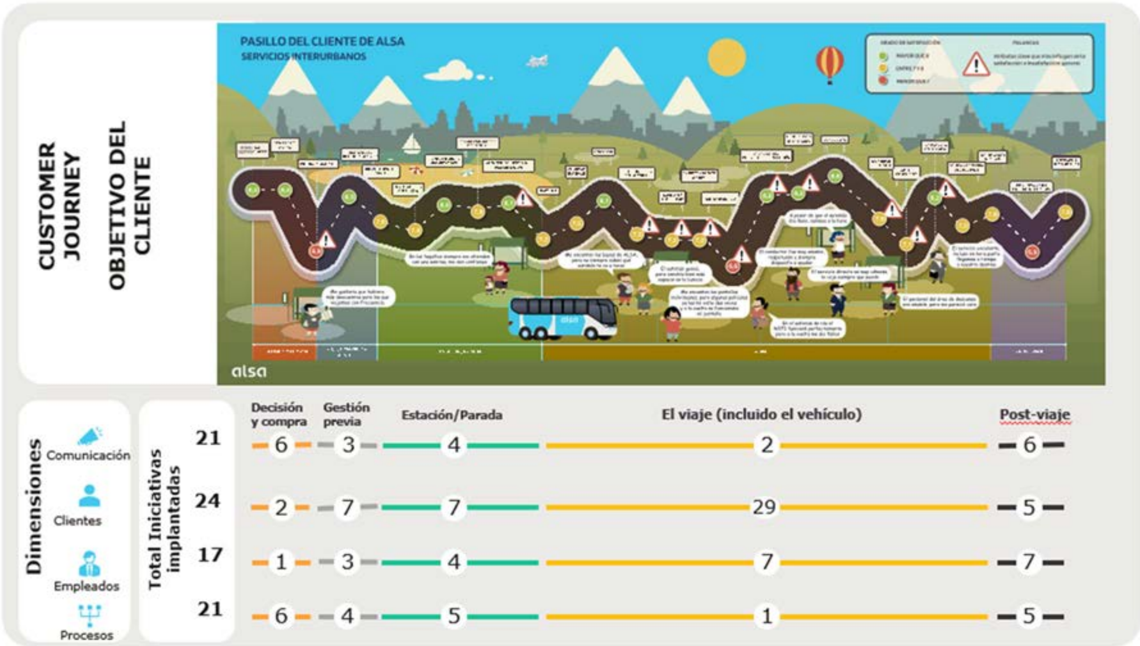

Figura 5: Desglose de las iniciativas implantadas en el programa "Alsa Movilidad Segura", alineadas con el Pasillo del Cliente.

Además, cada iniciativa se extiende a toda la compañía, incluyendo (hasta la fecha) la realización de acciones de formación para 7.380 empleados, la dotación de equipos de protección y mejora para 5.427 conductores, dotación de elementos de mejora en 2.981 vehículos, actuaciones en web y apps, y mejoras en todas las estaciones y puntos de parada.

Una característica determinante del programa es su mejora continua e iterativa, basada en la interacción con clientes y en los insights que se van identificando a nivel diario y semanal con técnicas de investigación de mercados.

Una vez implantada la primera fase del programa (ideación, definición de estándares y protocolos, acopios de elementos, primeras implantaciones, formaciones a empleados), se diseñó un modelo de mejora continua del mismo, basado en:

- el feedback de clientes (encuestas, literales)
- la realización de auditorías visión cliente (para evaluar la implantación de las mejoras a todos los niveles y en todos los ámbitos geográficos);
- benchmarking permanente de nuevas medidas implantadas en otros sectores y países; y
- análisis de nueva normativa y estándares internacionales.

Resumimos a continuación las magnitudes de los insights que hemos recogido en el programa "Alsa Movilidad Segura" en su primer año de implantación, que dan idea de la magnitud y complejidad del proyecto y de su fundamentación en la opinión de los clientes.

Figura 6: Principales insights de clientes utilizados como fuente de información para la mejora continua del programa “Alsa Movilidad segura” (marzo 2020 - abril 2021).

Sobre esta importante base de conocimiento, actualizada a nivel diario y semanal (encuestación post-viaje diaria), se trabaja de manera continua, adaptativa e iterativa para cumplir y superar unos estándares siempre cambiantes, y satisfacer así las expectativas de movilidad segura en el contexto de pandemia.

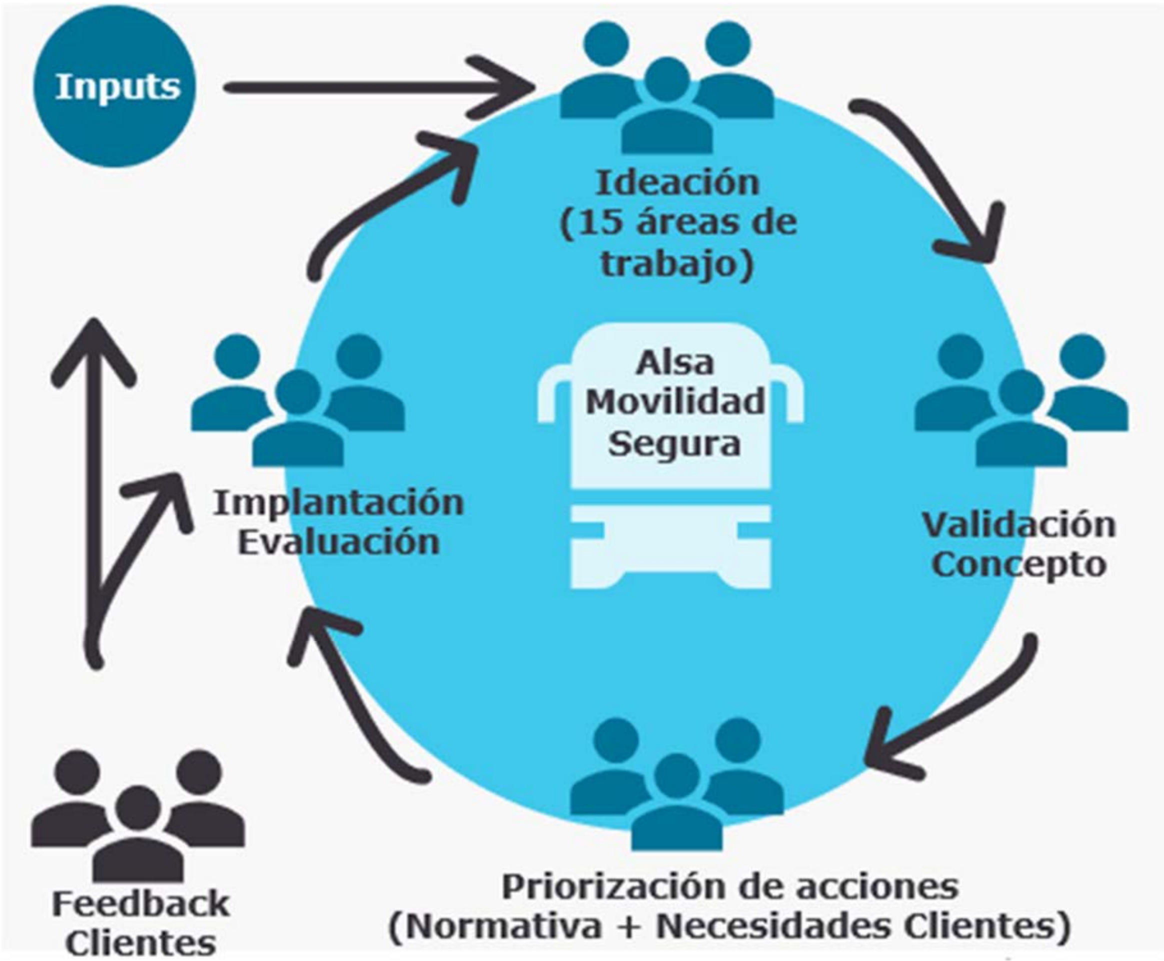

Figura 7: Proceso de mejora continua y adaptación de los estándares de servicio.

4. INICIATIVAS IMPLANTADAS

Detallamos a continuación algunos ejemplos de mejoras implantadas en el marco del programa “Alsa Movilidad Segura”, para ofrecer una experiencia de viaje con las mayores garantías de seguridad.

Fase previa al viaje:

- Información al cliente. Se ha implementado una nueva landing en la web www.alsa.es con recomendaciones para los viajeros, incluyendo además información sobre todas las medidas implantadas por la compañía para garantizar el viaje seguro.
- Mapa interactivo en la web sobre restricciones COVID a nivel nacional, en todas las CCAA y provincias.
- Nuevo formato de los títulos de transporte incluyendo con información sobre normas y recomendaciones a la hora de viajar.
- Se ha potenciado la compra por canales digitales.
- Se han flexibilizado las condiciones de cambios y anulaciones de billetes.
- Numerosas mejoras en la información en estaciones y paradas.
- Se han implementado nuevos protocolos de embarque, minimizando además el pago en efectivo a bordo.

Figura 8: Ejemplo de nueva landing “Alsa Movilidad Segura” con toda la información sobre las medidas implantadas y las recomendaciones de viaje.

Durante el viaje:

- Nuevo protocolo de ventilación interior que, junto con los sistemas de climatización y aire acondicionado de última generación de los vehículos, permite garantizar la máxima renovación de aire interior, forzando su renovación con aire exterior.
- Realización de estudios técnicos y mediciones de calidad del aire interior en los (interurbanos, metropolitanos y urbanos), empleando técnicas de sensorización monitorización on-line. Cada 2-3 minutos se renueva completamente el aire del habitáculo de pasajeros con aire procedente del exterior.
- Purificadores de aire y filtros de carbón bioactivo. Se han instalado purificadores de aire y filtros de carbón bioactivo que eliminan el 99% de partículas y destruyen contaminantes biológicos como bacterias y virus.
- Nuevo sistema de desinfección. Se ha desarrollado junto con BIOW un nuevo sistema de desinfección complementaria del aire interior, que cuenta con un filtro azul antibacteriano, un filtro "Hepa", un filtro de carbón activado, doble luz UV antibacteriano y un ionizador de plasma.
- Lámparas de luz ultravioleta en WC. En los servicios de largo recorrido se han instalado lámparas de luz ultravioleta "tipo C" para la desinfección automática de los WC después de cada uso. Así se consigue llegar a todos los rincones del habitáculo, destruyendo los virus y bacterias en cuestión de minutos
- Dispensadores de gel hidroalcohólico. Numerosos servicios cuentan con dispensadores de gel hidroalcohólico en accesos para su uso por los viajeros.
- Retirada de alfombras. Se han retirado las alfombras de los vehículos para facilitar las labores de limpieza y desinfección
- Entrega de toallitas o kits higiénicos. En servicios de largo recorrido se entregan toallitas o kits higiénicos a los pasajeros.
- Cartelería y elementos multimedia. Todos los vehículos cuentan con cartelería y elementos multimedia con las normas y recomendaciones de viaje
- Limpieza y desinfección. Se han reforzado las medidas de desinfección en los autobuses. Mediante un estricto protocolo, complementado con técnicas novedosas como la micropulverización, se garantiza una limpieza y desinfección profunda de los vehículos con periodicidad mínima diaria. Se presta especial atención a los elementos de mayor contacto como: pulsadores de acceso, asideros, pasamanos, reposabrazos, respaldo y cabecero de las butacas, bandejas individuales, WC, etc.

Figura 9: Ejemplos de cartelería y elementos informativos implantados en el programa “Alsa Movilidad Segura”.

5. RESULTADOS QUE ESTAMOS OBSERVANDO

El programa tuvo una implantación muy rápida, en su primera fase, que permitió llegar a tiempo a la compañía para el levantamiento del primer estado de alarma (junio 2020), con un producto mínimo viable que progresivamente está siendo objeto de mejoras. Gracias al arranque rápido, ALSA fue la primera compañía del sector de la movilidad en España en obtener el Certificado de Buenas Prácticas contra la Covid-19 de AENOR (Asociación Española de Normalización y Certificación). Esta acreditación conlleva además una auditoría periódica, lo que garantiza la implantación efectiva de las medidas. Además, también ha obtenido el sello “Safe Tourism” del ICT (Instituto de Calidad Turística).

Figura 10: Sellos y estándares obtenidos por “Alsa Movilidad Segura”.

El reto principal del programa, como se comentó, persigue recuperar la confianza del cliente en el transporte público, y en concreto en el modo autobús, a la hora de viajar. Para tener indicadores continuos de la percepción del viajero, ALSA ha adaptado las metodologías de insights de clientes a este nuevo contexto, implementando varias mejoras en sus procesos de investigación de mercado:

- Introducción de una nueva pregunta específica en la encuesta post-viaje, relativa a valoración de medidas de “Alsa Movilidad Segura” (escala de 0 a 10) y percepción general de la seguridad del viaje. Ofreciendo además a los viajeros la posibilidad de que responder mejoras o sugerencias de tipo cualitativo si lo desean.
- Lanzamiento de encuestas específicas de caracterización del perfil de cliente, necesidades de viaje y hábitos de movilidad a corto-medio plazo. Desarrolladas en diferentes momentos temporales durante la pandemia, y permitiendo observar una evolución en el comportamiento del cliente.
- Nuevo reporte de indicadores diarios de satisfacción, incluyendo conclusiones de indicadores relativos del programa “Alsa Movilidad Segura”, facilitando el acceso rápido a la información (decalaje de 3-5 días entre las fechas de encuesta y de remisión del dato) y agilizando la toma de decisiones derivada.
- Auditorías visión – cliente para verificar el cumplimiento efectivo de todas las mejoras implantadas.
- Numerosas acciones de concienciación y formación de la plantilla, basadas en la opinión del cliente y las mejoras de servicio implementadas.

Los resultados de este proceso de aprendizaje y mejora continua, que toma como base la opinión de los clientes y los propios empleados que tienen contacto directo con el servicio, están siendo muy positivos y permiten extraer conclusiones claras sobre los efectos de la pandemia sobre la movilidad y las necesidades de mejora en el corto y medio plazo.

A modo de ejemplo, el siguiente gráfico resume las mejoras solicitadas por clientes que hacen uso de los servicios (encuesta post-viaje diaria a viajeros de líneas regulares interurbanas). Se observa claramente la importancia que tienen, en el momento actual, las medidas que aseguren una mayor distancia entre viajeros a bordo y las limitaciones en la capacidad de plazas ofertadas en vehículos.

Ambas medidas tienen una traslación directa e implicaciones sobre el coste de funcionamiento de los transportes públicos, y su puesta en marcha trasciende del ámbito de decisión de los operadores al afectar el equilibrio económico de los contratos. Podemos concluir no sólo que la demanda del transporte público se ha contraído en su vertiente cuantitativa, sino que además los clientes que necesitan estos servicios tienen prioridades y consideraciones nuevas a la hora de elegir el modo con el que viajar.

Las variables cualitativas del viaje, perceptuales y emocionales, son determinantes en el contexto actual, y deben ser tenidas en consideración por las administraciones reguladoras y las empresas prestadoras de los servicios de movilidad.

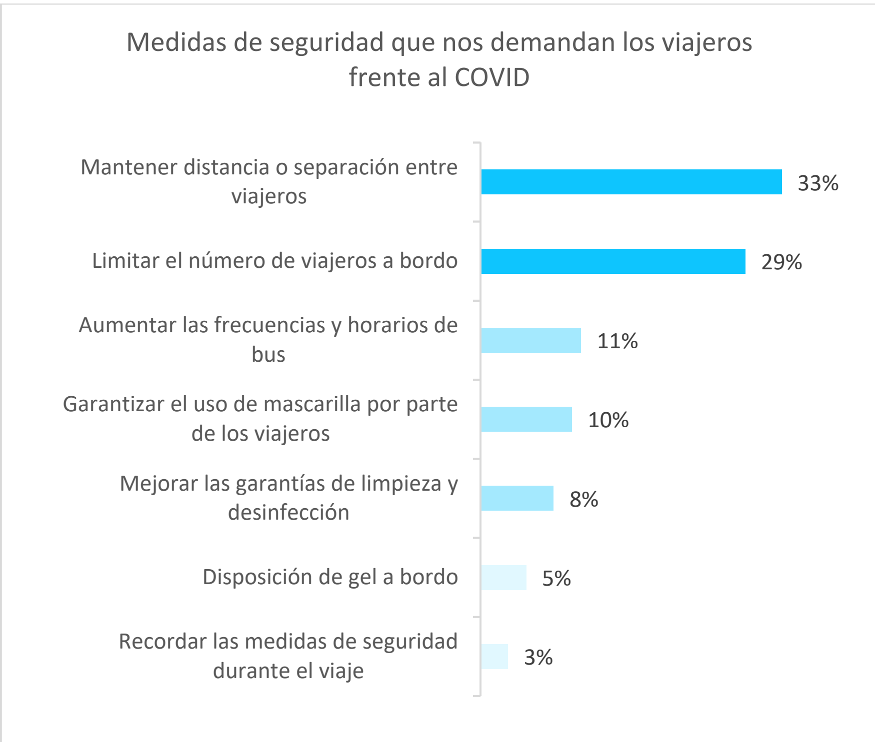

Figura 11: Medidas de seguridad que demandan los viajeros frente a la Covid-19 (resumen de respuestas de clientes de ALSA en la encuesta post-viaje diaria realizada en trayectos interurbanos 2020-2021).

6. CONCLUSIONES

La evolución de la pandemia ha constatado el valor estratégico del programa "Alsa Movilidad Segura", gracias al cual la compañía está consiguiendo recuperar progresivamente la confianza de los clientes en el transporte público, en los contratos de servicios de movilidad que gestiona a nivel nacional.

La iniciativa se desarrolla en un entorno de gran complejidad por las restricciones en los servicios públicos de movilidad y la reducción de oferta de servicios (cierres perimetrales, prohibición de la movilidad interurbana) que penalizan en gran medida la calidad percibida.

Gracias a este programa, ALSA ha implementado una propuesta nueva de valor de los servicios, basada en el viaje seguro y con garantías en todas las etapas del Pasillo del Cliente. El impacto de la pandemia continúa y va a perdurar muchos meses. "Alsa Movilidad Segura" es un programa vivo, que evoluciona implantando acciones nuevas basadas siempre en la opinión de clientes y empleados.

El programa se ha considerado un referente en el sector, y ha tenido múltiples reconocimientos de nuestros reguladores (incluyendo el Ministerio de Transportes, Movilidad y Agenda Urbana). En 2020 ALSA obtuvo el Sello BCX 2020 a "Mejor empresa de transporte de España".

Se han introducido nuevas métricas de valoración de medidas frente a la Covid-19, con seguimiento diario.

"Alsa Movilidad Segura" está permitiendo recuperar progresivamente los indicadores de satisfacción (ISC, NPS, VFM, NEV). Los ratios actuales son todavía inferiores a los registrados antes de la pandemia, si bien la calidad percibida está mejorando desde el peor momento vivido en el otoño de 2020 tras la proclamación del segundo estado de alarma.

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VEHÍCULOS, MATERIAL MÓVIL, AUTOMOCIÓN Y EQUIPOS
VEHICLES, AUTOMOTIVE AND EQUIPMENT

APLICACIÓN DE LAS REGIONES DE ESTABILIDAD ($\boldsymbol{R-\beta}$) AL DISEÑO DE VEHÍCULOS

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RESUMEN

En nivel de seguridad de los vehículos se ha incrementado significativamente en los últimos años gracias al desarrollo e implementación de sistemas electrónicos que suplen o complementan al conductor. Sistemas cómo el ABS (antibloqueo de ruedas durante la frenada), el ESP (control de estabilidad) o AYC (control de la guiñada) monitorizan la respuesta dinámica para predecir y actuar en situaciones de riesgo.

Una de las herramientas utilizadas por estos sistemas para monitorizar la respuesta dinámica es lo que se conoce como regiones de estabilidad, también denominadas regiones r–β (velocidad de guiñada-deriva del vehículo). Estas regiones permiten definir los límites de estabilidad de los vehículos.

El trabajo propuesto plantea utilizar esas regiones en la fase de diseño, buscando como objetivo su maximización. Son varios los elementos constructivos de un vehículo que tienen influencia en estas regiones, como puede ser el sistema de suspensión (muelles, amortiguadores...), los neumáticos o el sistema de dirección. En este trabajo, se analiza la influencia de los elementos elásticos del sistema de suspensión, definiendo la configuración óptima para un vehículo y condición operativa concreta. Para ello, se utiliza un modelo completo del vehículo implementado en un software de simulación multicuerpo (MSC Adams/View®) y se aplican diferentes técnicas de optimización.

1. INTRODUCCIÓN

Cuando un vehículo se pone en movimiento y circula está sometido a la interacción con el entorno, la vía, otros vehículos, etc, se genera una “demanda” de seguridad activa. Esa demanda, condicionada por las acciones del conductor, deberá ser inferior a los límites para que la circulación vial sea segura para todos los usuarios.

Estos límites son función de las condiciones de la carretera (el pavimento, agentes externos como una mancha de aceite o la meteorología), del neumático (desgaste, temperatura, etc), del tipo de conducción que se lleve a cabo, del estado del vehículo, entre otros (Luque y Mántaras, 2007), Figura 1.

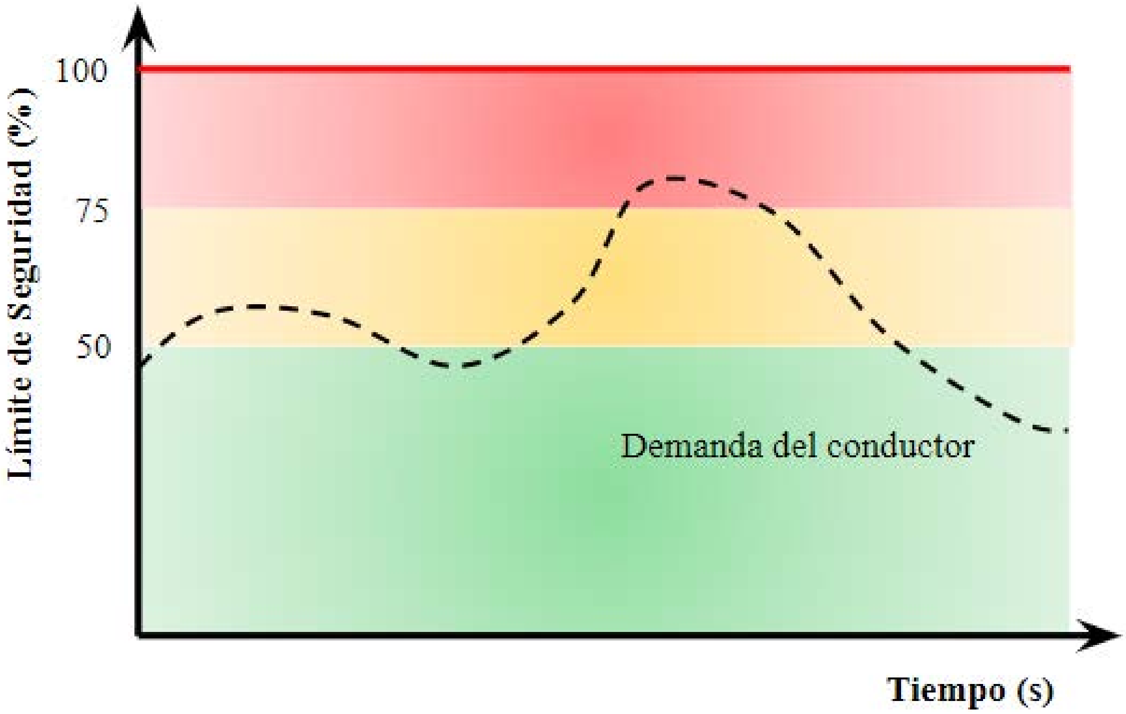


Figura 1: Evolución de la demande de seguridad en conducción y representación de los márgenes de seguridad disponibles en cada instante de tiempo.

De todos los factores que tienen influencia en la seguridad en carretera, uno de los más importantes es el vehículo y su comportamiento dinámico.

Entre los diferentes sistemas que componen un vehículo, los sistemas de suspensión y de dirección (Allonca, 2019) son la base de la respuesta dinámica del vehículo, por lo que su diseño, desde el punto de vista de la seguridad, es clave para mejorarla.

En un sistema de suspensión, son muchos los componentes que se pueden modificar para conseguir variar el comportamiento del vehículo, desde amortiguadores, muelles o silentbloks, hasta la geometría de la suspensión o los neumáticos.

En este artículo se analizará, desde el punto de vista de la seguridad, la influencia de las rigideces de los muelles de suspensión del vehículo (delanteros/traseros) y el coeficiente de amortiguamiento de los amortiguadores (delanteros/traseros), en función de variables operativas como la velocidad y la carga.

Para ello, se analizarán variables de estado como las aceleraciones longitudinal y lateral, la velocidad lateral, los ángulos de deriva, o las velocidades de cambio de los mismos y, en base a las líneas de trabajo abiertas junto al funcionamiento de los sistemas de control de vehículos, se utilizará un métrico objetivo que permite conocer el nivel de seguridad disponible (Alonso, 2019) a partir de las denominas Regiones de Estabilidad (Bobier, 2012; Beal, 2013; Bobier y Gerdes, 2013; Erlien, 2015) obtenidas a partir de los parámetros r-β (yaw rate-slip angle), Figura 2.

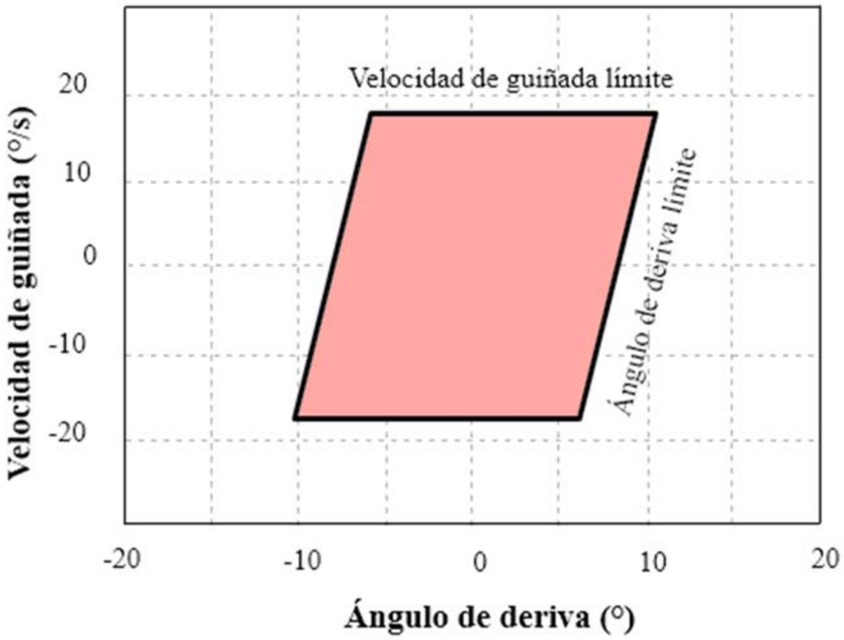


Figura 2: Región de estabilidad definida a partir de los valores límites de la velocidad de guiñada y del ángulo de deriva del vehículo.

Estas regiones de estabilidad dependen de la configuración de carga, de la velocidad de circulación y de la adherencia entre el neumático y la carretera (parámetro que no se tendrá en consideración en este análisis). Por tanto, con su utilización son varios los parámetros que se tienen en cuenta, y que afectan de manera significativa al comportamiento dinámico del vehículo.

2. METODOLOGÍA

2.1 Modelo virtual de vehículo

Para la realización de los ensayos se ha utilizado un modelo 3D, implementado en el programa de simulación dinámica multicuerpo MSC Adams View® y validado para reproducir fidedignamente el comportamiento dinámico del vehículo real, Figura 3.

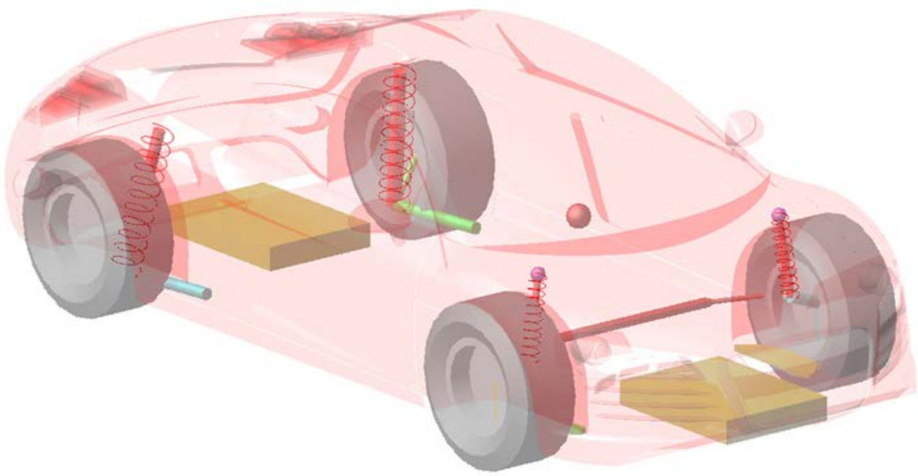


Figura 3: Modelo virtual utilizado para los ensayos de Ramp Steer

Se trata de un modelo con 16 grados de libertad y 21 partes móviles, con una suspensión delantera tipo Mcpherson y trasera independiente de brazos arrastrados.

Las características iniciales del vehículo, y que a posteriori se modificarán para el estudio de optimización, se indican a continuación, Tabla 1:

Masa OM (kg)	% Peso Delante	% Peso Detrás	L1 (m)	L2 (m)	Batalla (m)	Ancho Vías (m)	Kd (Nm)	Kt (Nm)	ξd (Ns/m)	ξt (Ns/m)
1642,8	59,7	40,3	1,07	1,57	2,64	1,6	33000	44000	2200	2000

Tabla 1: Carcaterísticas geométricas del vehículo utilizado

Para analizar la influencia de los parámetros en el comportamiento dinámico del vehículo, y así conocer el nivel de seguridad disponible en el vehículo, se realizan ensayos de tipo step-steer. Éstos consisten en introducir en la dirección un ángulo de volante determinado en un tiempo concreto, Figura 4, de forma que se puede analizar tanto la respuesta transitoria del vehículo como la permanente y, con ello, los efectos de la transferencia de carga debida a los elementos del sistema de suspensión.

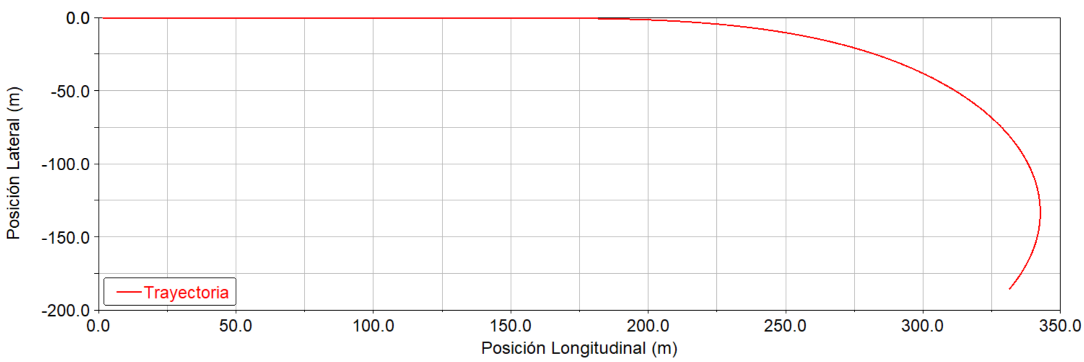


Figura 4: Ensayo de Ramp Steer aplicado sobre el modelo 3D

En este estudio no se han alcanzado situaciones próximas a las condiciones de deriva límite del neumático (derrape del vehículo). Se han considerado las tres configuraciones de tracción posibles sobre un vehículo de dos ejes, tracción delantera, tracción trasera y tracción 4x4.

2.2 Regiones de estabilidad

Cuando un vehículo toma una curva se desarrollan fuerzas laterales en el neumático, perpendiculares a su plano medio, que son función del ángulo de deriva, Figura 5.

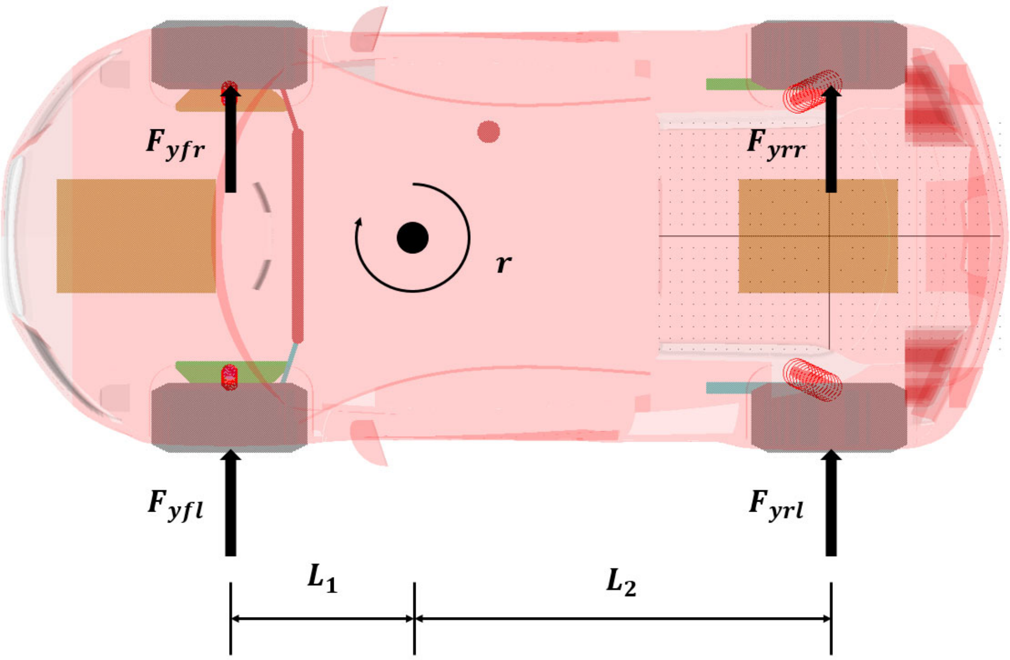


Figura 5: Representación de las fuerzas debidas al giro. Fy es la fuerza lateral por neumático y r la velocidad de guiñada en el centro de gravedad.

En un análisis cuasiestático del giro del vehículo los efectos debidos a las inercias se desprecian (Wong, 1978), con lo que la aceleración de la velocidad de guiñada debe satisfacer la siguiente ecuación:

$$\dot{r} = (L_1 \cdot (F_{yfr} + F_{yfl}) - L_2 \cdot (F_{yrr} + F_{yrl}))/I_{zz} \quad (1)$$

donde:

- $\dot{r}$: Aceleración de la velocidad de guiñada.
- Fyf: Fuerza lateral en el eje delantero (suma de la fuerza de ambas ruedas).
- Fyr: Fuerza lateral en el eje trasero (suma de la fuerza de ambas ruedas).
- $L1$: Distancia entre el eje delantero y el centro de gravedad del vehículo.
- $L2$: Distancia entre el eje trasero y el centro de gravedad.
- Izz: Momento de inercia respecto al eje vertical.

Además, en condición de giro cuasiestático se debe cumplir la siguiente condición:

$$F_{yf} = L_2/L_1 \cdot F_{yr} \quad (2)$$

La región de estabilidad se define en función de los límites de fuerza lateral que son capaces desarrollar los neumáticos, es decir, cuando se alcanza la fuerza lateral máxima en uno de los ejes (condición de saturación del eje), ya sea el delantero o el trasero.

La fuerza lateral máxima en el eje depende de la fuerza lateral máxima en cada rueda, siendo ésta, fundamentalmente, función de la carga vertical sobre el neumático y de la adherencia neumático/carretera.

Para determinar su valor es necesario un ensayo de caracterización sometiendo al neumático a una deriva variable. A continuación, se muestran las fuerzas laterales en los neumáticos, obtenidas a partir de un ensayo virtual de neumático realizado con el software MSC Adams® para cada configuración de carga y una adherencia de 0,9, Figura 6.

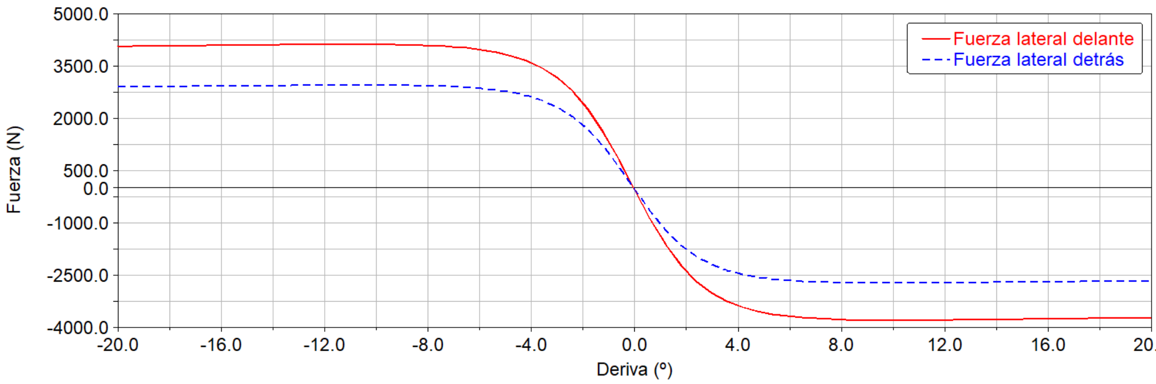


Figura 6: Ensayo virtual realizado con MSC Adams® para las dos configuraciones de carga y una adherencia de 0.9

Cuando se cumple la condición de la expresión (3), se ha alcanzado la saturación del eje delantero, siendo éste, el que define los límites de la región de estabilidad.

$$F_{yfmax} < L_2/L_1 \cdot F_{yrmax} \quad (3)$$

En caso contrario, es el eje trasero el que alcanza la saturación en primer lugar y, por tanto, es el que define los límites de la región de estabilidad, cumpliéndose la siguiente ecuación:

$$F_{yfmax} \geq L_2/L_1 \cdot F_{yrmax} \quad (4)$$

Considerando lo anterior, la velocidad de guiñada límite se calcula de acuerdo a las siguientes ecuaciones:

$$r_b = \{[F_{yrmax} \cdot (1 + L_2/L_1)/(m \cdot v_x) \text{ para } F_{yrmax} \geq (L_2/L_1) \cdot F_{yrmax}], [F_{yrmax} \cdot (1 + L_1/L_2)/(m \cdot v_x) \text{ para } F_{yrmax} < (L_2/L_1) \cdot F_{yrmax}]\} \quad (5)$$

Para el cálculo de los límites debidos al ángulo de deriva se utiliza un modelo de vehículo simplificado, conocido como modelo bicicleta y con dos grados de libertad, Figura 7.

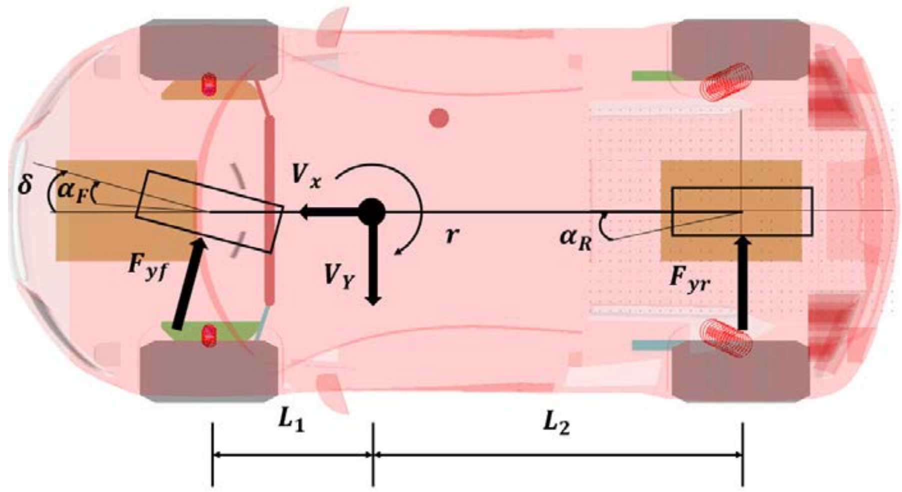


Figura 7: Representación de los parámetros del modelo bicicleta

La situación más peligrosa se produce cuando se satura el eje trasero del vehículo, ya que el vehículo se vuelve direccionalmente inestable. Esto ocurre cuando las ruedas traseras alcanzan la fuerza lateral máxima y el ángulo de deriva que corresponde con dicha situación es el siguiente:

$$\beta_b = \alpha_{r\text{lim}} + (L_2/v_x) \cdot r_b \quad (6)$$

2.3 Métricos de seguridad

En la Figura 8, se muestran los parámetros para definir la seguridad disponible en cada caso, aplicando las ecuaciones 7 y 8.

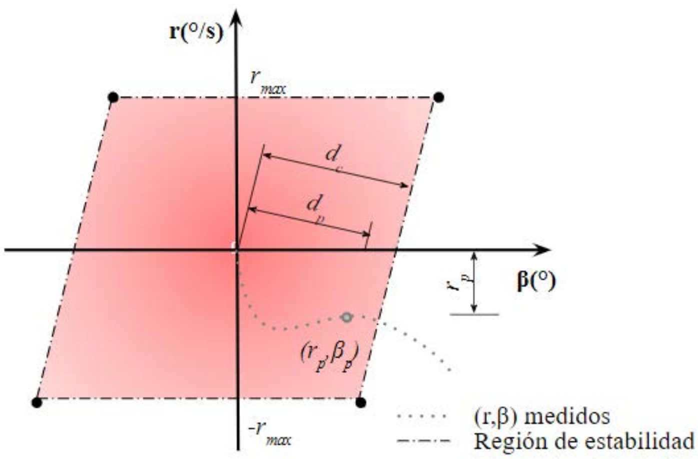


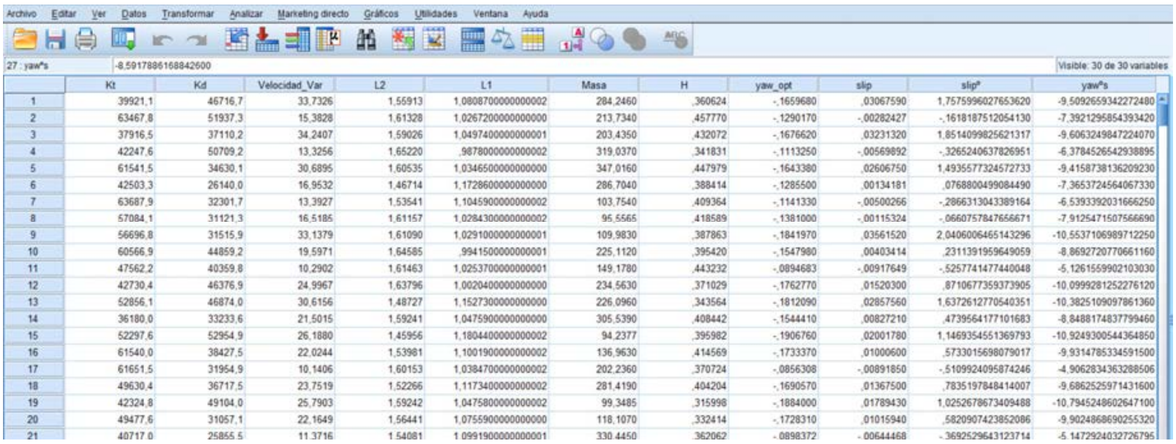
Figura 8: Parámetros para definir la seguridad disponible en cada caso

$$S_\beta(\%) = ((d_c - d_p)/d_c \cdot 100) \quad (7)$$

$$S_r(\%) = ((r_c - r_p)/r_c \cdot 100)) \quad (8)$$

3. RESULTADOS

Para analizar la influencia de cada uno de los parámetros de diseño del vehículo considerados en este trabajo, se ha utilizado el software estadístico IBM SPSS®.



	Kt	Kd	Velocidad_Var	L2	L1	Masa	H	yaw_opt	slip	slip*	yaw*s
1	39921,1	46716,7	33,7326	1,55913	1,0808700000000002	284,2460	,360624	-,1659680	,03067590	1,7575996027653620	-9,5092659342272480
2	63467,8	51937,3	15,3828	1,61328	1,0267200000000000	213,7340	,457770	-,1290170	-,00282427	-,1618187512054130	-7,3921295854393420
3	37916,5	37110,2	34,2407	1,59026	1,0497400000000001	203,4350	,432072	-,1676620	,03231320	1,8514099825621317	-9,6063249847224070
4	42247,6	50709,2	13,3256	1,65220	,9878000000000002	319,0370	,341831	-,1113250	-,00569892	-,3265240637826951	-6,3784526542938895
5	61541,5	34630,1	30,6895	1,60535	1,0346500000000000	347,0160	,447979	-,1643380	,02606750	1,4935577324572733	-9,4158738136209230
6	42503,3	26140,0	16,9532	1,46714	1,1728600000000000	286,7040	,388414	-,1285500	,00134181	,0768800499084490	-7,3653724564067330
7	63687,9	32301,7	13,3927	1,53541	1,1045900000000002	103,7540	,409364	-,1141330	-,00500266	-,2866313043389164	-6,5393392031666250
8	57084,1	31121,3	16,5185	1,61157	1,0284300000000002	95,5565	,418589	-,1381000	-,00115324	-,0660757847656671	-7,9125471507566690
9	56696,8	31515,9	33,1379	1,61090	1,0291000000000001	109,9830	,387863	-,1841970	,03561520	2,0406006465143296	-10,5537106989712250
10	60566,9	44859,2	19,5971	1,64585	,9941500000000001	225,1120	,395420	-,1547980	,00403414	,2311391959649059	-8,8692720770661160
11	47562,2	40359,8	10,2902	1,61463	1,0253700000000001	149,1780	,443232	-,0894683	-,00917649	-,5257741477440048	-5,1261559902103030
12	42730,4	46376,9	24,9967	1,63796	1,0020400000000000	234,5630	,371029	-,1762770	,01520300	,8710677359373905	-10,0999281252276120
13	52856,1	46874,0	30,6156	1,48727	1,1527300000000000	226,0960	,343564	-,1812090	,02857560	1,6372612770540351	-10,3825109097861360
14	36180,0	33233,6	21,5015	1,59241	1,0475900000000000	305,5390	,408442	-,1544410	,00827210	,4739564177101683	-8,8488174837799460
15	52297,6	52954,9	26,1880	1,45956	1,1804400000000002	94,2377	,395982	-,1906760	,02001780	1,1469354551369793	-10,9249300544364850
16	61540,0	38427,5	22,0244	1,53981	1,1001900000000002	136,9630	,414569	-,1733370	,01000600	,5733015698079017	-9,9314785334591500
17	61651,5	31954,9	10,1406	1,60153	1,0384700000000002	202,2360	,370724	-,0856308	-,00891850	-,5109924095874246	-4,9062834363288506
18	49630,4	36717,5	23,7519	1,52266	1,1173400000000002	281,4190	,404204	-,1690570	,01367500	,7835197848414007	-9,6862525971431600
19	42324,8	49104,0	25,7903	1,59242	1,0475800000000002	99,3485	,315998	-,1884000	,01789430	1,0252678673409488	-10,7945248602647100
20	49477,6	31057,1	22,1649	1,56441	1,0755900000000000	118,1070	,332414	-,1728310	,01015940	,5820907423852086	-9,9024868690255320
21	40717,0	25855,5	11,3716	1,54081	1,0991900000000001	330,4450	,362062	-,0898372	-,00644468	-,3692529643123714	-5,1472924032726795

Figura 9: Datos en el software de análisis estadístico IBM SPSS

Mediante el software de simulación dinámica multicuerpo MSC Adams® se realizan simulaciones modificando las rigideces de los muelles de la suspensión, el coeficiente de amortiguamiento de la suspensión, la posición del centro de gravedad (longitudinal y vertical), la masa o la velocidad (variables independientes). Como resultado se obtienen los valores de velocidad de guiñada y ángulo de deriva para la determinación del métrico de seguridad.

Para un vehículo de tracción trasera:

$$S_r = -0.001 \cdot A_d - 23.087 \cdot L_2 - 0.00012 \cdot K_d - 2.915 \cdot V_x + 160.262 \quad (9)$$

$$S_\beta = (1.87E-5) \cdot K_d + (2.14E-5) \cdot K_t - 3.53 \cdot L_2 - 0.007 \cdot M + 1.135 \cdot V_x - 4.417) \quad (10)$$

Según los resultados obtenidos para un vehículo tracción trasera, la seguridad disponible en guiñada, es inversamente proporcional a la rigidez de la suspensión delantera, a la velocidad y al amortiguamiento delantero. Valores elevados de estos parámetros, penalizan la seguridad disponible en el vehículo.

Por otro lado, en el caso de la seguridad disponible en deriva, ésta, es directamente proporcional a las rigideces, tanto delantera como trasera, y a la velocidad, mientras que una posición adelantada del centro de gravedad y una gran masa penalizan su valor. En este caso, tener valores de rigidez delantera y trasera elevados y una posición retrasada del centro de gravedad mejoran la seguridad disponible.

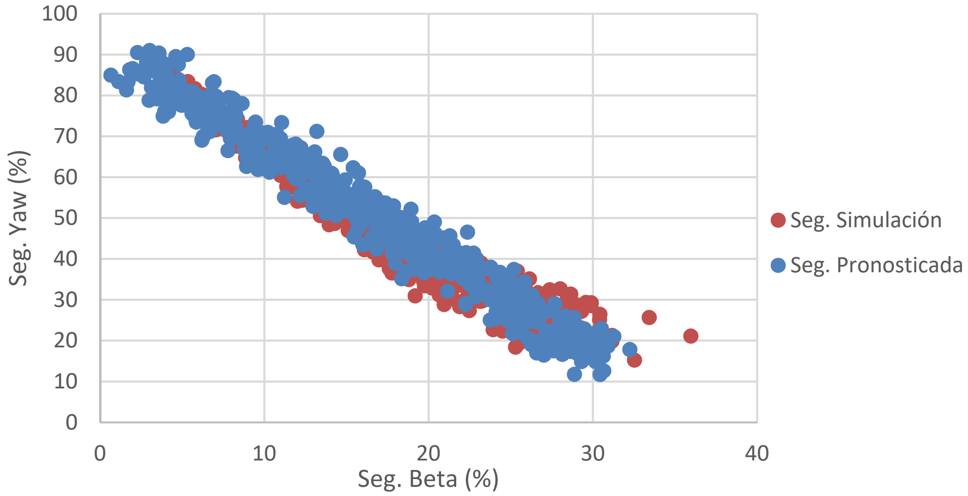


Figura 10: Comparación entre la seguridad obtenida de simulación y la pronosticada para un vehículo de tracción trasera

Se comete un error en el pronóstico de S_β del 4%, mientras que en S_r es del 3.5%.

Para un vehículo de tracción delantera:

$$S_r = -0.000106 \cdot K_d - 0.000106 \cdot K_t - 27.422 \cdot L_2 - 2.622 \cdot V_x + 164.615 \quad (11)$$

$$S_\beta = (5.72E-5) \cdot K_t + 3.429 \cdot H - 4.433 \cdot L_2 - 0.01 \cdot M + 1.135 \cdot V_x - 4.343) \quad (12)$$

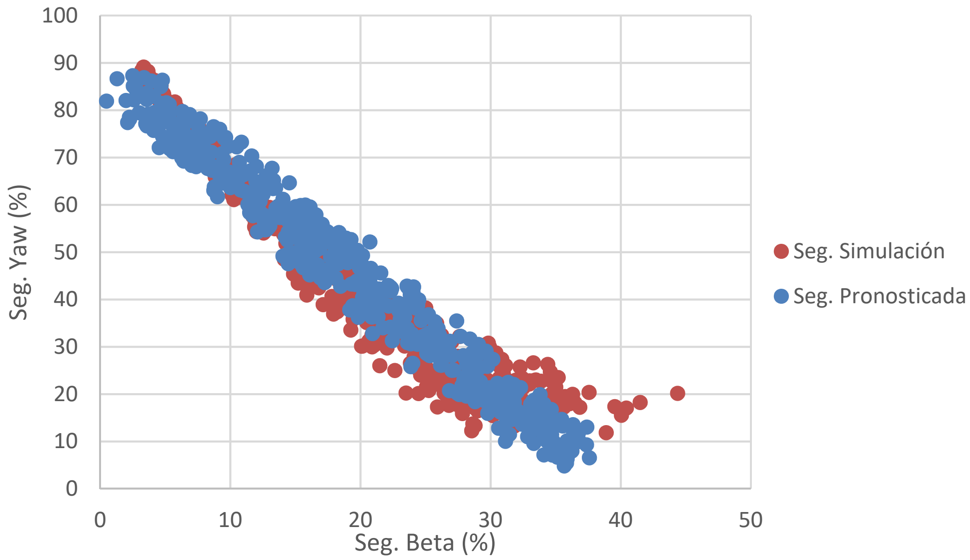


Figura 11: Comparación entre la seguridad obtenida de simulación y la pronosticada para un vehículo tracción delantera

Como se puede apreciar, en comparación con el modelo de ajuste para el vehículo de tracción trasera, en el vehículo de tracción delantera, las variables utilizas para el pronóstico han cambiado.

Por un lado, para la seguridad disponible en guiñada, son ahora las dos rigideces, delantera y trasera, las que afectan de forma negativa, además de la velocidad y la posición del centro de gravedad. Una posición del centro de gravedad adelantada, valores de rigidez de la suspensión altos y una velocidad elevada, perjudican el valor de la seguridad disponible.

Analizando la seguridad disponible en deriva, se obtiene, que una rigidez trasera alta, un centro de gravedad elevado (en altura) y una velocidad elevada, aumentan el valor de la seguridad, mientras que una posición adelantada (longitudinalmente) del centro de gravedad y una masa grande, perjudican los niveles de seguridad disponible.

Se comete un error en el pronóstico de S_β del 4,3%, mientras que en S_r es del 7,0%.

Para un vehículo de tracción 4x4:

$$S_r = -0.000106 \cdot K_d - 0.000106 \cdot K_t - 27.361 \cdot L_2 - 2.591 \cdot V_x + 163.997 \qquad (13)$$

$$S_\beta = (5.339E - 5) \cdot K_t + 3.071 \cdot H - 4.228 \cdot L_2 - 0.01 \cdot M + 1.102 \cdot V_x - 3.960) \qquad (14)$$

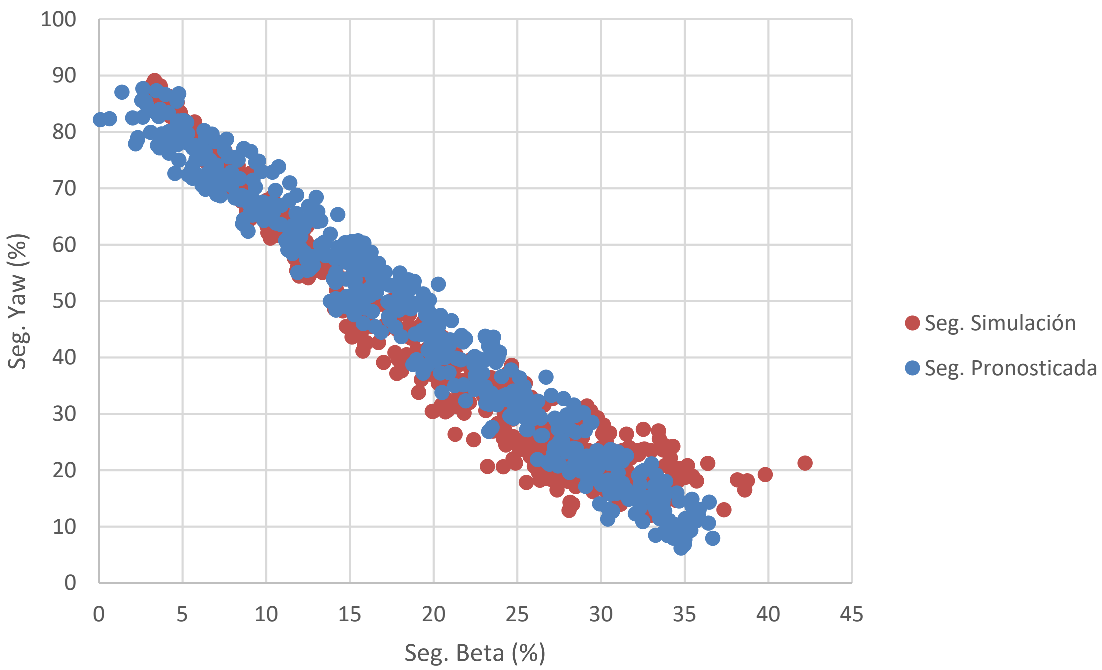


Figura 12: Comparación entre la seguridad obtenida de simulación y la pronosticada para un vehículo con tracción 4x4

Como se puede apreciar en los modelos de aproximación obtenidos para un vehículo 4x4 se parecen bastante a los obtenidos para un vehículo con tracción delantera. Existe una misma relación entre las variables, y el error cometido, es parejo. En las conclusiones, se analizará la posibilidad de unificar estos dos modelos (tracción 4x4 y tracción delantera), en uno solo que permita estudiar ambas configuraciones.

Se comete un error en el pronóstico de S_β del 4,1%, mientras que en S_r es del 7,0%.

4. CONCLUSIONES

En el presente trabajo se ha evaluado la aplicación de las regiones de estabilidad ($\dot{\varphi}$-β) al diseño de vehículos. Estas regiones definen los límites de conducción segura de un vehículo, por tanto, se plantea como objetivo maximizarlas en función de diferentes variables de diseño.

Como metodología para evaluar la aplicación de las regiones de estabilidad se ha desarrollado un diseño de experimentos, empleando un modelo virtual de vehículo sometido a una maniobra de giro. Se ha analizado la respuesta del vehículo en función de variables de diseño del sistema de suspensión y condición de funcionamiento, cuantificando el margen de seguridad disponible.

Tras analizar estadísticamente los resultados, se deduce, que para el diseño de vehículos de tracción delantera y de tracción 4x4, es significativa la influencia de los mismos parámetros, la altura del cdg (H), la posición del cdg (L), la rigidez del muelle trasero (K_t) y la masa total (M). Debido al rango de valores considerado y a la combinación de variables el incremento de la altura del centro de gravedad aumenta la región de estabilidad.

En vista de la gran similitud entre los modelos de pronóstico obtenidos, se plantea la posibilidad de usar un único modelo para pronosticar la seguridad disponible en ambas configuraciones.

$$S_r = -0.000131 \cdot K_d - 0.000131 \cdot K_t - 27.392 \cdot L_2 - 2.607 \cdot V_x + 164.306 \quad (15)$$

$$S_\beta = (5.561E - 5) \cdot K_t + 3.250 \cdot H - 4.430 \cdot L_2 - 0.01 \cdot M + 1.118 \cdot V_x - 4.151) \quad (16)$$

Con este ajuste, se comete un error en el pronóstico de S_β del 4,3%, mientras que en S_r es del 7,0%. Análogo a lo que se tenía anteriormente.

En el caso de vehículos de tracción trasera, es significativa la influencia de la rigidez de los muelles delantero y trasero (K_d) (K_t), la posición longitudinal del cdg (L) y la masa total (M).

Los errores que se comenten a la hora de realizar el pronóstico, pueden deberse a diversas causas, una de ellas, la existencia de otros parámetros de diseño de la suspensión que afecten a la seguridad durante la circulación del vehículo. Además, la linealidad del modelo utilizado, ya que, aunque los valores de R2, son del orden de 0.96-0.98, valores próximos a la unidad, éste dato, se puede mejorar.

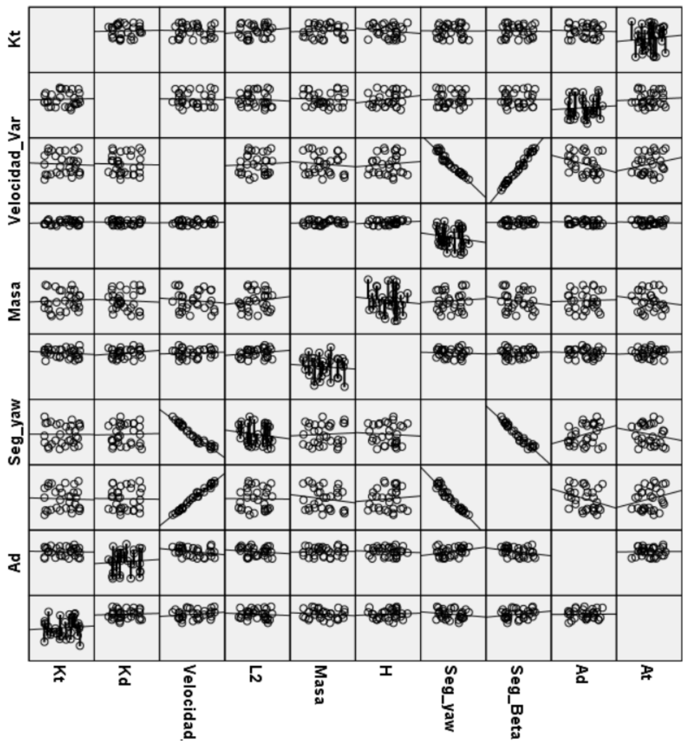


Figura 13: Matriz de correlaciones

Como se puede intuir en la matriz de correlaciones anterior, la variable velocidad, guarda una relación polinómica con la seguridad de guiñada disponible.

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CONSIDERACIONES FUNCIONALES DE LAS CVTs INERCIALES

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RESUMEN

Existen multitud de patentes y estudios centrados en transmisiones continuamente variables (CVTs) de tipo inercial. En estos documentos se presentan nuevos sistemas de este tipo apelando a la ventaja de autorregulación de la relación de transmisión que presentan. Sin embargo, este tipo de CVTs no han calado en el mercado actual de cajas de cambio. En este trabajo se analizan algunas de las cusas técnicas de este hecho. Específicamente, se analizan diferentes fuentes de vibraciones que son intrínsecas al funcionamiento de este tipo de transmisiones, que se unen al problema principal del uso de ruedas libres. Para llevar a cabo este trabajo se ha seleccionado un sistema CVT a modo de caso de estudio; sin embargo, las conclusiones son fácilmente extrapolables al resto de CVTs inerciales.

A pesar de que las vibraciones analizadas están asociadas al principio de funcionamiento de las CVTs inerciales y no pueden ser eliminadas, se proponen una serie de medidas para mitigarlas. Igualmente se demuestra que el funcionamiento de este tipo de transmisiones depende del tipo de motor de accionamiento mostrando diferencias de comportamiento cuando son accionadas por un motor eléctrico o por un motor de combustión interna.

Este trabajo se ha basado tanto en estudios analíticos como computacionales y los resultados han sido corroborados mediante ensayos reales.

1. INFORMACIÓN GENERAL

Una de las características fundamentales del funcionamiento de una CVT de tipo inercial es la regulación de un movimiento oscilante en alguna de las etapas de la transmisión (Morales y Benitez, 2014a; Morales y Benitez, 2014b).

Este movimiento oscilante (al tener no ser constante ya que tiene que ser regulado para el correcto funcionamiento de la CVT) será una fuente de fuerzas no equilibradas y por tanto igualmente de vibraciones. En este documento, se analizarán las distintas fuentes de vibración de este tipo de transmisiones asociadas a su principio de funcionamiento. Otras fuentes de vibración (tales como ejes desequilibrados, por ejemplo) quedarán fuera de este estudio.

Para una mejor comprensión del análisis realizado, se utilizará un ejemplo de específico de transmisión, sin embargo, todos los resultados obtenidos son fácilmente extrapolables a cualquier sistema de transmisión de la misma naturaleza dinámica. Para ello, se realizará una breve exposición de la transmisión utilizada como ejemplo, no siendo ésta la parte principal de este documento. Esta presentación se realizará en la sección 3.

En este análisis se demostrará igualmente, que el funcionamiento de una transmisión CVT de tipo dinámico está condicionado por la fuente de potencia. Es decir, el comportamiento de la transmisión será diferente en función de si se encuentra accionada por un motor eléctrico o bien por un motor de combustión interna. Este hecho no es fundamental en el caso de ensayos de transmisiones cinemáticas. Debido a esto, y a que su fabricación y control es más sencillo, la inmensa mayoría de los bancos de ensayo para transmisiones disponen de un motor eléctrico como accionamiento.

Por último, y basadas en las conclusiones del estudio, se realizan una serie de recomendaciones que, si bien no eliminan las vibraciones inherentes a este tipo de transmisiones, al menos pueden ayudar a mitigarlas.

2. ESTADO DEL ARTE

Las CVT de tipo inercial han sido ampliamente estudiadas desde los estudios pioneros de Hunt (1912). Uno de los trabajos más importantes en los orígenes de este tipo de transmisión fue realizado por Constantinesco (1922), el cual llegó a construir un prototipo funcional presentado en el Motor Show de Paris en 1926.

Después de esto, multitud de distintas CVTs de tipo dinámico han sido analizadas y patentadas. En Morales y Benitz (2014) se presenta una revisión detallada de este tipo de transmisiones las cuales llegas a clasificarse claramente de dos categorías: a) CVTs con masas oscilantes y b) CVTs con masas excéntricas. De la primera categoría, los desarrollos más importantes son los llevados a cabo por Howards (2005), Benitez et al. (2009) o Franch (1981). En cuanto al segundo grupo destacan los desarrollos de Chalmers (1932), Tam (1992), Williams y Williams (1999), Lester (2006) y Shea (1982). En este documento solo se citan unos pocos ejemplos de cada familia de CVTs inerciales, sin embargo, existen infinidad de dispositivos de este tipo patentados.

En estos trabajos anteriormente mencionados se presentan innovaciones de sistemas de transmisión, sin embargo, también existen estudios donde se analizan en detalle alguno de estos sistemas. Cabe destacar el trabajo presentado por Stecki (1981) en el que la transmisión patentada por Constantinesco es profundamente analizada, obteniendo para ello las ecuaciones de movimiento mediante el uso de la metodología “bond graph”. Este estudio es continuación de otras publicaciones previas (Berselli y. Stecki 2008; Berselli, 2004).

Mas recientemente, ejemplos que merecen un interés especial se encuentra en los trabajos presentados por S. Aliukov (2017) y Aliukov et al. (2018), en los que se analizan y proponen mejoras para el uso de CVTs inerciales. Aliukov continua en este trabajo con la misma línea en la que había presentado varios papers previamente (Alyukov y Keller, 2018; Alyukov, 2014; Alyukov y Gorshenin, 2014; Alyukov y Gladyshev, 2013 y Alyukov, 2010).

A pesar de la cantidad de patentes referentes a este tipo de CVTs, actualmente no existen soluciones comerciales. La principal razón de este hecho es que este tipo de mecanismos necesitan un sistema rectificador basado en ruedas libres (Morales y Benitez, 2014b). Las ruedas libres, en este tipo de transmisiones, están sometidas a altos pares y velocidades angulares. En la actualidad, no se comercializan ruedas libres que sean capaces de soportar conjuntamente altos pares y altas velocidades de oscilación. Además de este problema principal, en este documento otra serie de problemas intrínsecos a este tipo de CVTs son analizados siendo éstos la causa principal de que este tipo de transmisiones no hayan proliferado.

Como se ha mencionado anteriormente, uno de los principales problemas de este tipo de transmisión radica en las vibraciones del sistema. Enfocándose en vibraciones mecánicas, existen estudios específicos dedicados a cajas de cambio. Por ejemplo, destacan los trabajos realizados por Mehmet Bozca (Mehmet, 2010) en el que analiza la optimización de una caja de cambio desde el punto de vista de reducción de la vibración de traqueteo de los elementos que componen la transmisión. Otro ejemplo sobre la misma temática, es el trabajo realizado por Parra y Molina (Parra y Molina, 2017) en el que proponen dos métodos para modelar las vibraciones de trenes planetarios. Otros estudios interesantes son los presentados por Wojnar y Juzek (2018) y Grega at al. (2016).

Sin embargo, todos estos estudios se encuentran enfocados en fuentes de vibración típicas de sistemas mecánicos. En este documento, este tipo de vibraciones serán ignoradas, ya que se centra en identificar y analizar las vibraciones generadas por el principio de funcionamiento de las transmisiones inerciales.

3. CVT AUTOADAPTABLE

Como se ha mencionado anteriormente, este estudio se centra en CVTs de tipo inercial. En este tipo de transmisión, aparte de un sistema externo de regulación, el sistema se autorregula para adaptar la relación de transmisión a las condiciones a las que la transmisión está sometida tales como el par resistente y la velocidad de giro del eje de entrada.

A pesar de que las conclusiones de este estudio pueden extrapolarse a cualquier caja de cambios de tipo inercial, se ha seleccionado un caso de estudio para para facilitar la comprensión del análisis.

Se ha seleccionado como caso de estudio la CVT Autoadaptable patentada por Benitez et al (2009) y es por eso por lo que a continuación se dará una breve explicación de su funcionamiento (una descripción más detallada puede encontrarse en Morales y Benitez (2019) y en Centeno et al. (2010).

La CVT autoadaptable contiene un elemento inercial que consiste en un tren epicicloidal con una masa adicionad a la corona (Figura 1). Este elemento inercial es conducido por un mecanismo de accionamiento cuya función es transformar el movimiento constante del motor en un movimiento oscilante. Esto es necesario para tener continuos periodos de aceleración y desaceleración en el elemento inercial (corona del tren epicicloidal).

Disponer de aceleraciones continuas es necesario ya que durante los procesos de aceleración se transmite un par al eje de salida del epicicloidal (eje del planeta). El movimiento del planeta será igualmente oscilante, por lo que es necesario que el sistema disponga de una última etapa que rectifique este movimiento. Resumiendo, el motor se conecta al mecanismo de accionamiento que transmite un movimiento oscilante al tren epicicloidal que regula el par transmitido a la salida de éste en función de las variables tales como el par resistente y la velocidad de entrada y por último, un mecanismo rectificador convierte el movimiento oscilante en un giro en un único sentido.

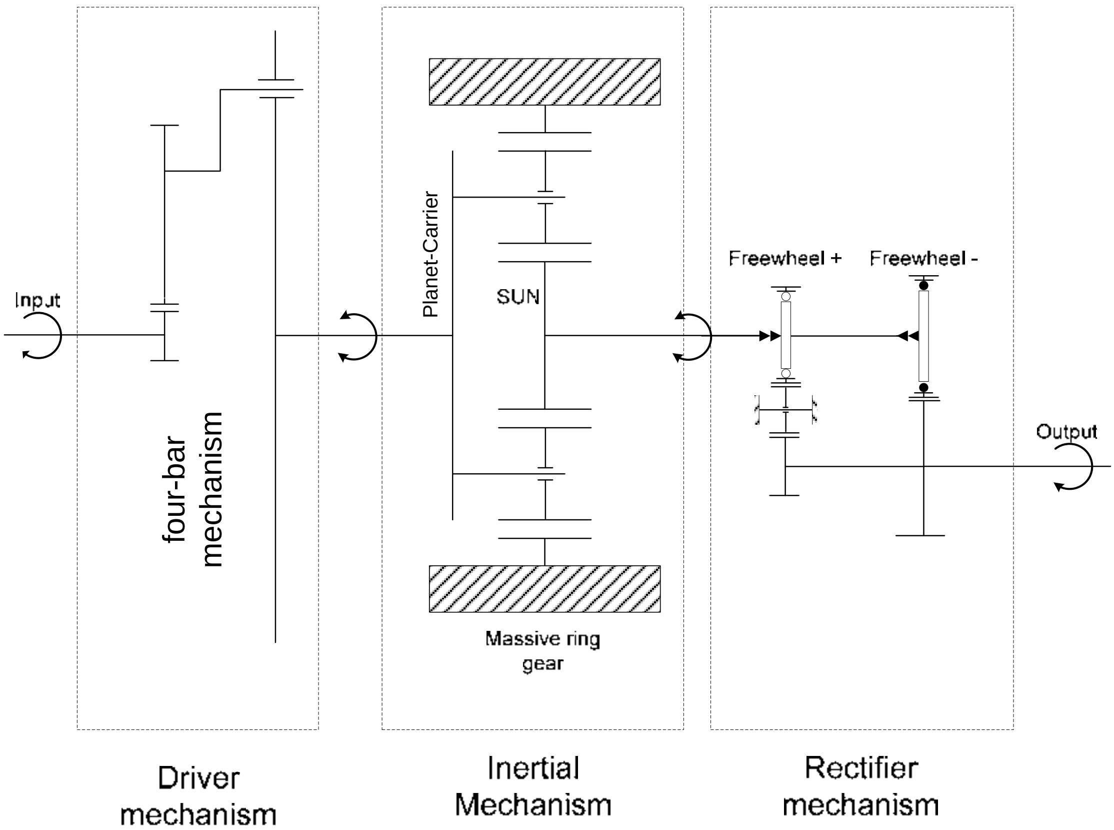

Figura 1: Esquema de la transmisión autoadaptable

4. VIBRACIONES DEBIDAS AL MECANISMO DE ACCIONAMIENTO

La más obvia y una de las más fuertes fuentes de vibración en este sistema de transmisión es la generada por el mecanismo de accionamiento. En la CVT seleccionada como caso de estudio el sistema de accionamiento es un mecanismo de cuatro barras (manivela-biela - balancín). En el análisis llevado a cabo en este estudio, la longitud de la manivela se ha mantenido constante haciendo que el sistema completo funcione como un convertidor de par (Centeno et al., 2010), ya que este estudio se centra en las vibraciones del sistema y, excepto por las vibraciones debidas al mecanismo de accionamiento que son tratadas en esta sección, este parámetro (longitud de la manivela) no es fundamental para entender cada una de las fuentes de vibración. En este caso particular (longitud de la manivela constante) es posible equilibrar el mecanismo de accionamiento (Berkof, 1973). Sin embargo, en la CVT real es necesario cambiar esta longitud de la manivela para poder modificar la relación de transmisión y de esta forma poder mantener la velocidad del motor a la velocidad deseada. De esta forma, al modificar la longitud de la manivela es necesario realizar igualmente un equilibrado que varíe con esa longitud. Este hecho es bastante complicado por lo que finalmente se producirá un desequilibrio al modificar la longitud de la manivela. Este desequilibrio se añade al resto de fuentes de vibración que serán enumeradas en este documento.

5. VIBRACIONES DEBIDAS AL PRINCIPIO DE FUNCIONAMIENTO DE LA CVT

El principio de funcionamiento de la CVT autoadaptable se basa en acumulaciones y cesiones de potencia por el sistema masivo (corona masiva de la Figura 2).

En el sistema, la corona masiva se usa como elemento intermedio entre la entrada (portasatélites) y la salida (planeta). De esta forma, la entrada de potencia que se introduce a través del portasatelite puede, o directamente ser transmitida hacia el planeta, o bien ser almacenada en el elemento masivo para ser utilizada posteriormente.

La potencia en cada elemento se representa por:

$$P_{PC} = T_{PC} \cdot \omega_{PC} \tag{1}$$

$$P_S = T_S \cdot \omega_S \tag{2}$$

$$P_{RG} = -I_{RG} \cdot \omega_{RG} \cdot d\omega_{RG}/dt \tag{3}$$

donde:

- P_{PC} es la potencia en el portasatélites
- T_{PC} el par en el portasatélites (par de entrada)

- P_S potencia en el planeta (salida)
- T_S par en el planeta (par resistente "visto" por el tren epicicloidal)
- P_{RG} potencia en la corona masiva
- I_{RG} inercia de la corona masiva
- ω_{PC}, ω_S, ω_{RG} son las velocidades angulares del portasatélites, planeta (eje de salida) y la corona respectivamente.

Como se ha mencionado anteriormente, el principio de funcionamiento de la CVT inercial se basa en generar aceleraciones en la corona masiva del tren epicicloidal. Debido a esto es por lo que se introduce un movimiento oscilatorio en el tren epicicloidal, resultando que ω_{RG} y $\frac{d\omega_{RG}}{dt}$ serán igualmente oscilantes y por consiguiente la potencia de la corona.

El par en la corona del tren epicicloidal viene dado por:

$$T_{RG} = I_{RG} \cdot d\omega_{RG}/dt \quad (4)$$

En estas ecuaciones, la potencia es positiva cuando entra en el Sistema. De esta forma, la potencia de la corona será negativa cuando este elemento almacena energía (cuando se acelera).

Realizando un equilibrio de potencias:

$$P_{PC} + P_{RG} + P_S = 0 \rightarrow P_{PC} = -(P_{RG} + P_S) \quad (5)$$

Según esta ecuacion (5), la entrada de potencia al sistema a través del portasatélites es igual a la absorbida por la corona del tren epicicloidal más la potencia transmitida a través del planeta. Igualmente, la potencia que transmite la corona masiva cuando cede su potencia acumulada viene dada por:

$$P_{RG} = -(P_{PC} + P_S) \quad (6)$$

De esta forma, la energía acumulada en la corona masiva será trasmitida o bien hacia la salida (a través del planeta) o será devuelta a la entrada (a través del portasatélites). La cantidad de potencia transmitida a cada elemento será función del par en cada uno de ellos.

Como ejemplo, la Figura 2 muestra la evolución de la potencia en cada elemento del tren epicicloidal cuando se introduce una señal senoidal (y por tanto oscilante) en el portasatélites y un par resistente constante en el planeta. En esta figura pueden apreciarse claramente tres diferentes modos de funcionamiento.

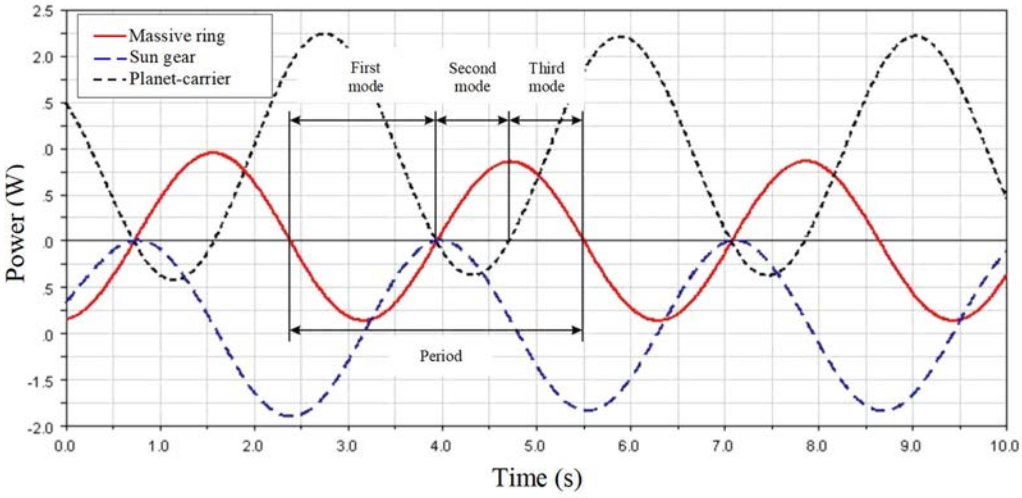

Figura 2: Evolución de la potencia en los elementos del tren epicicloidal

- Primer modo: La corona masiva almacena energía incrementando su velocidad angular. La potencia de la entrada es utilizada para acelerar la corona masiva y para mover el eje de salida.
- Segundo modo: Este modo es indeseado, ya que la corona masiva está transmitiendo potencia tanto a la salida (planeta) como a la entrada (portasatélites). Esta ultimo flujo de potencia es indeseado ya que parte de la energía se transmite a la entrada en lugar de la salida que sería el flujo correcto de potencia. Este modo de funcionamiento será una Fuente de vibraciones del Sistema.
- Tercer modo: En este modo, las dos potencias (la introducida por la entrada y la cedida por el elemento masivo al decelerarse) son transmitidas a la salida.

Según estos tres modos de funcionamiento, la potencia de la entrada (portasatélites) se transfiere a:

- dos elementos (modo 1)
- solo un elemento (modo 3), o
- recibe potencia del elemento masivo (modo 2).

Esto implica que el par en el eje de entrada siempre se ve alterado por los tres modos de funcionamiento. Al no ser un par constante, será una fuente de vibraciones indeseadas.

Debido a esto, para mantener constante la velocidad angular en el eje de entrada es necesario “frenar” el eje de entrada cuando recibe potencia de la corona masiva y proporcionar un par positivo en el resto de modos de funcionamiento. Si bien puede “frenarse” el eje de entrada si el mecanismo es accionado con un motor eléctrico, esto no será posible con un motor de combustión interna al no poder proporcionar un par negativo de forma que el eje acelerará y desacelerará en función del modo de funcionamiento en el que se encuentre el sistema.

Por esto, y como se ha mencionado anteriormente, el comportamiento del sistema será distinto en función del motor de accionamiento.

5.1 Sistema accionado por motor eléctrico

La peculiaridad del motor eléctrico es que, mediante un variador de frecuencia, es posible mantener una velocidad cuasi constante en el eje de entrada de la transmisión. El motor eléctrico proporcionará el par necesario, ya sea positivo o negativo, para que esto suceda.

Como se ha mencionado anteriormente, el par debe ser oscilante para mantener la velocidad constante debido a los tres modos de funcionamiento distintos del sistema de transmisión. Es decir, cuando la corona masiva ceda potencia hacia la entrada, el motor eléctrico debe proporcionar un par negativo para "frenar" el eje de entrada y un par positivo en el resto de casos. Este efecto será más severo en cuanto mayor sea el par resistente en el planeta del tren epicicliodal, ya que la corona masiva cederá más potencia hacia el elemento que menor resistencia ponga de las dos posibilidades que tiene (o hacia la entrada o hacia el planeta).

En otras palabras, si existe un par resistente pequeño (vehículo circulando en una carretera plana a una velocidad moderada), la corona masiva cederá una mayor potencia hacia la salida. Sin embargo, si el par resistente es alto (vehículo ascendiendo una pendiente y/o acelerando), la mayoría de la potencia será transmitida al eje de entrada cuando la transmisión se encuentre en el segundo modo de funcionamiento.

Por tanto, según las explicaciones dadas anteriormente, el par proporcionado por el motor eléctrico será oscilante y por tanto una fuente de vibraciones.

Este análisis fue corroborado experimentalmente mediante ensayos (los equipos utilizados y como se llevaron a cabo los tests se encuentra profundamente detallado en Centeno et al. (2010)). La figura 3 muestra el par medido en un ensayo real con un par resistente bajo. Como puede comprobarse, la señal no es simétrica respecto al eje y=0. Esto es debido a que, como el par resistente es bajo, existe una mayor cesión de potencia de la almacenada en la corona masiva hacia la salida y poca hacia la entrada, por lo que el motor eléctrico no tiene que ejercer un gran par negativo para evitar que se acelere la entrada.

Sin embargo, manteniendo la velocidad de entrada constante, pero aumentando considerablemente el par resistente a la salida de la transmisión, la corona cede una mayor potencia hacia la entrada necesitando el motor eléctrico proporcionar un mayor par negativo (Figura 4) llegando a ser prácticamente del mismo valor que el par positivo.

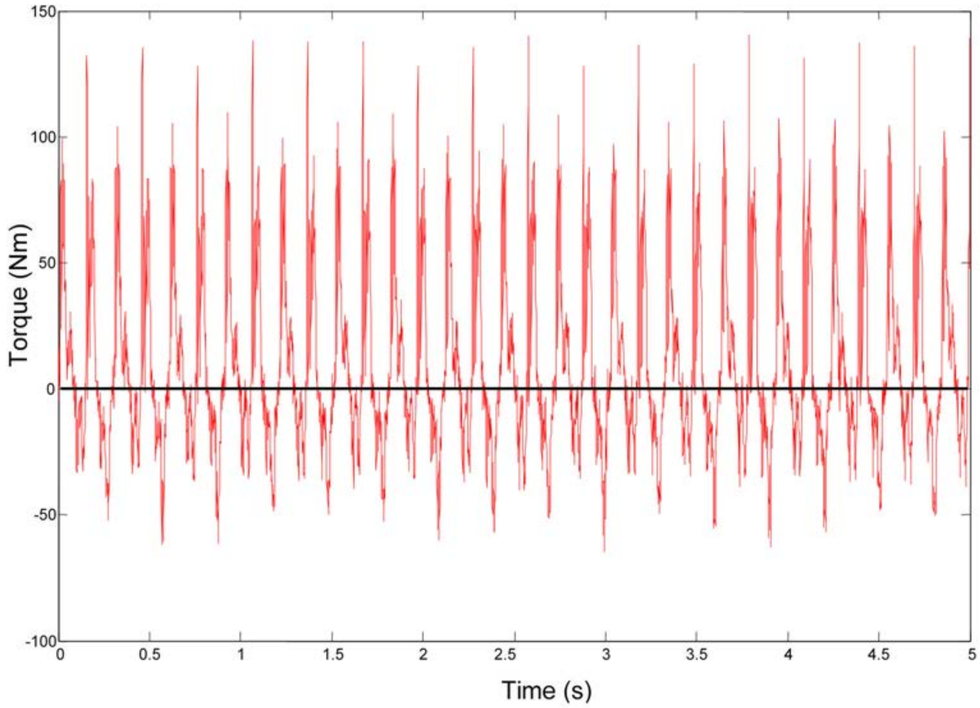

Figura 3: Par de entrada (bajo par resistente)

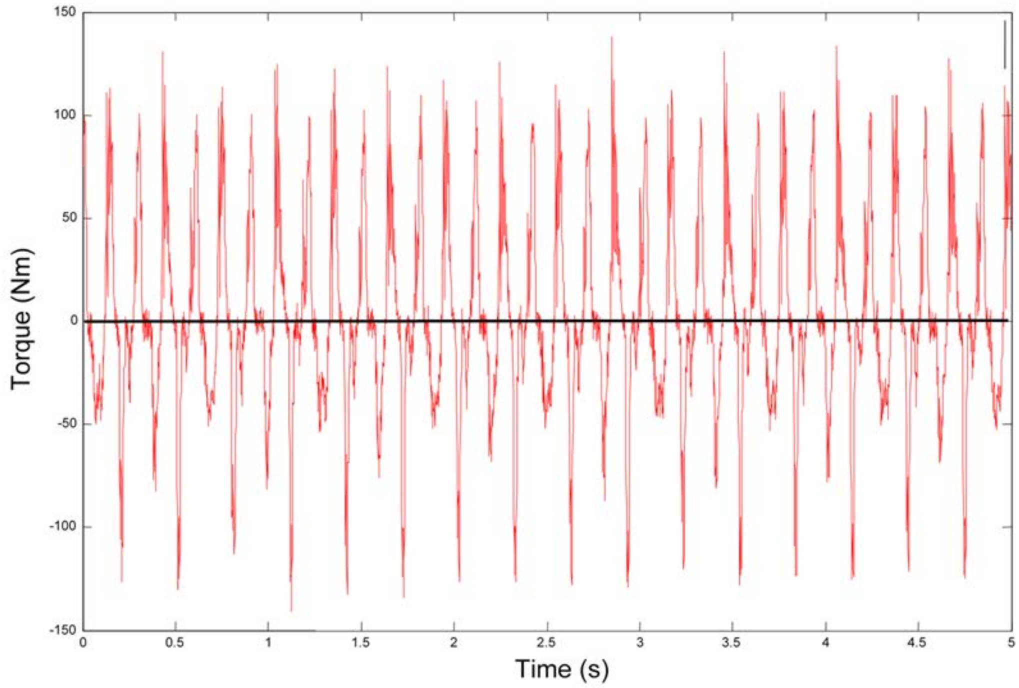

Figura 4: Par de entrada (alto par resistente)

Como se ha comprobado, el par de entrada que debe proporcionar el motor eléctrico es de naturaleza oscilante debido al principio de funcionamiento de la transmisión. Por la tercera ley de Newton, la carcasa del motor eléctrico transmite un par oscilante de la misma magnitud, pero de signo contrario, al chasis del banco de ensayos causando unas vibraciones indeseadas (Figura 5).

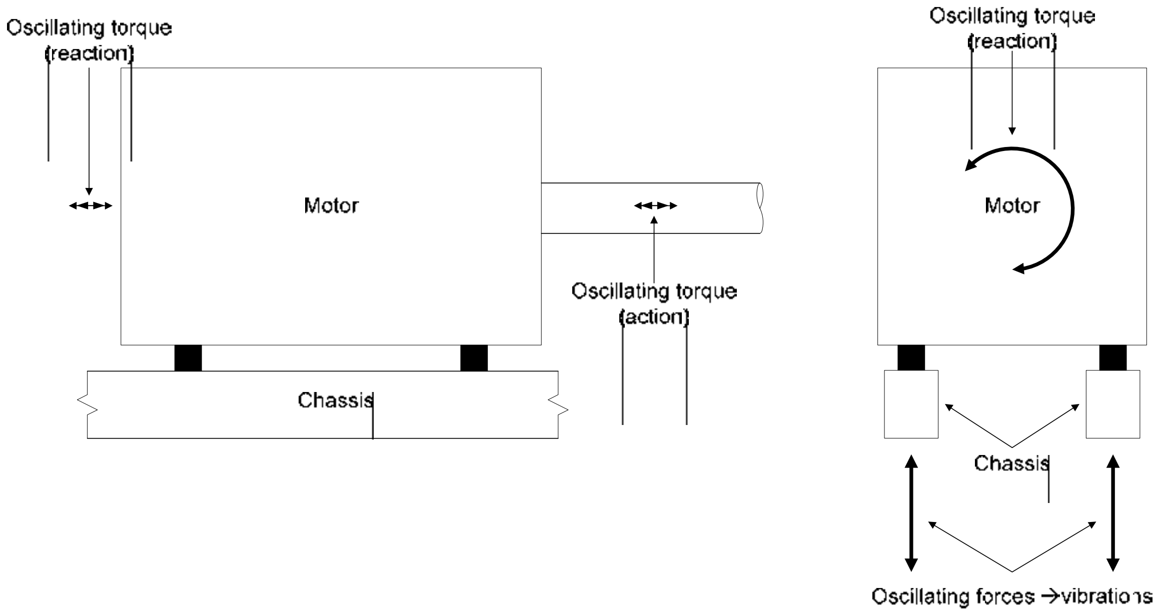

Figura 5: Transmisión del par oscilante al chasis del banco de ensayos

5.2 Sistema accionado por motor de combustión interna (ICE)

Este caso es diferente al anterior debido a que el motor de combustión interna no es capaz de proporcionar un par negativo. Esto implica que la velocidad del eje de entrada no podrá ser constante. Tomando el eje de entrada como elemento de control, el flujo de potencia presenta tres escenarios:

- durante el primer modo de funcionamiento, la entrada transfiere potencia hacia la salida (planeta del tren epicicloidal) y hacia la corona masiva
- Durante el segundo modo, el eje de entrada recibe potencia desde la corona masiva y finalmente,
- durante el tercer modo, la entrada solo transmite potencia hacia la salida (planeta).

Este flujo de potencia implica que el par resistente que “siente” el motor de combustión interna no sea constante y provoca que la velocidad del eje de entrada no sea constante tal y como se aprecia en la Figura 6. Estos resultados han sido obtenidos mediante un modelo realizado en un software de dinámica multicuerpo y previamente calibrado con ensayos reales (ver Morales y Benitez, 2019).

Cuando la corona masiva transfiere parte de su potencia hacia la entrada, el motor de combustión se acelera, incrementando la velocidad del eje de entrada. Sin embargo, cuando el motor de combustión transmite potencia hacia la salida y a la corona masiva, la velocidad del eje de entrada decrece.

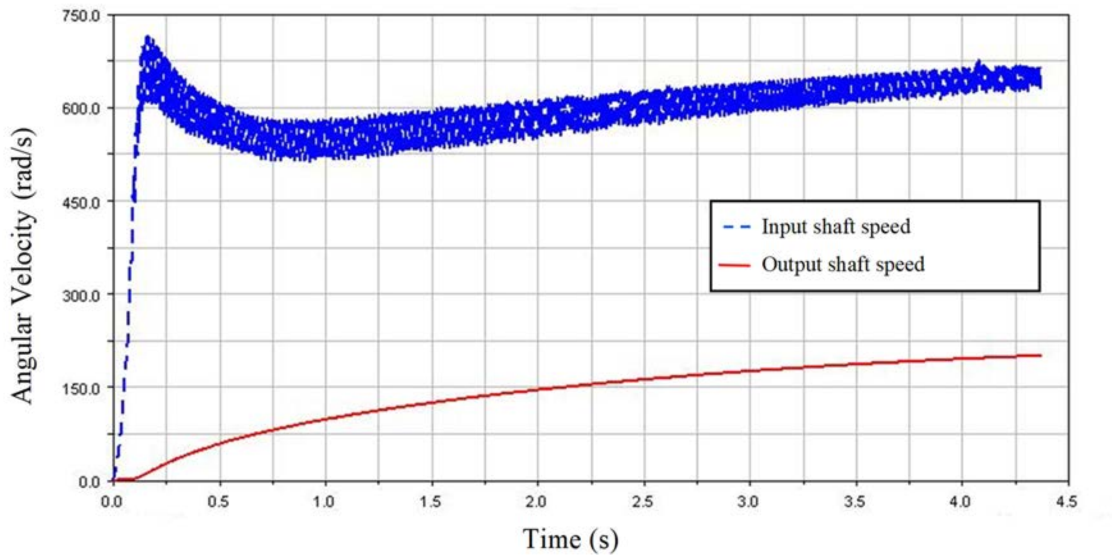

Figura 6: Oscilación de la velocidad angular del eje de entrada (ICE)

Este comportamiento puede ser explicado analizando el punto de equilibrio entre la curva de par del motor de combustión interna y la curva del par resistente. En el caso de las CVTs inerciales, el par resistente cambia dependiendo de los tres modos de funcionamiento descritos previamente (Figura 7). Esto hace que el punto de equilibrio cambie constantemente provocando una velocidad de entrada no constante.

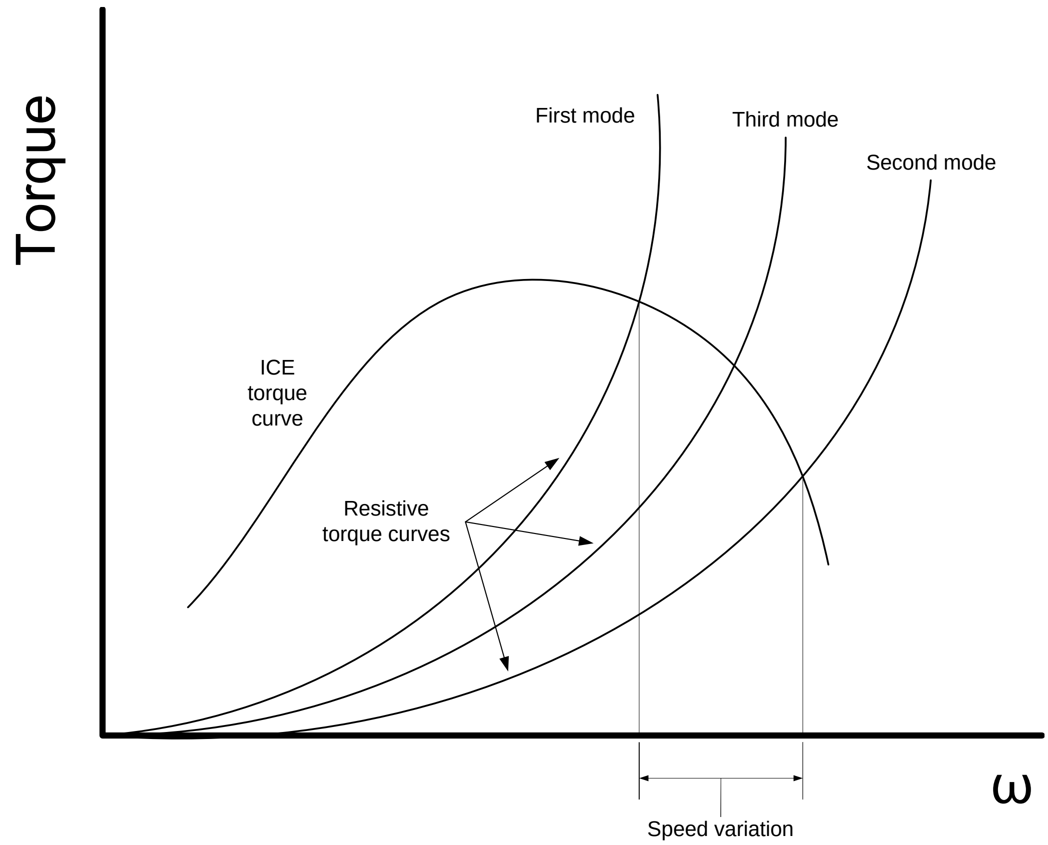

Figura 7: Punto de equilibrio entre la curva de par del motor de combustión y la curva del par resistente.

5.3 Soluciones propuestas para reducir vibraciones debidas al principio de funcionamiento.

Una vez conocida la naturaleza de las vibraciones debidas al principio de funcionamiento de este tipo de CVTs es possible proponer soluciones para reducirlas.

Ya es conocido que el par proporcionado por un motor de combustion interna no es constante y la solución para suavizar este par consiste en introducir un volante de inercia. Debido a esto, un primer método para reducir las vibraciones es aumentar la inercia de este volante de inercia. De esta forma, a la potencia cedida por la corona masiva hacia la entrada le costará más acelerar al eje de entrada. En la Figura 8 puede verse una comparativa entre el sistema con y sin disco de inercia aumentado en el eje de entrada. La figura muestra como la oscilación en la velocidad de entrada se ha visto drásticamente reducida. Sin embargo, se ha visto afectada la velocidad y la aceleración del vehículo a la salida. Debido a esto, debe llegarse a un compromiso para obtener un resultado final adecuado.

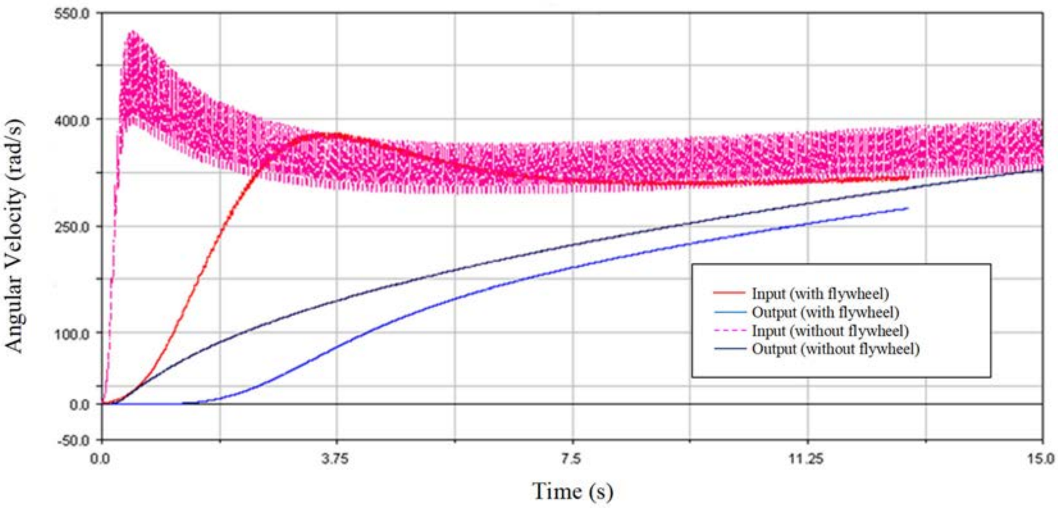

Figura 8: Comportamiento de la CVT inercial con y sin aumento de disco de inercia en el eje de entrada.

Puede proponerse una segunda solución teniendo en cuenta que las vibraciones debidas al principio de funcionamiento se deben a que la corona masiva tiene dos alternativas para transferir su potencia: i) hacia la salida (planeta del tres epicicloidal) o ii) hacia la entrada (portasatélites). En este último caso es cuando se generan las mayores vibraciones. Por tanto, si se reduce el par resistente en la salida del tren epicicloidal (planeta) una mayor proporción de potencia será transferida hacia esta salida. Sin embargo, el par resistente viene fijado por la dinámica longitudinal del vehículo, por lo que no puede ser modificado. Sin embargo, el par que afecta al tren epicicloidal y por tanto al que afecta a la cantidad de potencia transmitida hacia la salida es el par resistente que "ve" el planeta y éste si puede ser modificado utilizando un reductor como sistema rectificador (subsistema rectificador de la Figura 1). Esta solución se esquematiza en la Figura 9:

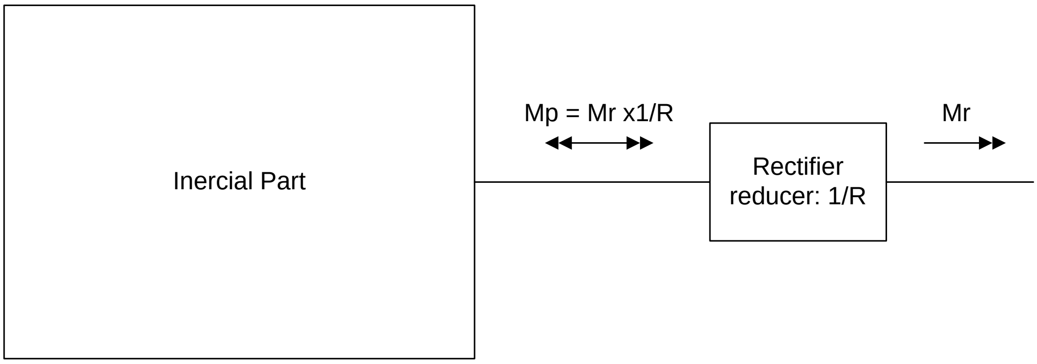

Figura 9: Esquema de la solución basada en el uso de un rectificador reductor

Con esta solución podría parecer que la velocidad del vehículo se vería reducida en la misma proporción. Sin embargo, aunque en principio parezca contradictorio, un reductor a la salida puede tener efectos positivos en la velocidad de salida. Esto se debe a que en el caso de una CVT inercial, cuando el par en el planeta (salida del tren epicicloidal) es reducido, se transfiere una mayor potencia desde el elemento masivo hacia esta salida (disminuyendo la potencia transferirá hacia la entrada y con ello las vibraciones indeseadas) haciendo que se aumente la velocidad final del sistema completo. Este comportamiento sucede hasta que el efecto de tener una reducción compensa al efecto de tener una mayor cesión de potencia hacia la salida (punto máximo en la Figura 10).

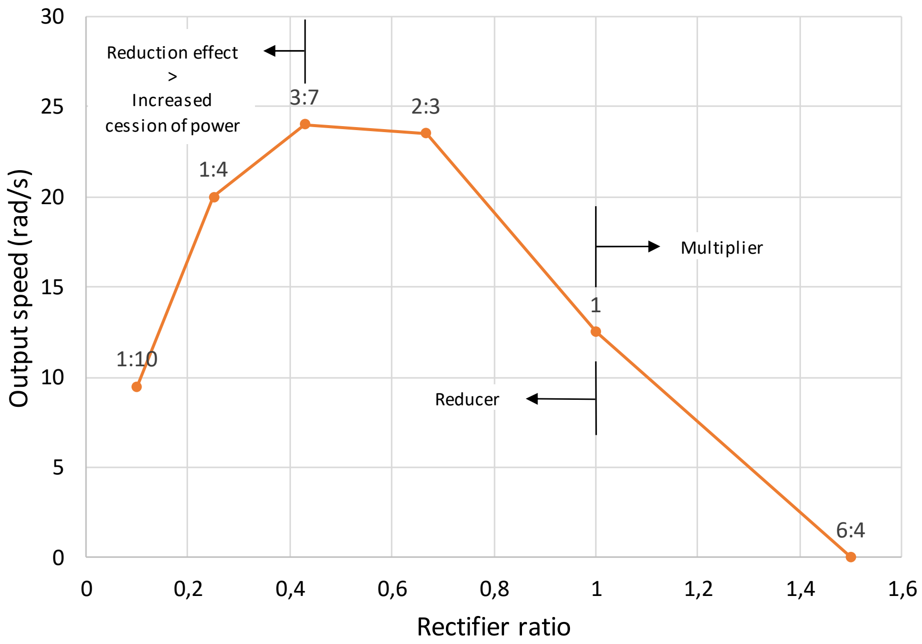

Fig. 10 – Efecto de usar un reductor/multiplicador como sistema rectificador

Los resultados mostrados en esta Figura 10 no son generales, ya que dependen de multitud de parámetros tales como la inercia del elemento masivo, la relación de transmisión del tren epicicloidal, el mecanismo de entrada, etc. Debido a esto, es necesario obtener la relación de transmisión del sistema óptima para cada caja de cambios de forma individual (una explicación más detallada de este comportamiento puede verse en Alyukov (2014)).

6. VIBRACIONES DEBIDAS AL MECANISMO RECTIFICADOR

Como se ha mencionado anteriormente, a la salida del tren epicicloidal se tiene un movimiento oscilatorio que es necesario rectificar para obtener un movimiento en un único sentido y poder ser utilizado por el vehículo. Tomando como ejemplo el sistema rectificador de la Figura 11, cuando el planeta del tren epicicloidal (sun) gira en sentido horario, la rueda libre positiva se encuentra bloqueada y la potencia se transmite a través de los engranajes G1, G2 y G3. Al mismo tiempo, la rueda libre negativa se encuentra desengranada. En la segunda mitad del periodo (cuando el planeta gira en sentido antihorario) la transmisión de potencia se realiza a través de los engranajes G4 y G5 (una explicación mas detallada del funcionamiento de este mecanismo puede encontrarse en Morales y Benitez (2014b).

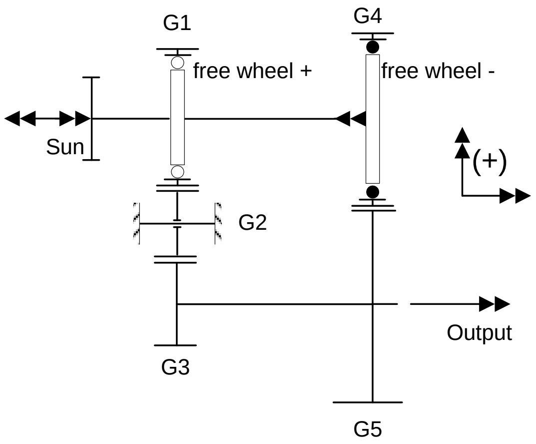

Figura 11: Mecanismo rectificador

Si se analiza por ejemplo las fuerzas transmitidas al chasis del banco de ensayos a través de G4 y G5 se obtiene que cuando se transmite potencia a través de ellas existen unas fuerzas de reacción en el chasis, en cambio, cuando la rueda libre alojada en el engranaje G4 se encuentra desacoplada estas fuerzas se anulan. Debido a esto existen unas fuerzas intermitentes (Figura 12) y consecuentemente unas vibraciones indeseadas.

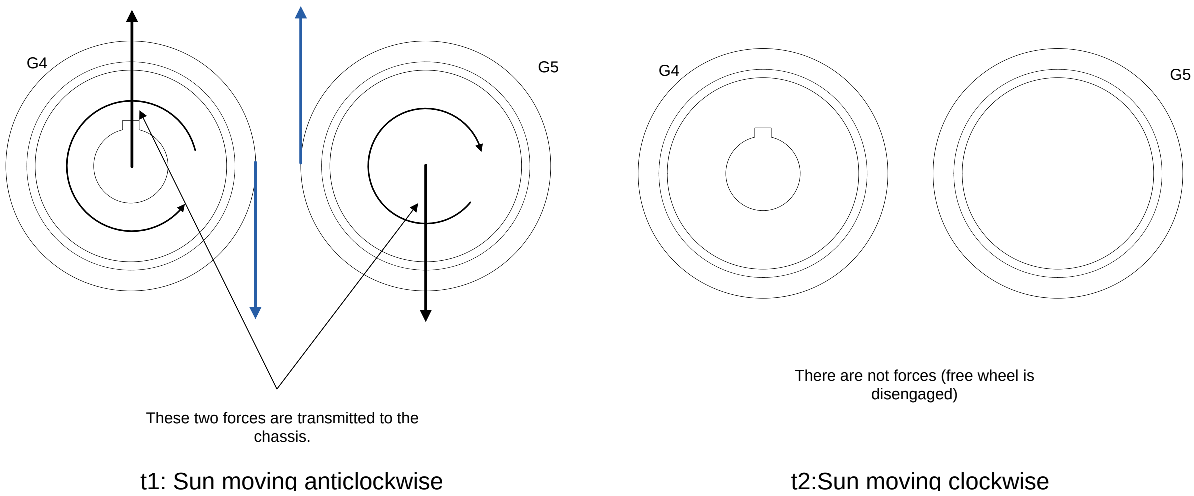

Figura 12: Fuerzas transmitidas por G4 y G5

6.1 Soluciones propuestas para reducir vibraciones debidas al rectificador

Una posible solución para reducir estas vibraciones es la de utilizar dos trenes epicicloidales trabajando en paralelo de forma que se compensen parcialmente las vibraciones entre uno y otro (Figura 13). Para que esta solución funcione correctamente, los sistemas de accionamiento de ambos trenes epicicloidales deben estar desfasados 90º.

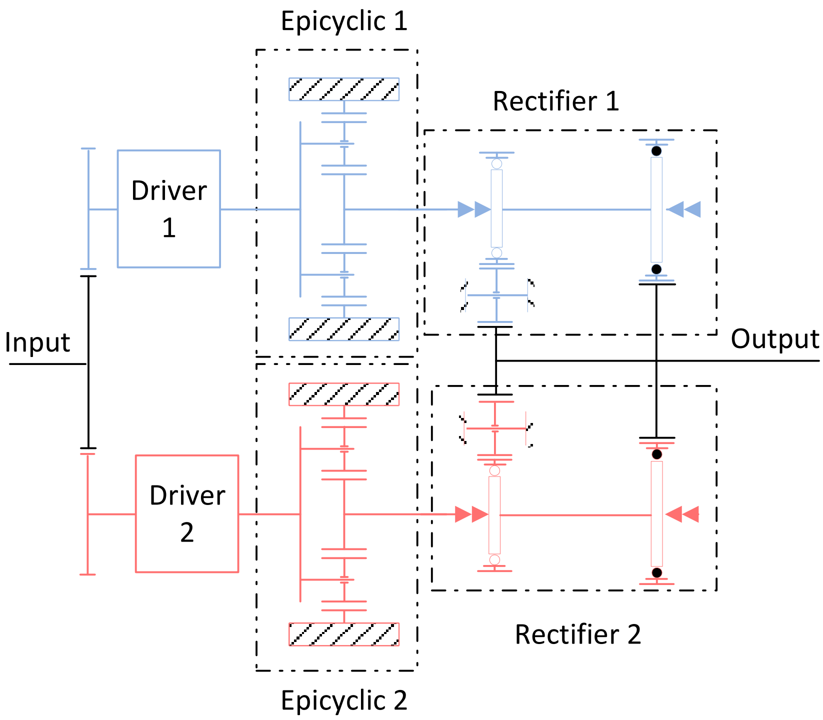

Figura 13: Esquema del sistema con dos trenes epicicloidales

Debido al desfase que existe entre los dos sistemas, cuando uno de ellos se encuentra en el segundo modo de funcionamiento, el otro se encuentra o bien en el 1 o bien en el 3, por lo que de esta forma también se compensan parcialmente las vibraciones debidas al principio de funcionamiento analizado anteriormente.

Analizando los pares transmitidos por las ruedas libres y las velocidades de los planetas (sun) de los trenes epicicloidales (Figura 14) puede comprobarse como el desfase introducido por los mecanismos de accionamiento se mantienen de forma que al menos una rueda libre siempre se encuentra transmitiendo movimiento y existe un solapamiento la mayoría del tiempo. Como en este sistema existen ahora 4 ruedas libres, el par transmitido por cada una de ellas es menor que en el caso de un único tren.

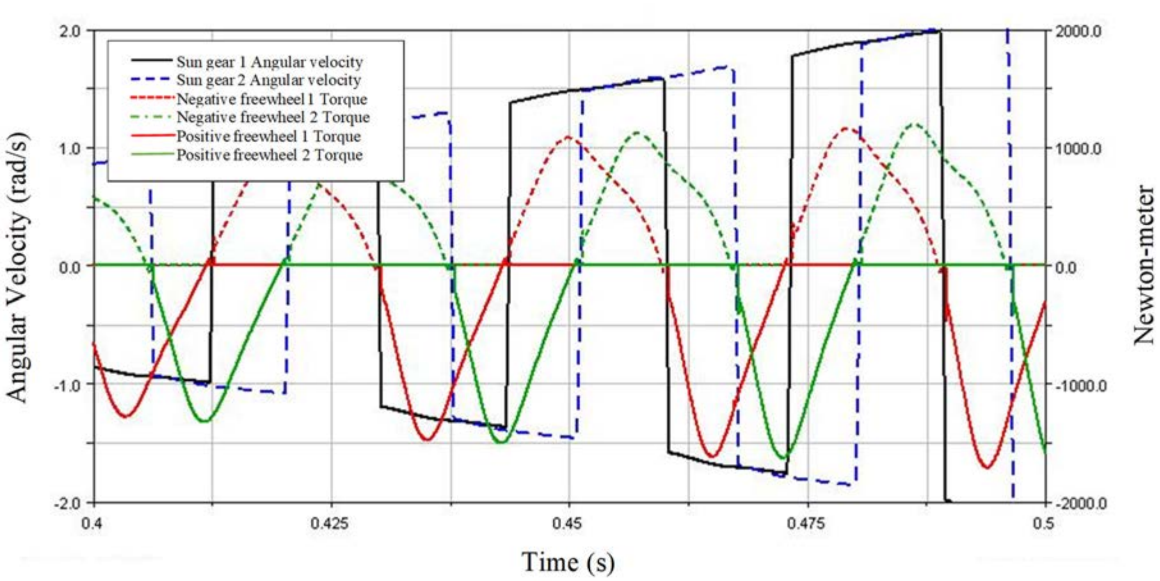

Figura 14: Pares transmitidos por las ruedas libres

Como conclusión, puede decirse que el hecho de usar dos trenes epicicloidales reduce las vibraciones del Sistema en base a:

- El par transmitido por las ruedas libres es menor.
- La velocidad de salida es mas suave debido al solapamiento entre la potencia transmitida por las ruedas libres.
- Hay una compensación parcial entre los modos de funcionamiento de los dos trenes epicicloidales reduciendo las oscilaciones del eje de entrada.

7. CONCLUSIONES

En este documento se analizan las distintas fuentes de vibraciones generadas por las CVTs de tipo inercial.

Las fuentes de vibraciones analizadas son intrínsecas al principio de funcionamiento de este tipo de CVTs y por lo tanto no pueden ser eliminadas. Sin embargo, se han propuesto una serie de posibilidades para reducir en lo posible estas vibraciones.

Para realizar estos análisis se han utilizado tanto modelos analíticos como computacionales y test en banco de ensayos.

Una conclusión importante de este estudio es que el comportamiento de una CVT inercial depende en gran medida de la fuente de potencia. Es decir, es dependiente de si se acciona mediante un motor eléctrico o mediante un motor de combustión interna y este hecho es fundamental a la hora de realizar ensayos, ya que la inmensa mayoría de los bancos de ensayo de transmisiones se encuentran accionados por motores eléctricos.

Este trabajo es parte de una línea completa de investigación. Este documento se ha centrado en las vibraciones de los sistemas de transmisión inerciales, pero no explica su principio de funcionamiento en detalle. Un estudio detallado de estos sistemas puede encontrarse en artículos y documentos previos (Morales y Benitez, 2019; Centeno et al., 2010; Perez, 2010; Morales, 2011).

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INFLUENCE OF TIRE DYNAMICS ON A BRAKING PROCESS WITH ABS

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ABSTRACT

This article analyzes the influence of the proper modeling of the anti-lock brake system control loop components. Both the use of a stationary tire model and not considering the delays due to measurement, estimation, and actuation tend to be overlooked. Therefore, this affects the efficiency of the control algorithms developed through simulation. Thus, this work proposes to analyze the influence of the modeling of the components by performing experimental tests on a flat-track test bench. These tests demonstrate the need for taking these effects into account.

1. INFLUENCE OF TIRE DYNAMICS ON A BRAKING PROCESS WITH ABS

Correct modeling of the anti-lock brake system (ABS) components is crucial in the process of setting and optimizing a control algorithm through simulation. Therefore, this paper models all the components and analyzes their influence on the controllability of the braking system. The ABS control loop (Fig. 1) is composed of 4 main components: The system to be controlled, also called plant (tire-road interaction), the actuator (braking system), the measurement and estimation system (speed sensing), and finally the control algorithm.

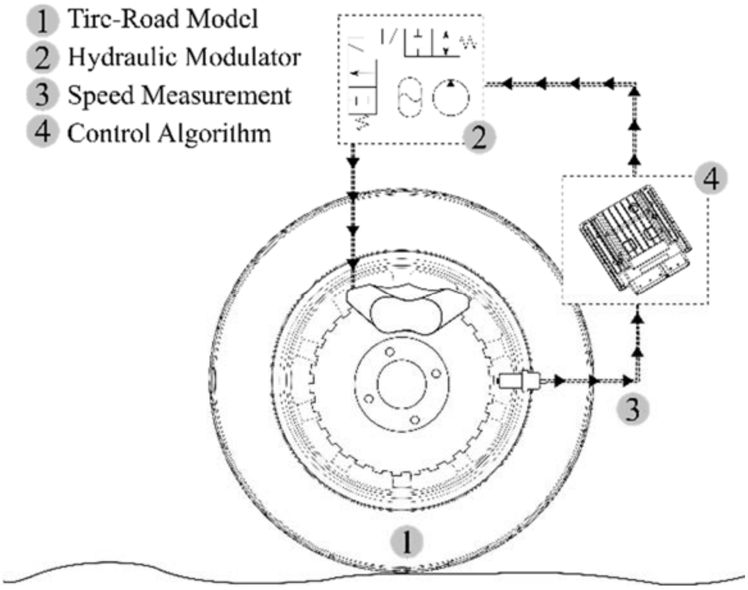

Figure 1: ABS Control Loop

First of all, the most commonly used tire model is the well known Pacejka's Magic Formula in its steady-state formulation (Pacejka, 2012). This model (1) relates the friction coefficient (μ)defined as the coefficient between the longitudinal and vertical forces to the slip ratio (κ) according to expression (2).

$$\mu = D_x sin[C_x\ arctan\{B_x\kappa - E_x(B_x\kappa - arctan(B_x\kappa))\}] \quad (1)$$

$$\kappa = -V_{sx}/|V_x| = (R_e\omega - V_x)/|V_x| \quad (2)$$

Where R_e is the wheel effective radius, ω the wheel angular speed, V_x the vehicle speed and (B_x, C_x, D_x, E_x) are the stationary parameters of the tire obtained on a test bench.

Since wheel locking occurs in a short time and with large variations in the contact forces (Arrigoni et al., 2017), a transient model (3) has to be used (Pauwelussen et al., 2003). This model uses the relaxation length (σ_κ) to add a delay between the transient longitudinal slip (κ') and the corresponding longitudinal force.

$$\kappa\sigma_\kappa \cdot d\kappa'/dt + |V_x|\kappa' = \sigma_\kappa\dot{\kappa}' + |V_x|\kappa' = -V_{sx} \quad (3)$$

Because the tire model parameters are obtained at a constant speed in test benches, it does consider the speed variation during braking processes. In Cabrera et al. (2018), this dependence is analyzed and is included in the tire model (4):

$$\kappa\lambda_{\mu x} = P_{x1} + P_{x2}exp(-P_{x3}\kappa'\, V_x) \quad (4)$$

Where (P_{x1}, P_{x2}, P_{x3}) are the parameters that describe the increase in adherence. All this modifies the adherence and optimal slip ratio (Ružinskas & Sivilevičius, 2017) throughout the braking process.

The actuator commonly used is a hydraulic control valve system (Tavernini et al, 2019) which, by increasing or decreasing the pressure, changes the contact force between the brake pads and the disc. This control system has an opening and closing time modeled using a first-order system including the fluid and friction dynamics (5) with a time constant (τ).

$$\tau\, dT_b/dt = \tau\, \dot{T}_b = K_b P_b - T_b \tag{5}$$

The torque applied (T_b) by the braking system is proportional (K_b) to the brake pressure (P_b). The measurement of the variables to be controlled is either carried out by sensors in a direct mode or by estimating their value in an indirect mode. The main variables in a braking control system are the speed of the vehicle and the speed of the wheel to be controlled. The latter is measured using a sensor that produces a wave whose frequency is proportional to the rotation speed. Both the variable resolution and the delay of the wheel speed sensor have to be considered to fit the one used in the vehicle. On the other hand, the speed of the vehicle is obtained indirectly as the technology that allows its direct measurement for commercial vehicles is costly. Therefore, the estimator used has to be implemented in the simulation in order to include the delays associated with estimation. Finally, the last of the four main components are the control algorithm that regulates the pressure to maximize the adherence preventing the wheel from locking. The simulation of an ABS optimizes this component to maximize braking. The main contribution of this research is to ensure that the simulation is accurate, so it behaves in the same way as the real. Therefore, it is proposed to keep the control algorithm fixed, with a simple control logic (6), (7) and analyze how the model of the other components influences the simulation and the real experimentation.

$$P_b = \{[P_{max} \quad \kappa' < \kappa_{opt}], [P_{min} \quad \kappa' > \kappa_{opt}]\} \tag{6}$$

$$\kappa_{opt}(\lambda_{\mu x}) = \lambda_{\mu x} \cdot P_{C_x} P_{D_x} \tan\left(\frac{\pi}{2 P_{C_x}}\right) / P_{B_x} \cdot \kappa = -V_{sx}/|V_x| = (R_e \omega - V_x)/|V_x| \tag{7}$$

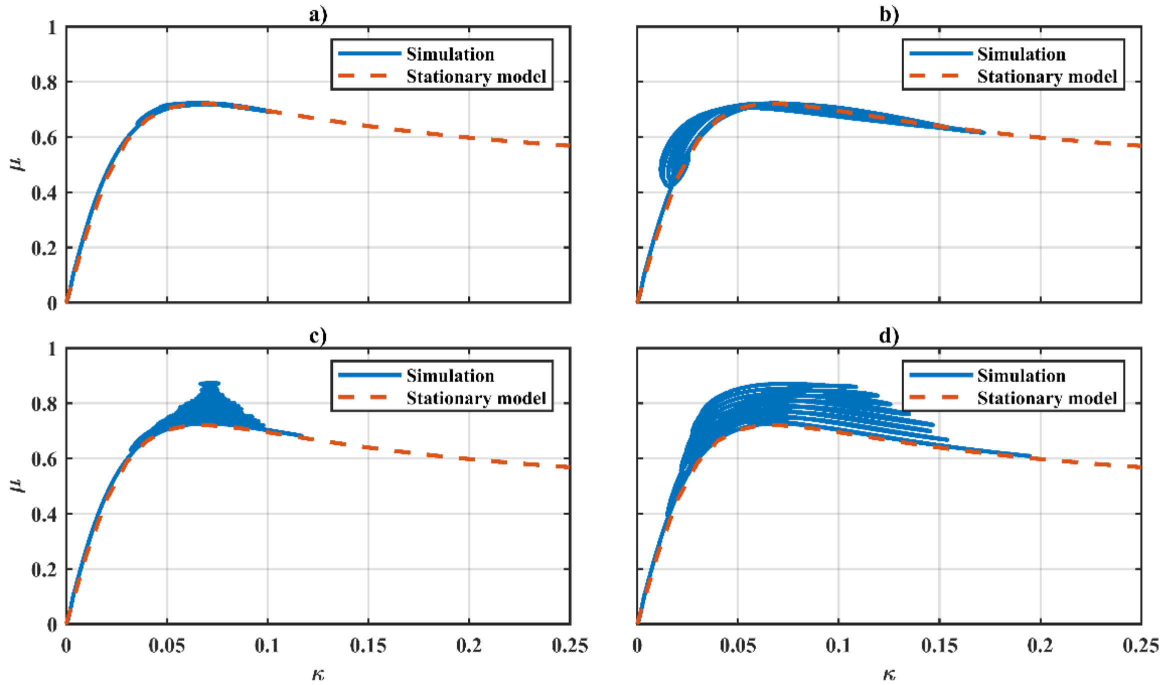

Figure 2: Influence of increasing adherence and measuring time in simulation: none (a), only measuring time (b), only increasing adherence (c), both (d).

2. CONCLUSIONS

The following conclusions can be drawn after analyzing the modeling of the different components of the ABS control loop. Both the adherence dependence with speed and the delays due to the measurement or estimation of variables are the ones that cause more fluctuations in the system response (Fig. 2). These introduce large oscillations, as well as affect the friction coefficient obtained throughout the simulation. In addition, both components tend to go overlooked in most of the literature that develops control algorithms for ABS systems. Usually, they are not supported by experimental tests or they do not show a proper fit with the simulation. This paper tries to emphasize the importance of the proper modeling of the ABS control loop components as well as to highlight the importance of experimental validation when developing control algorithms.

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NUMERICAL SIMULATION OF A SEMITRAILER'S LATERAL PROTECTION SYSTEM AGAINST CAR FRONTAL CRASH

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ABSTRACT

The present study is focused on the dynamic simulation of a car frontal crash against a lateral protection system for semitrailers. This system is a barrier fixed laterally to each side in semitrailers, designed to reduce damages on car passengers in case of lateral collision. From the basis of an already existing design, different designs and finite element models where created, adapting the system to the European regulation UNECE nº 73, concerning lateral protection devices' homologation. Finite element models were developed and different materials were considered on the metallic barrier beams. Then, crash simulations using the software LS-DYNA were performed, where a passenger car Toyota Yaris Sedan (2010 model) was impacted against the barrier at 50 km/h, 90 km/h and 120 km/h. Results such as maximum car displacements and deceleration on passengers could be analysed in these simulations. It was assessed the possibility of achieving a weight reduction of the barrier by means of design and material modifications.

1. INTRODUCTION

Current European lateral protection devices installed in semitrailers are designed according to UNECE regulation no 73 (UNECE, 2011), which is focused on the protection of vulnerable road users such as pedestrians, cyclist and motorcyclist, preventing them from being dragged and ran over by the semitrailer's wheels in the event of a collision. In this sense, this regulation defines dimensional, strength and stiffness requirements for the lateral protection systems. Nevertheless, this regulation does not offer protection for more aggressive impacts such as those in which a car collides head-on against the lateral of the semitrailer. In many of these accidents, the car passes through the semitrailer and its roof is torn apart, often resulting in fatal consequences for the car occupants. Considering all kind of vehicles, it can be pointed out that fatalities in lateral and frontal-lateral collisions represented 12% of the total casualties (at 24 h) reached between 2015-2019 at Spanish intercity roads (Observatorio Nacional de Seguridad Vial, 2021). It is also reported that considering all kind of accidents involving heavy goods vehicles in the European Union during 2016-2018, the share of car occupants killed in collisions accounted for 50% of all deaths (Adminaité-Fodor & Jost, 2020). Therefore, it seems plausible that future safety developments and regulations contemplate this type of collision and include more stringent stiffness and strength requirements for lateral protection devices, in the same way as current rear protection systems assembled to semitrailers are demanded to protect car occupants in frontal collisions. In this sense, in the U.S. a new regulation on mandatory requirements to prevent side and front underride accidents was discussed in the “Stop Underrides Act” (H.R.1511, 2019). Crash simulation with finite element software offers the possibility of modeling and simulating the crash behavior of new protection devices at lower costs than actual tests where vehicles are needed to be crashed; in order to guarantee an accurate numerical-experimental correlation several prototypes should always be tested, though. For instance, simulations performed with LS-DYNA could greatly contribute to estimate the vehicles’ crash performance, when new designs of lateral protection systems are included in the model. In order to explore simulation possibilities on this scenario, this paper is focused on the finite element simulation of a semitrailer’s lateral protection system in a car frontal crash situation, with the car colliding perpendicularly to the semitrailer. It was analyzed not only the device’s mechanical performance for different materials and geometric configurations, but also the deceleration reached inside the car and the car displacement when is running at different speed values before hitting.

2. MATERIALS AND METHODS

2.1 “AngelWing” side guard

On the one hand, the starting point was an already existing lateral protection system called “AngelWing” developed by the manufacturer “Airflow deflection” (airflowdeflector, 2021). It was assembled to both sides of a semitrailer and then crash-tested by the IIHS (Insurance Institute for Highway Safety) in 2017 against a Chevrolet Malibu (2009 model) impacting frontally. The test proved that the passive safety offered by this truck side guard prevents the car from underrunning the semitrailer: according to the manufacturer, the guard prevents Passenger Compartment Intrusion at speeds of up to 64.37 km/h (40 mph). Therefore, this device added to other car safety devices such as seat belts, airbags, proximity sensors and emergency brake systems, can highly improve the survival chances for the car occupants. This guard was made of galvanized ASTM A500 steel beams, its global dimensions were

6090×584×2565 mm and its weight was 364 kg; according to the manufacturer, this guard is currently sold by length and truck application.

2.2 Regulation no 73

On the other hand, European regulation no 73 contains the requirements that lateral protection devices (LPD) for vehicles of categories N2, N3, O3 and O4 must comply for their approval in the European Community. Concerning the analysis included in this paper, it has been considered a semitrailer with a maximum mass exceeding 10 tonnes, which corresponds to vehicle category O4 (European Parliament, 2007). The following points, extracted from regulation no 73, detail the dimensional requirements established for LPD in O4 vehicle category:

- LPD shall not increase the overall width of the vehicle and the main part of their outer surface shall not be more than 150 mm inboard from outermost plane of the vehicle. Their rearward end shall not be more than 30 mm inboard from the outermost edge of the rear tyres over at least the rearmost 250 mm.
- LPD may consist of a continuous flat surface, or of one or more horizontal rails, or a combination of surface and rails: when rails are used they shall be not more than 300 mm apart and not less than 100 mm high and essentially flat (O4 case).
- The forward edge of LPD shall be not more than 250 mm to the rear of the transverse median plane of the support legs, if support legs are fitted, but in any case the distance from the front edge to the transverse plane passing through the centre of the kingpin in its rearmost position may exceed 2.7 m.
- Where the forward edge lies in an open space of more than 25 mm, the edge shall consist of a continuous vertical member extending over the whole height of the device; the outer and forward faces of this member shall measure at least 100 mm rearwards and be turned 100 mm inwards or have a minimum radius of 100 mm.
- The rearward edge of LPD shall not be more than 300 mm forward of the vertical plane perpendicular to the longitudinal plane of the vehicle and tangential to the outer surface of the tyre on the wheel immediately to the rear; a continuous vertical member is not required on the rear edge.
- The lower edge of LPD shall at no point be more than 550 mm above the ground.
- The upper edge of LPD shall not be more than 350 mm below that part of the structure, cut of contacted by a vertical plane tangential to the outer surface of the tyres.

With respect to strength and stiffness performance, regulation nº 73 defines the following requirements:

- LPD shall be essentially rigid, securely mounted (not liable to loosening due to vibration) and made of metal or any other suitable material. LPD shall be considered suitable if they are capable of withstanding a horizontal force of 1 KN applied perpendicularly to any part of their external surface by the centre of a ram the face of which is circular and flat, with a diameter of 220 mm ± 10 mm, and if the deflection of the device under load measured at the centre of the ram is then not more than 30 mm over the rearmost 250 mm of the device; and 150 mm over the remainder of the device.

As stated before, while these mechanical requirements are focused on protecting vulnerable road users, it is clear that they are not stringent enough to avoid severe damages in high energy collisions such that with a car hitting the device laterally. For instance, rear protection systems are required to reach much higher forces when tested according to regulation no 58 (UNECE, 2017), with a maximum of 100 KN or 180 KN depending on the location of the points tested.

2.3 Finite element models created for the lateral protection systems

Taking into account all the previous considerations, three different finite element (FE) models were created. Figure 1 shows the six-post model and its main structural dimensions. It used shell elements and consisted of four longitudinal beams (100×100×3 mm) joined by six vertical posts (100×50×3 mm) at each side and six sets of crossed beams (100×50×3 mm) transversally connected to the posts. Bolted and weld joints were simplified by means of equivalent nodes between adjacent parts. Two more variants were created as a simplification from this model: three-post model and two-post model, which are showed in figure 2 and were also analysed.

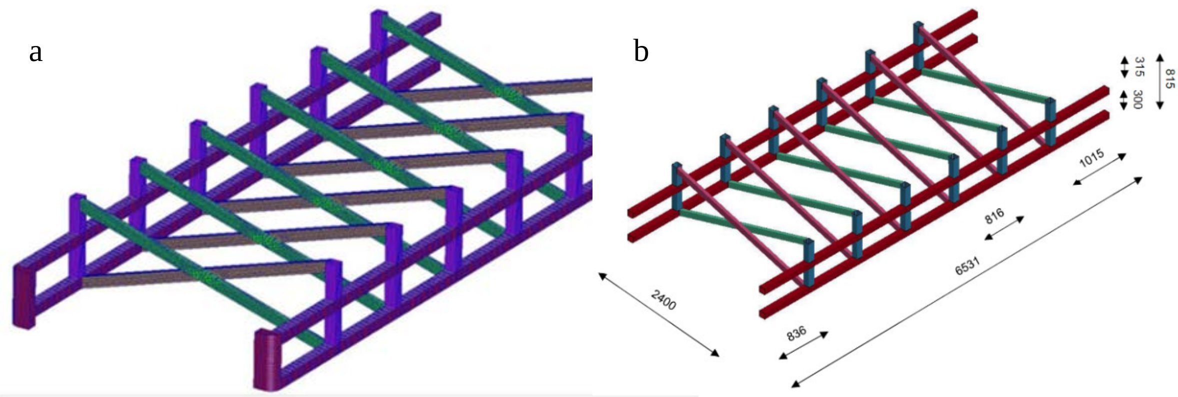

Figure 1: (a) Six-post lateral protection system's FE model; (b) Main structural dimensions

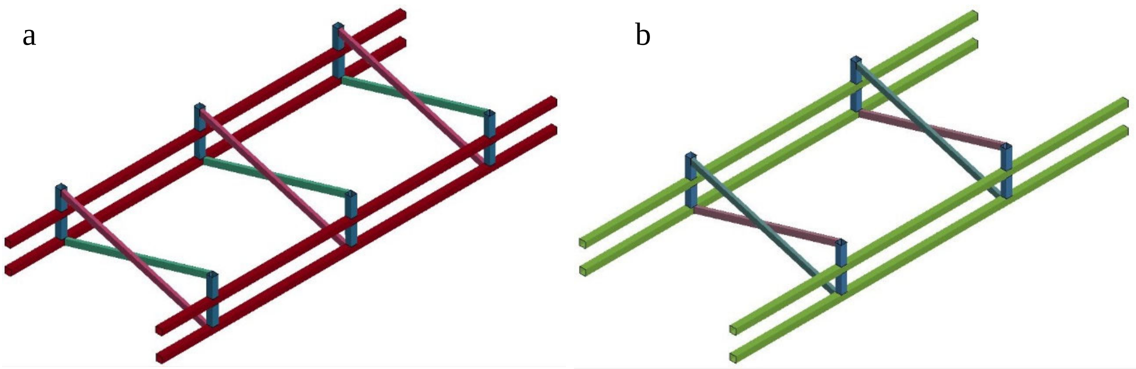

Figure 2: (a) Three-post lateral protection system's FE model; (b) Two-post lateral protection system's FE model

All were modeled using 4-node shell elements with Hughes-Liu formulation and a mesh size of 20 mm. They were created with the software MSC Patran and later on imported in LS-DYNA prepost. The crash behavior of each model was simulated and compared using three different materials for the whole system: S275 (structural steel), Strenx Tube 700MH (high strength steel) and AL 6005A T6 (aluminium alloy with cooling in press). Table 1 shows the main mechanical properties of materials considered in the models and table 2 shows the total weight that resulted from each lateral protection system design.

Material		Density (kg/m^3)	Young modulus (MPa)	Poisson ratio	Yield strength (MPa)	Ultimate strength (MPa)	Elongation at break ($^{o}/_{1}$)
Steel	S275 [8]	7850	210000	0.33	275	500	0.2
	Strenx Tube 700MH [9]	7850	210000	0.33	700	850	0.1
Aluminium	6005A – T6 [10]	2710	69500	0.33	215	255	0.08

Table 1: Mechanical properties of materials considered in the FE models

Material		Six-post model Weight (kg)	Three-post model Weight (kg)	Two-post model Weight (kg)
Steel	S275	526.61	388.58	342.60
	Strenx Tube 700MH			
Aluminium	6005A – T6	184.77	137.12	121.25

Table 2: Total weights of the lateral protection systems simulated

2.4 Finite element car model for the crash simulation

All the crash simulations were performed using LS-DYNA, and the FE car model was a Toyota Yaris Sedan (2010), which is available at the National Highway Traffic Safety Administration (NHTSA) web page and has been used in support of several NHTSA programs (NHTSA, 2021). This FE car model was developed by a reverse engineering process at the George Washington University National Crash Analysis Center (NCAC). Its collision performance has been validated with the NCAP 5677 and 6221 tests against a rigid wall (impacting at 40.23 and 56.32 km/h) and it presents also a robust response for the study of a variety of crash scenarios (Marzougui et al., 2012; NCAC, 2011). This model consists of 1480422 nodes and 1514068 elements and it is showed in Figure 3.

3. CALCULATION. BOUNDARY CONDITIONS AND LOAD CASES

In the first place, the EuroNCAP (European new car assessment programme) full width frontal impact test against a concrete barrier (Euro NCAP, 2019) was used as reference, in order to assess the car's deceleration values obtained during the collision against the lateral protection system. The concrete barrier was simulated with rigid shell elements, as showed in figure 3. In this case the car was simulated impacting at 50 km/h, 90 km/h and 120 km/h speed. Since the total mass of the car was 1306.29 kg, the kinetic energies involved in the collision were respectively 125994.49 J, 408215.62 J and 711274.9 J. It can be noted that, starting at a collision speed of 50 km/h, an increase of 40 km/h leads to 3.2 times higher kinetic energy and an increase of 70 km/h leads to 5.6 times higher kinetic energy. Being the wall completely rigid, these simulations represent a highly unfavorable crash situation where all the plastic strain energy was absorbed by the car structure (mainly by the front structural components).

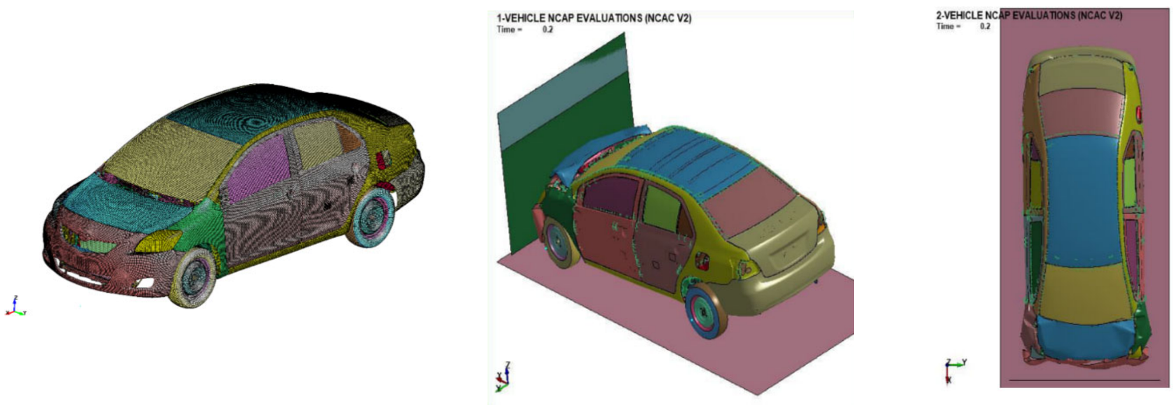

Figure 3: NCAC's FE model for the 2010 Toyota Yaris Passenger Sedan and EuroNCAP full width frontal impact test simulation

In this way, the deceleration results obtained for the lateral protection systems simulated later on, could be compared with these previous results obtained colliding the car frontally against a rigid wall. A rigid shell element simulated the ground and all the nodes of both the wall and the ground were fully constrained (all linear and rotational degrees of freedom). An initial velocity condition was applied to all nodes of the vehicle, with an additional rotational velocity at those nodes comprising the wheels' parts; it also included the gravity acceleration and a general contact condition applied to all the elements of the model.

Regarding the crash simulations for the lateral protection systems analysed, an equivalent approach was considered. In this case, all the nodes located at the top of the vertical posts were fully constrained, corresponding to those regions welded or bolted to the semitrailer's structure. This boundary condition represented a much stiffer situation than what occurs in reality, since the semitrailer's structure could also absorb some strain energy during the collision. Moreover, depending on the energy level involved, among other factors, the semitrailer could even gain kinetic energy and be pushed laterally by the car through the ground. Therefore, the simulations performed were conservative and peak deceleration values reached inside the car were expected to be higher under simulation conditions than under real conditions.

Figure 4 shows the constrained nodes at the top of the posts beams (blue posts in the figure) and the numerical model for simulating the collision against the six-post lateral protection system. In all simulations performed for this study, the car was positioned colliding at the centre of the barrier.

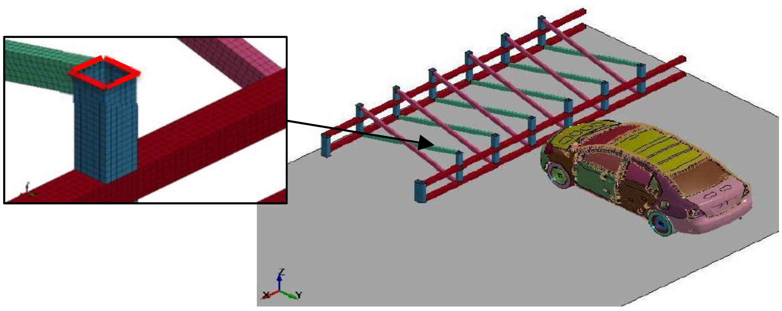

Figure 4: Numerical model simulating a collision against the six-post lateral protection system. Detail with constrained nodes at the top of the posts

4. RESULTS AND DISCUSSION

4.1 Variation in the lateral protection system's geometry

Once the models were created, the first analysis was focused on comparing the performance of the three different designs considered. Figure 5 shows the final frame at the end of each simulation, all calculated with the car impacting at 50 km/h and applying S275 steel to the barriers. While the six-post and the three-post systems were able to stop the car and performed correctly, the two-post system was not stiff enough and collapsed completely. The car model has an accelerometer positioned at its center of gravity for registering the acceleration inside the vehicle. Since the impact time is around 0.14 s, the impact's frequency is near 7 Hz. Then, a 7-Hz low-pass SAE filter was applied to the acceleration signal in order to filter higher frequencies. The car deceleration values, measured in g's, and the car total displacements registered during these simulations can be seen in figures 6 and 7 respectively.

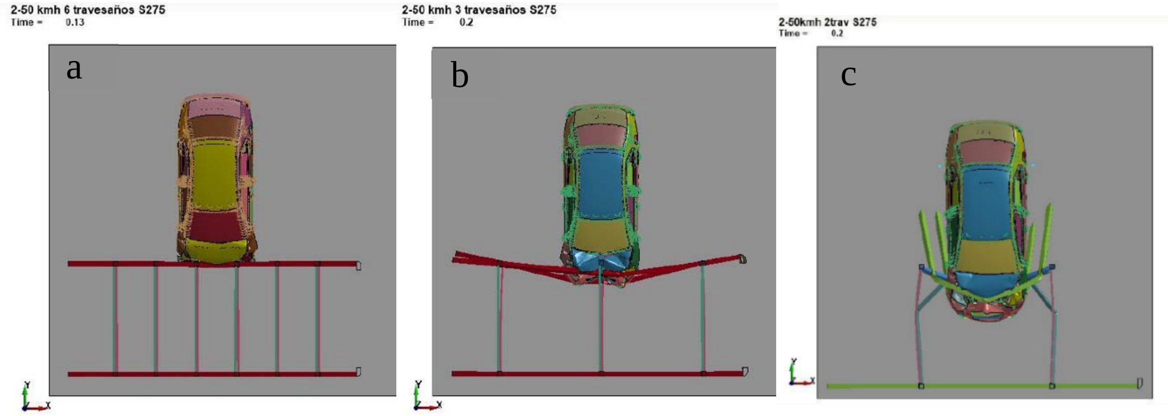

Figure 5: Final frame for simulations at 50 km/h with S275 lateral protection systems: (a) Six-post system; (b) Tree-post system; (c) Two-post system

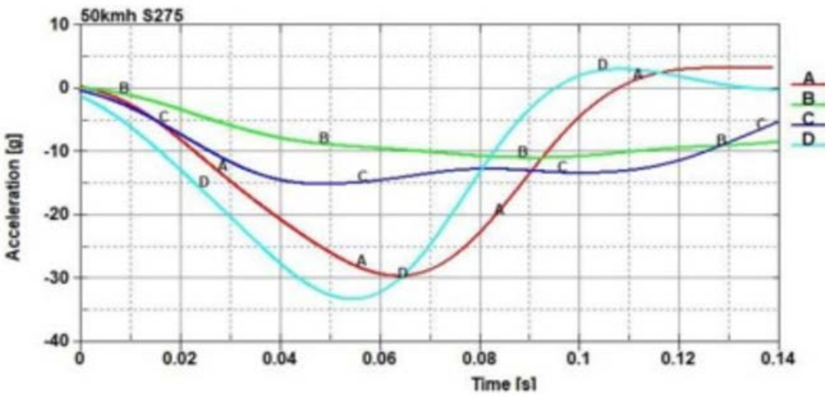

Figure 6: Car deceleration (g's) for simulations at 50 km/h with S275 lateral protection systems: (A) Six-post system; (B) Two-post system; (C) Three-post system; (D) NCAP rigid wall

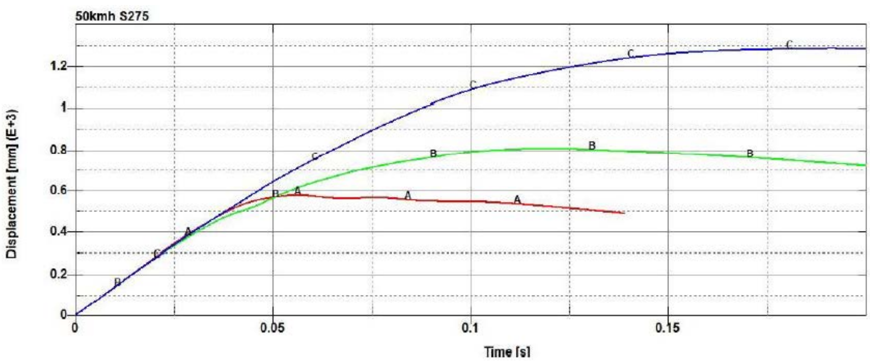

Figure 7: Car displacements (mm) for simulations at 50 km/h with S275 lateral protection systems: (A) Six-post system; (B) Three-post system; (C) Two-post system

While the two-post system collapsed and was not able to stop the car properly, with a displacement value of 1.2 m, the other two systems stopped the car with quite lower displacement values: 0.8 m in the two-post system and near 0.57 m in the six-post system. From these graphs, it can be observed that the three-post system produced a maximum deceleration of 15 g's and the six-post system produced a maximum deceleration of 30 g's. Therefore, the three-post design was preferred to the six-post design. The latter performed with a much stiffer response, with its peak deceleration very close to the rigid wall's one (approximately 33 g's).

4.2 Variation in the lateral protection system's material

In order to compare the performance for the three materials considered (steel S275, high strength steel Strenx 700 MH and aluminium alloy 6005 A-T6), the three designs were simulated applying the same material to all barrier components, at each case. Figure 8 shows the final frame at the end of each simulation for the six-post system. Likewise, they were all calculated with the car impacting at 50 km/h.

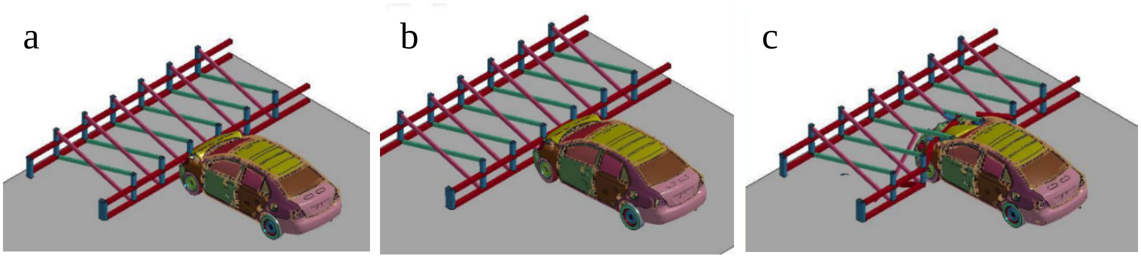

Figure 8: Final frame for simulations at 50 km/h with different materials in the lateral protection systems: (a) S275; (b) Strenx 700 MC; (c) AL 6005A-T6

Figure 9 shows the deceleration values for the simulations with the six-post design, as well as the NCAP rigid wall test' deceleration values (in g's). Figure 10 shows the car displacement values in mm.

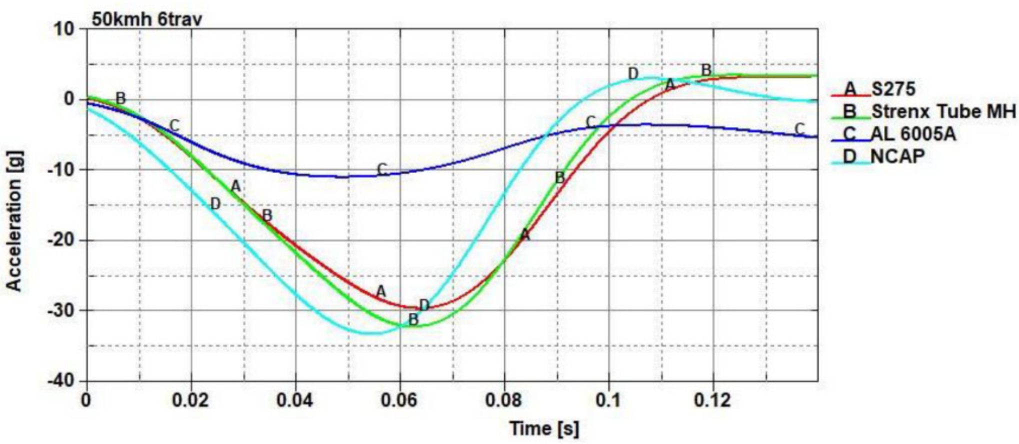

Figure 9: Car deceleration (g's) for simulations at 50 km/h applying different materials to the six-post system: (A) S275; (B) Strenx 700 MH; (C) AL 6005A-T6; (D) NCAP rigid wall

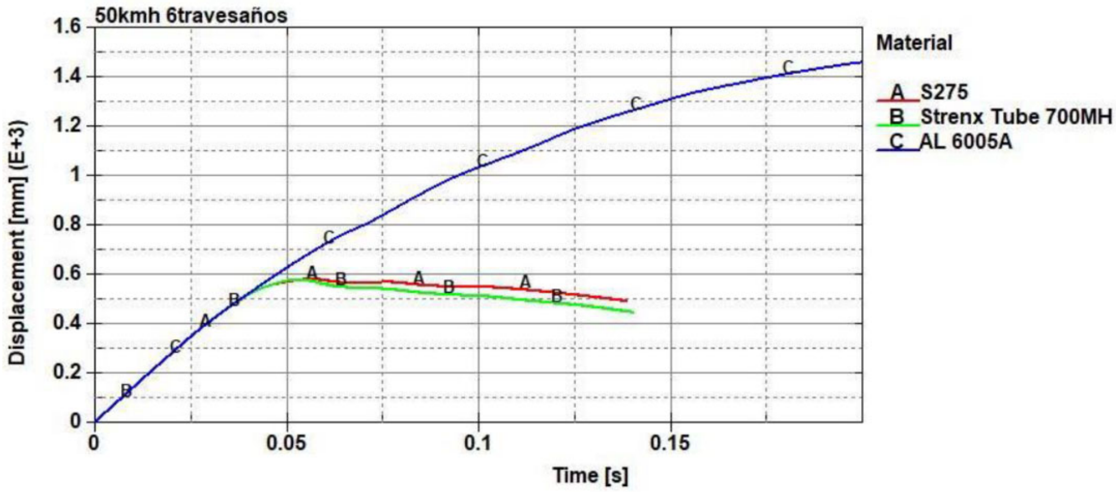

Figure 10: Car displacement (mm) for simulations at 50 km/h with different materials in the lateral protection systems: (A) S275; (B) Strenx 700 MH; (C) AL 6005A-T6

As can be observed from figure 9, the application of high strength steel gave a closer response to the rigid wall collision simulation. However, the aluminium design could not stop the vehicle, with the barrier failing and the car passing through it, as can be observed from figure 10. Both steel systems showed a maximum car displacement of approximately 0.57 m.

4.3. Variation in car's impact velocity

The performance of the lateral protection system with the car colliding at different speed values was also assessed. A collision case at 50 km/h could correspond to an urban road, but, depending on the road category and the speed limits allowed, the lateral collision may take place with the car running at higher speeds.

In order to analyze the system's response at higher kinetic energies, all designs were also simulated applying initial velocities of 90 km/h and 120 km/h. Figure 11 shows the final frame of the simulations with the car impacting at 50 km/h, 90 km/h and 120 km/h, all against the same three-post S275 design.

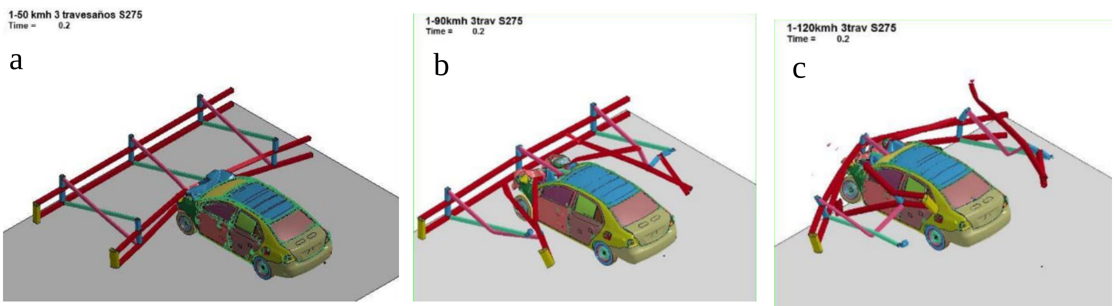

Figure 11: Crash against S275 three-post system: (a) 50 km/h; (b) 90 km/h; (c) 120 km/h

As can be observed in figure 11 (a), the S275 three-post protection system was able to stop the car impacting at 50 km/h, with the energy absorption shared between the protection system and the car's frontal.

Nevertheless, at higher collision speeds of 90 km/h and 120 km/h, the device could not stop the car due to the higher energies involved (respectively, 3.2 and 5.6 times as much as the 50 km/h case), which led the barrier to a full collapse. In both cases the car would continue its movement through the semitrailer, which would be fatal for the car occupants. Figure 12 shows the car deceleration values measured in g's for these simulations. Figure 13 shows the car displacement values in mm.

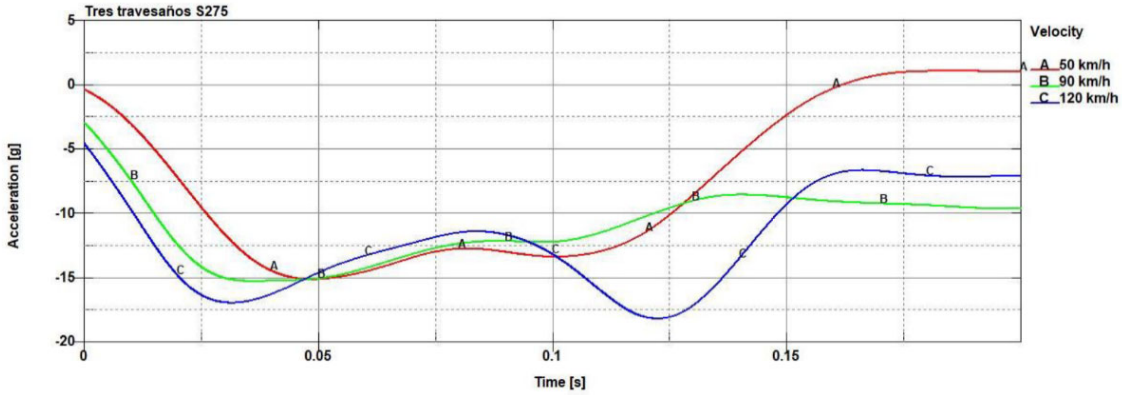

Figure 12: Car deceleration (g's) for S275 three-post system: (A) 50 km/h; (B) 90 km/h; (C) 120 km/h

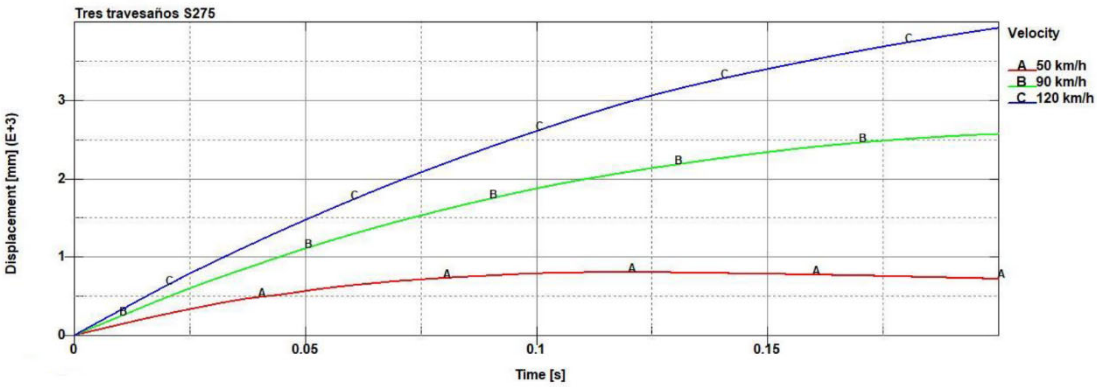

Figure 13: Car displacement (mm) for S275 three-post system: (A) 50 km/h; (B) 90 km/h; (C) 120 km/h

5. CONCLUSIONS

Crash simulation numerical tools can contribute to develop efficient and effective lateral protection systems for semitrailers. On the one hand, in order to improve safety in frontal-lateral car-semitrailer collisions, these systems should be able to resist a certain kinetic energy level as well as to avoid the underrun phenomenon. On the other hand, taking into account that semitrailers must normally cover long range travels, it is desirable to produce light designs that do not lead to an increase in fuel consumption and CO_2 emissions. It has been analysed a car frontal crash against a lateral protection system for semitrailers adapted to the European regulation by means of finite element dynamic simulations performed with the software LS-DYNA. Three different models were created using beam with rectangular hollow sections, referred to as the two-post, three-post and six-post lateral protection systems, varying their number of posts and cross-members. Three different materials were compared: S275 structural steel, Strenx Tube 700MH high strength steel and aluminium alloy 6005A T6. Lastly, three different car impact speeds where simulated: 50 km/h, 90 km/h and 120 km/h.

For simulations with the car running at 50 km/h, the aluminium stiffest design (the six-post one) was not able to resist the energy level involved. Therefore, all aluminium alloy designs were discarded despite their lower weights. At 50 km/h, the two-post system performed poorly in general, all producing underrun situations. On the contrary, the six-post system was found to be excessively stiff in both structural steel and high strength steel models, producing high deceleration peak values inside the car, that could damage the occupants. Then, at that speed, the intermediate three-post system with S275 was the preferred option in terms of cost, weight and safety. The car stopped with a 15 g's peak deceleration and the strain energy was absorbed with better balance by both the barrier and the car.

Therefore, this design could be supposed to perform adequately in urban roads. However, when the car was launched at 90 km/h and 120 km/h, the three-post system was not able to stop the car, and the underrun would be fatal to its occupants. As the kinetic energy level in these collisions depends on the mass and the speed of the car, the results suggest that these lateral protection systems could be designed to offer a proper response at a certain kinetic energy range. A trade-off between peak deceleration values and the allowable car displacement due to the barrier deformation will always be necessary. For instance, although highly stiff designs could lead to peak decelerations near to the rigid wall test's values and would probably add a higher structural weight, they could possibly avoid the car underrun in non-urban road accidents.

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THERMAL COMFORT IN CONVENTIONAL VEHICLES (ICE) AND ELECTRIC (EV) - EVALUATION METHODS

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ABSTRACT

Development and fine-tuning of a procedure for measuring the temperature in the car windshield area, with respect to the European demisting standard (CEE 78/317): by using a high-speed infrared thermography camera.

Carry out a differential analysis of the experimentally obtained results both in terms of thermal comfort, between vehicles equipped with ICE technology (conventional) and vehicles equipped with EV technology.

1. INTRODUCTION

Electric mobility is expanding at a rapid rate. Electric car deployment has been growing rapidly over the past ten years, with a global stock of electric passenger cars surpassing 5 million in 2018, a 63% increase over the previous year.

About 45% of electric cars on the road in 2018 were in China, a total of 2.3 million, compared with 39% in 2017. By comparison, Europe accounted for 24% of the world's fleet, and the United States 22%.

Sales of electric vehicles in the world grew 64% in 2018. Sales of electric vehicles in the world during 2018 reached 2.1 million. 69% of sales were all electric (EV) and 31% were plug-in hybrids (PHEV).

These figures include electric and plug-in hybrid passenger cars, light trucks in the US and Canada, and light commercials in Europe and China.

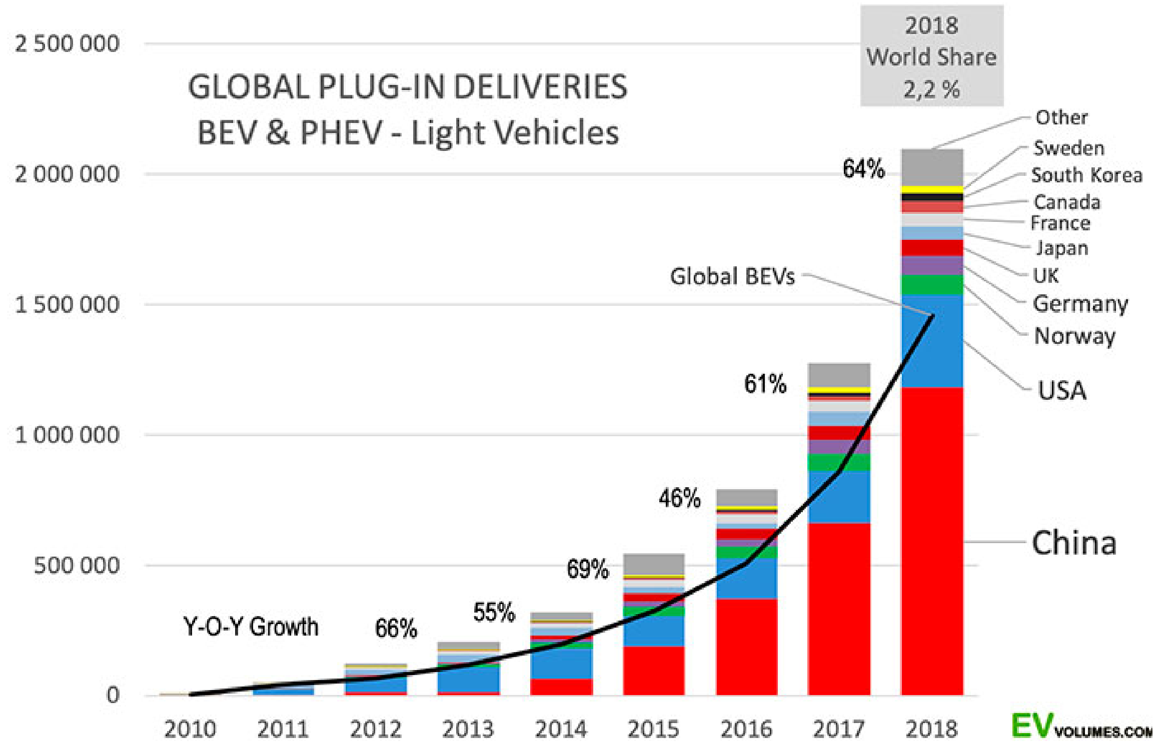


Figure 1: Global BEV & PHEV Light Vehicles Deliveries

69% of sales were all electric (EV) and 31% were plug-in hybrids (PHEV). Fully electric vehicles have reached a 3% share since 2017. The causes, according to the Swedish consultancy EV-volumes, lie mainly in three factors. The first, growth in China. The second, the arrival of the Tesla Model-3. The third, the losses for PHEVs in Europe due to the entry into force of the WLTP protocol.

The largest contributor to growth, by far, was China. Its electricity sales increased by more than 500,000 units, to 1.2 million in 2018. It represented 56% of all electrified sales. (Figure 1).

Growth in Europe was moderate, at 34% (Figure 2). It was held back by limited ranges and long waiting lists for popular EVs. Also, due to the exhaustion of sales of PHEVs in stock. In the US, sales were up 79% and the expected Tesla Model-3 contributed 138,000 units. It became the best-selling EV of all categories in 2018. It even dominated luxury car sales in North America. Sales outside of China, Europe and the US were 150,000 units (+ 39%), with Japan again the opposite. However, other markets such as Canada and South Korea grew much faster than average.

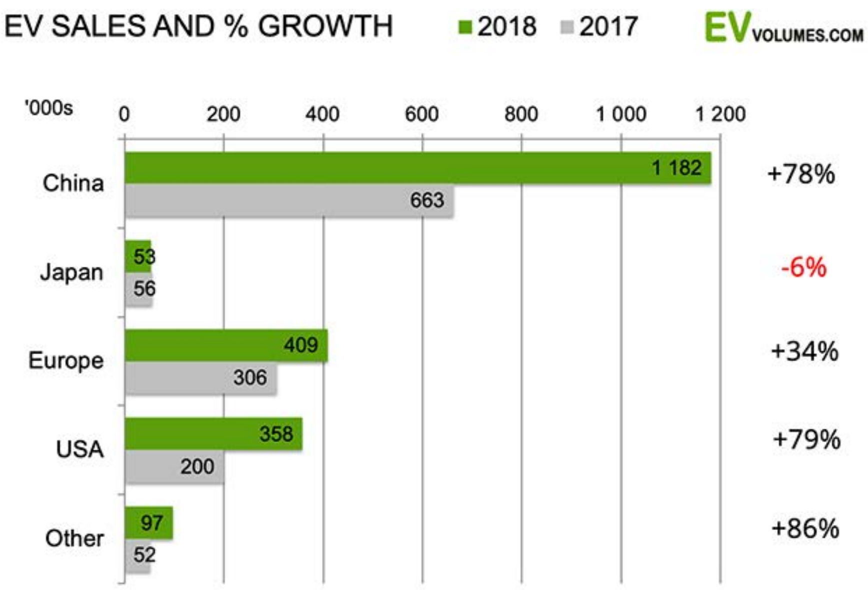


Figure 2: EV Sales and % Growth 2018 vs 2017

2. PURPOSE

Development and fine-tuning of a procedure for measuring the temperature in the car windshield area, with respect to the European Standard for demisting (CEE 78/317): by using a high-speed infrared thermography camera.

In this study, we aim to evaluate the effectiveness of windshield demisting systems in electric vehicles by using thermography (IR) techniques and infrared image analysis. Thermography allows obtaining objective information (temperature values) in relation to the condition of the windshield, unlike other studies in which the evaluation of thermal comfort inside vehicle cabs is based on subjective evaluations. Due to the use of other methods, such as digital thermometers and liquid crystals, there are few previous works where infrared thermography is used for the evaluation of temperature or thermal comfort inside vehicle cabs.

3. MATERIALS AND METHODS

3.1 Thermal camera:

- InfraTec ImageIR.
- Software: IRBIS 3 Professional.
- Lenses: 100mm + 500mm.
- Minimum spatial resolution of 30 µm.
- Image size: 320 x 256 pixels.
- Speed: 1000 fps.
- Resolution: 30 mK @ 30 ºC
- Integration times from 1 µs to 10 ms.

We check that the entire windshield of the car is at -2ºC of temperature, we start the engine, we close all the aerators except those for demisting the windscreen, we close all the doors and gate, we begin the test t = 0 at the right moment to start the engine. (Figure 3)

Test carried out on 3 vehicles: one equipped with a conventional heat engine (ICE), an EV equipped with resistance, and an EV equipped with a heat pump.

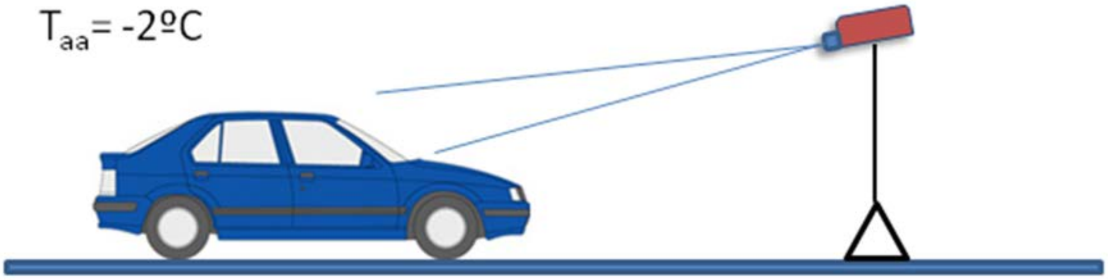


Figure 3: Scheme of the Measurement Method

Average temperature on the windshield at the beginning of the Test, the average temperature is -2º C (We perfectly comply with the European Regulation CEE78 / 317, which requires between -1ºC and -3ºC), see Figure 4, average temperature throughout the windshield (for the 3 models tested, stabilized 24 hours):

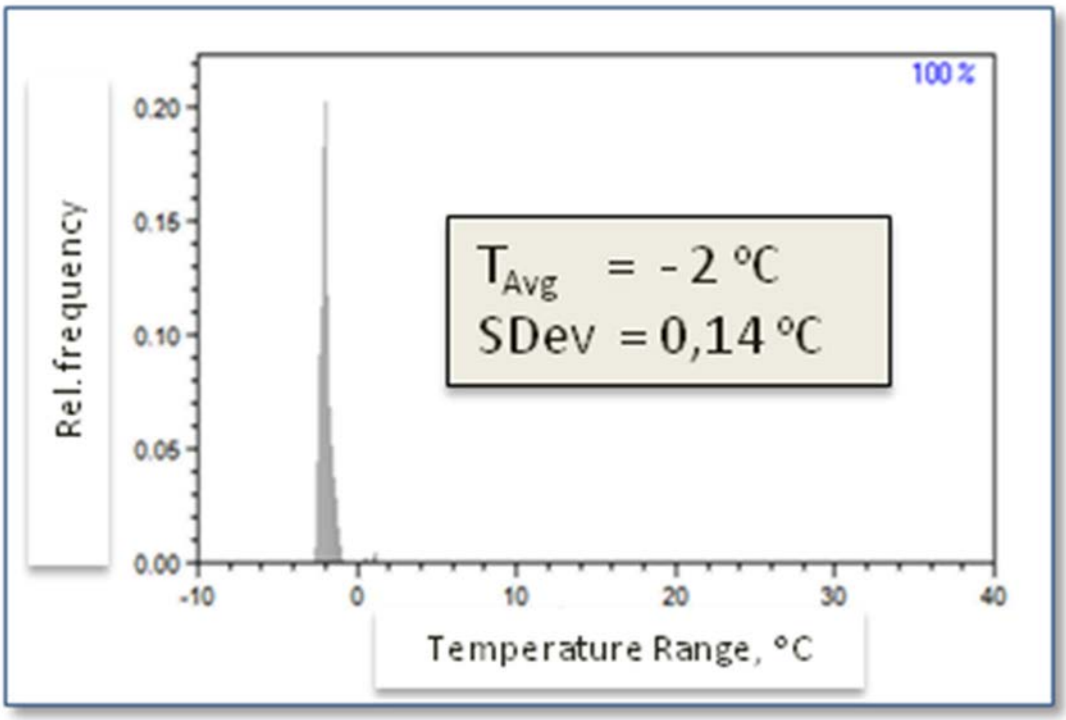


Figure 4: Average temperature on the windshield at the beginning of the Test

4. RESULTS

Illustrative example: Minute 5, Thermal ICE (Figures 5 & 6)

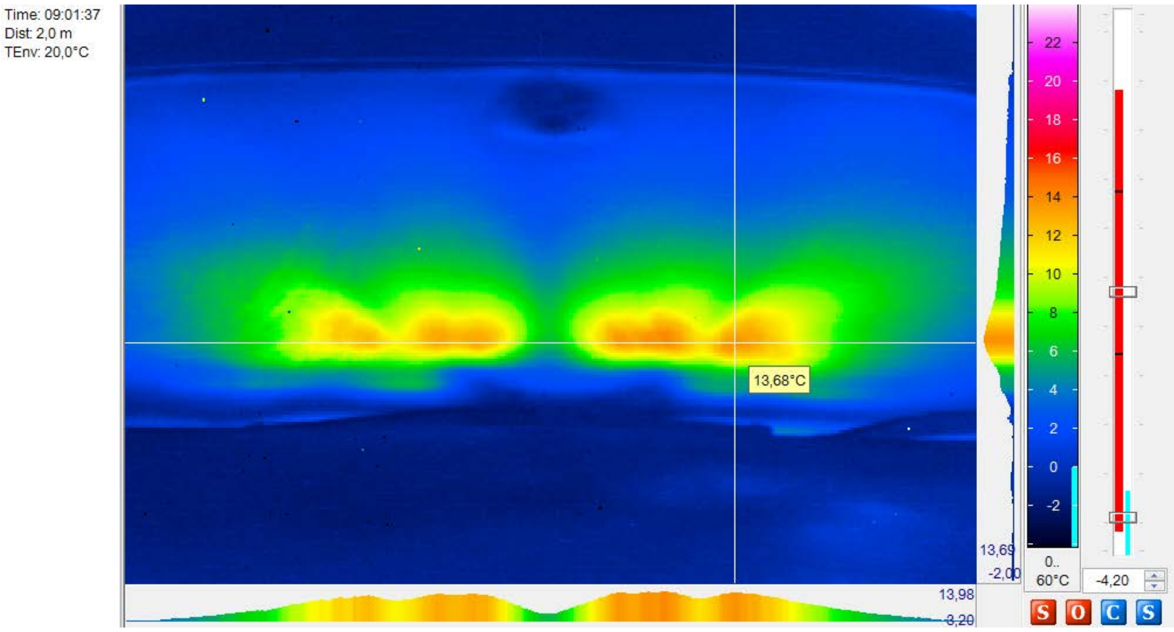


Figure 5: Example: Thermography map on the windshield (minute 5 – ICE Vehicle)

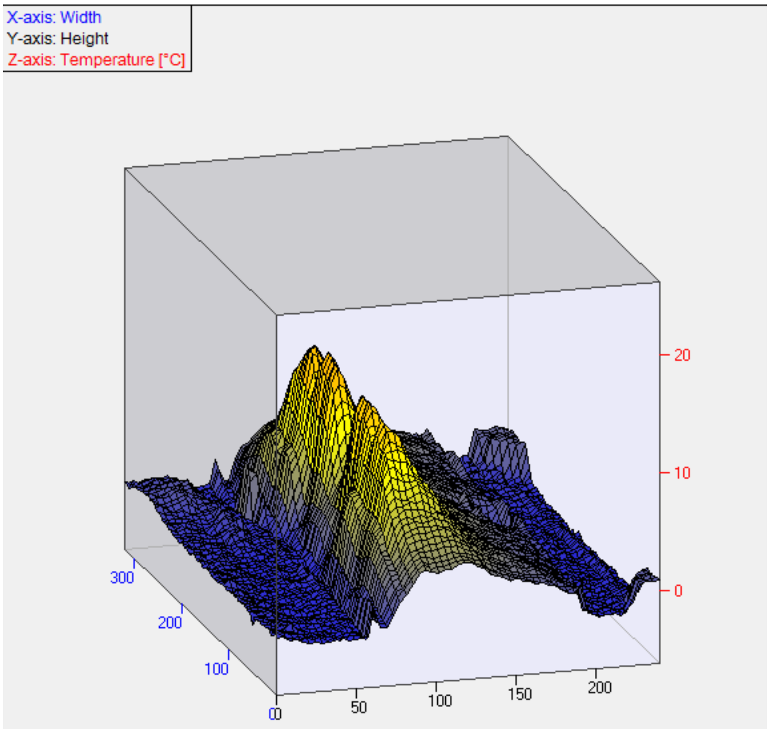


Figure 6: 3D graph of temperature on the windshield

Making a summary graph by average, maximum and minimum temperature in area R1, during the 20 minutes that the Test lasts, we obtain the following (ICE – Figure 7):

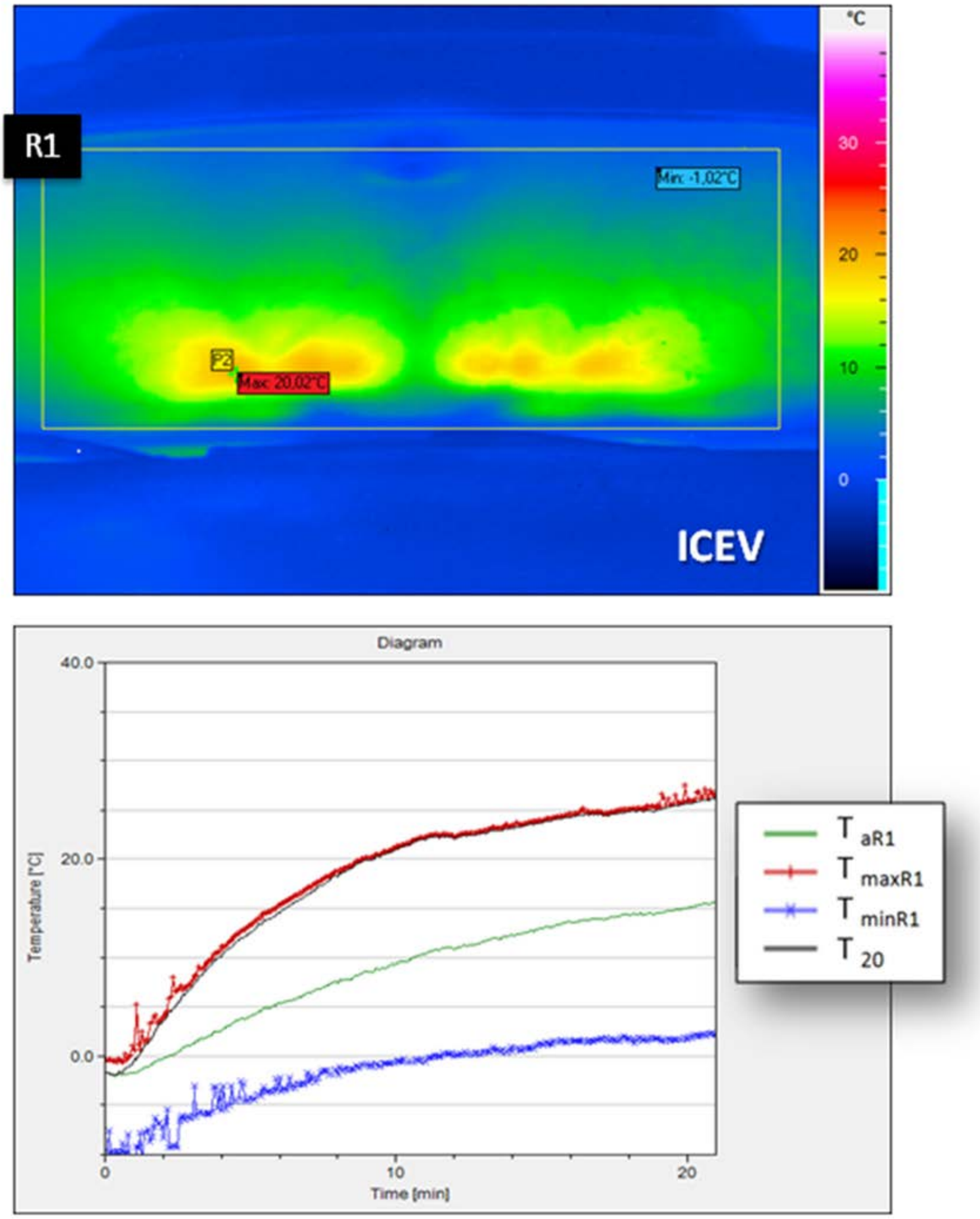


Figure 7: Average, maximum and minimum temperature in area R1 - ICEV

Making the same summary graph by average, maximum and minimum temperature in area R1, during the 20 minutes that the Test for the Electric Car with Resistance Heating lasts (Figure 8):

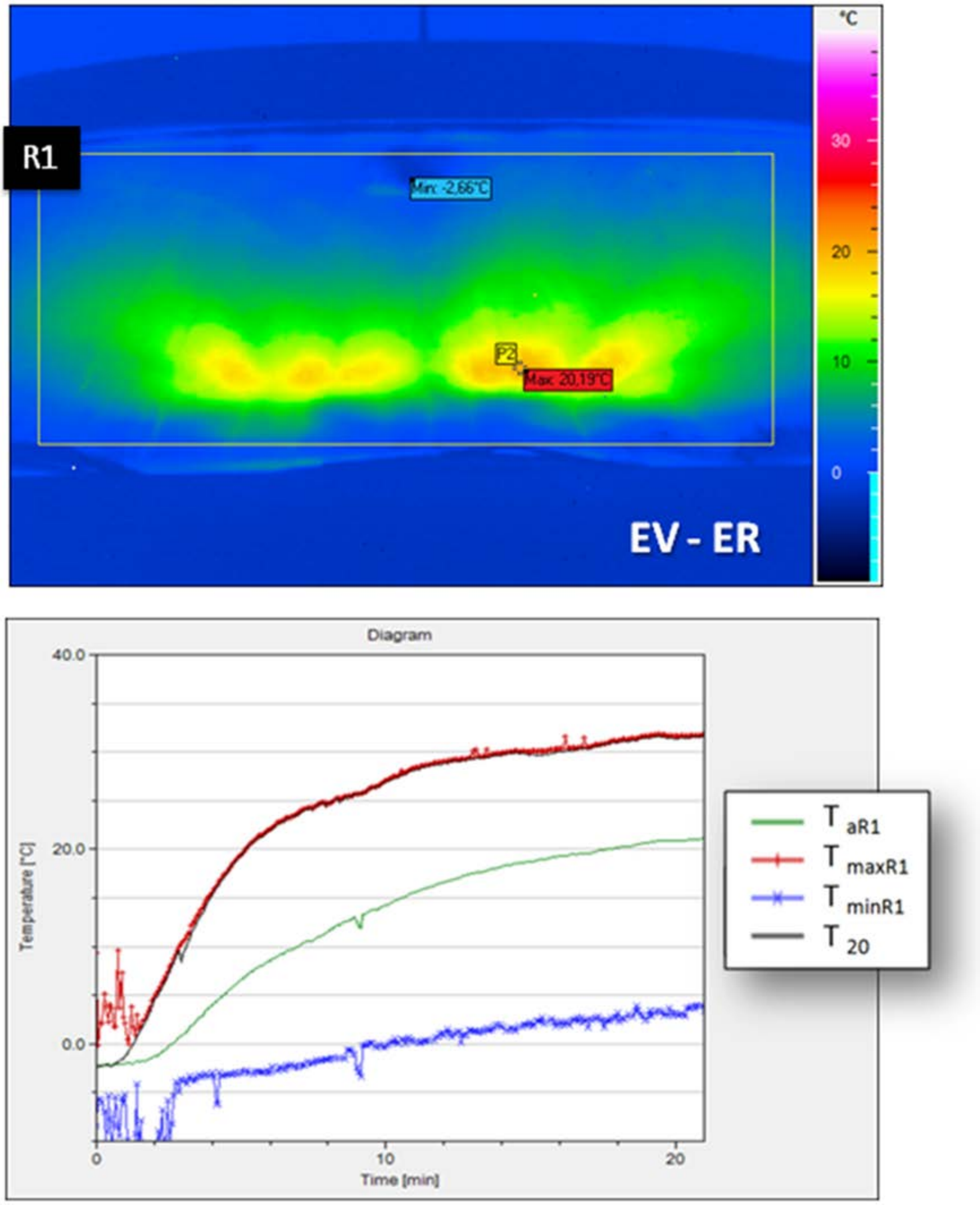


Figure 8: Average, maximum and minimum temperature in area R1 – EV-ER

Making the same summary graph for average, maximum and minimum temperature in area R1, during the 20 minutes that the Test lasts, we obtain the following for the Electric Car with Heat Pump Heating (Figure 9):

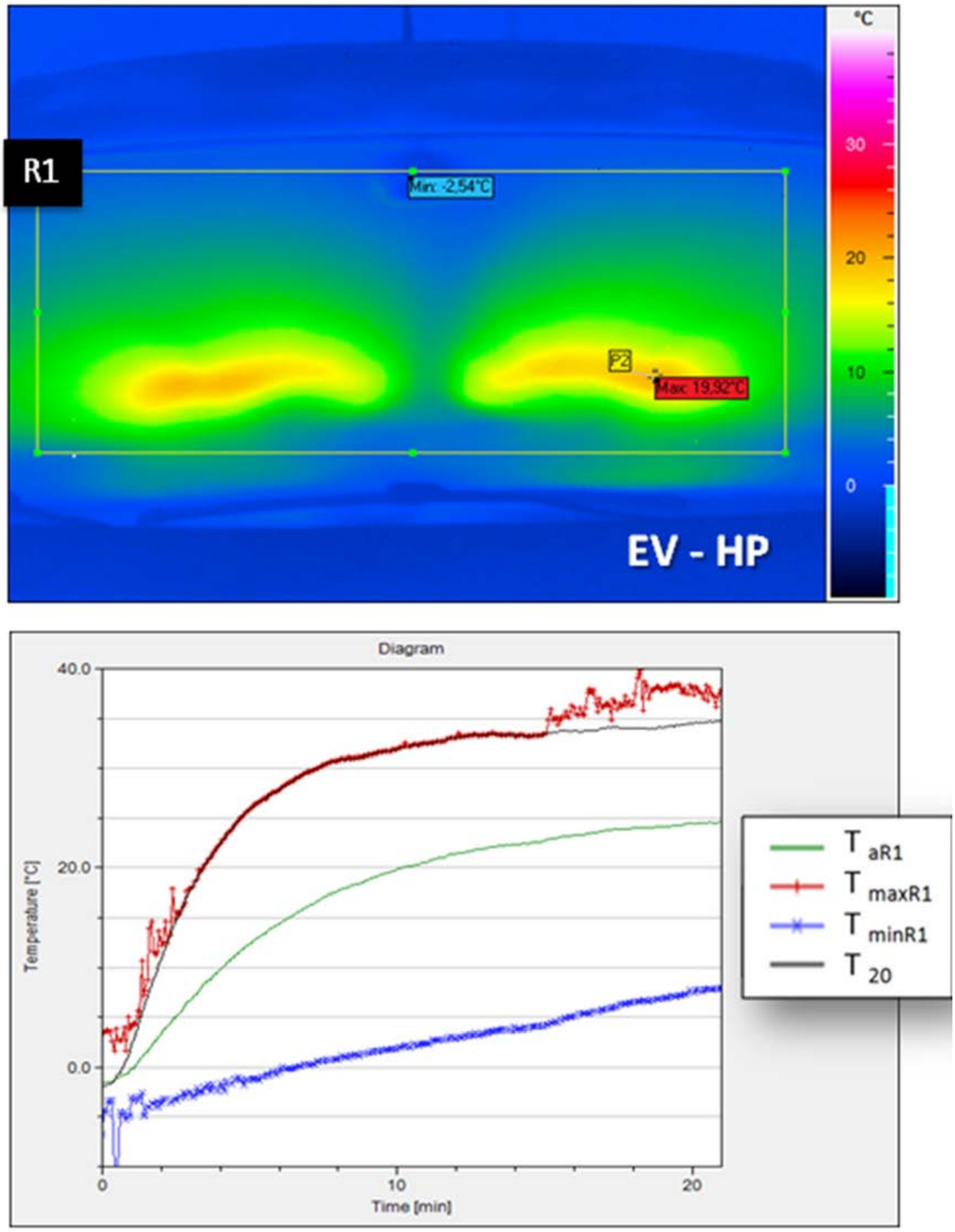


Figure 9: Average, maximum and minimum temperature in area R1 – EV- HP

5. CONCLUSIONS

We can see in these Thermographic measurements that the most efficient vehicle in the demisting function is the EV (with heat pump), we rely on the following graphs and Tables to make it clear (Figure 10): We make a graphical comparison Tª-time of the 3 models by average T, highlighting the time to reach 10º C in area R1 (Windshield):

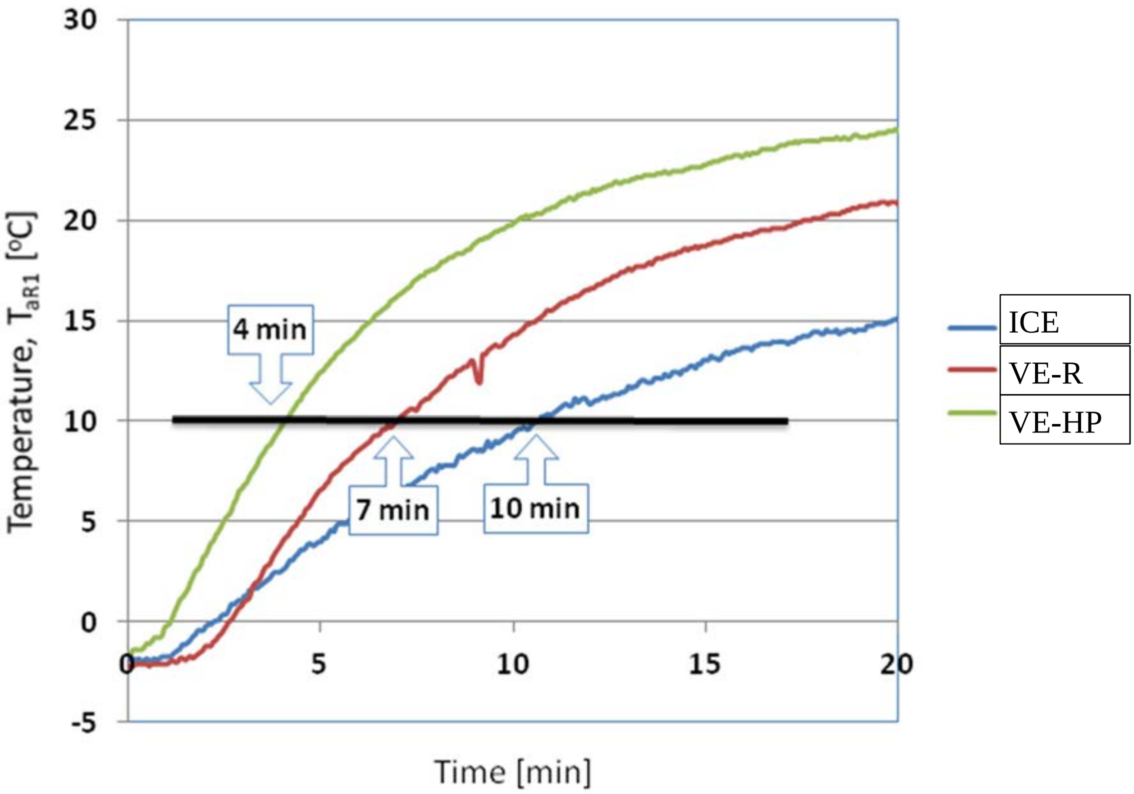
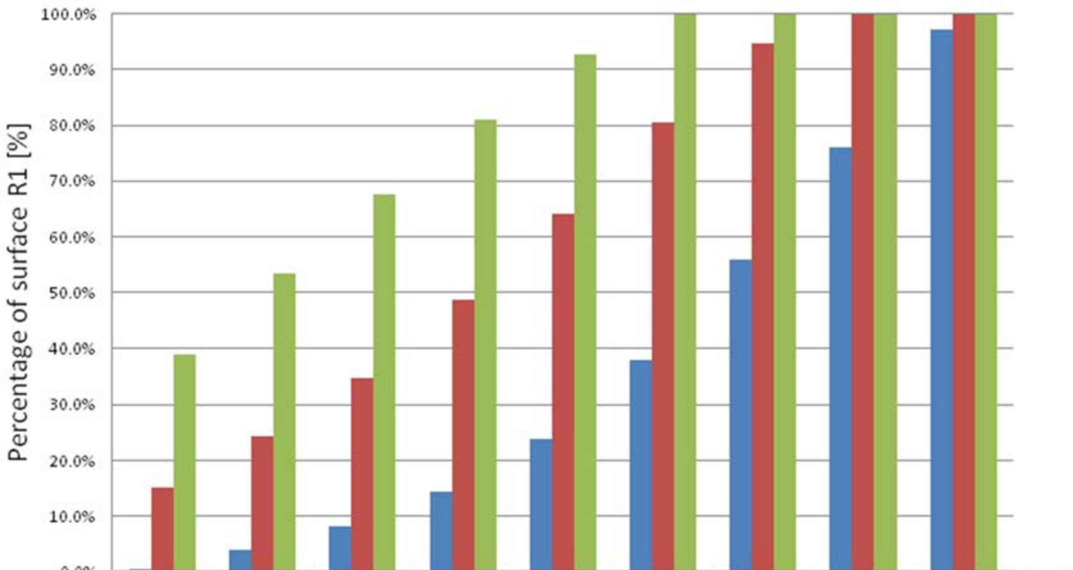


Figure 10: Graphical comparison Tª-time of the 3 models by average T

Lastly, these 2 graphs that show more clearly if possible that the demisting efficiency is VE-HP> VE - R> ICE, it shows the percentage of the area R1 whose Tª is above a certain value at t = 10 minutes; this % is cumulative, that is, it is the sum of the areas whose temperature is above a certain temperature (in percentage).



	> 20	> 18	> 16	> 14	> 12	> 10	> 8	> 6	> 4
ICEV	0.4%	4.1%	8.3%	14.4%	23.7%	38.1%	56.0%	76.0%	97.2%
EV - ER	15.1%	24.3%	34.8%	48.7%	64.2%	80.5%	94.8%	100.0%	100.0%
EV - HP	39.0%	53.5%	67.5%	81.1%	92.8%	100.0%	100.0%	100.0%	100.0%

Fig. 11 - Percentage of the area R1 whose Tª is above a certain value at t = 10 minutes

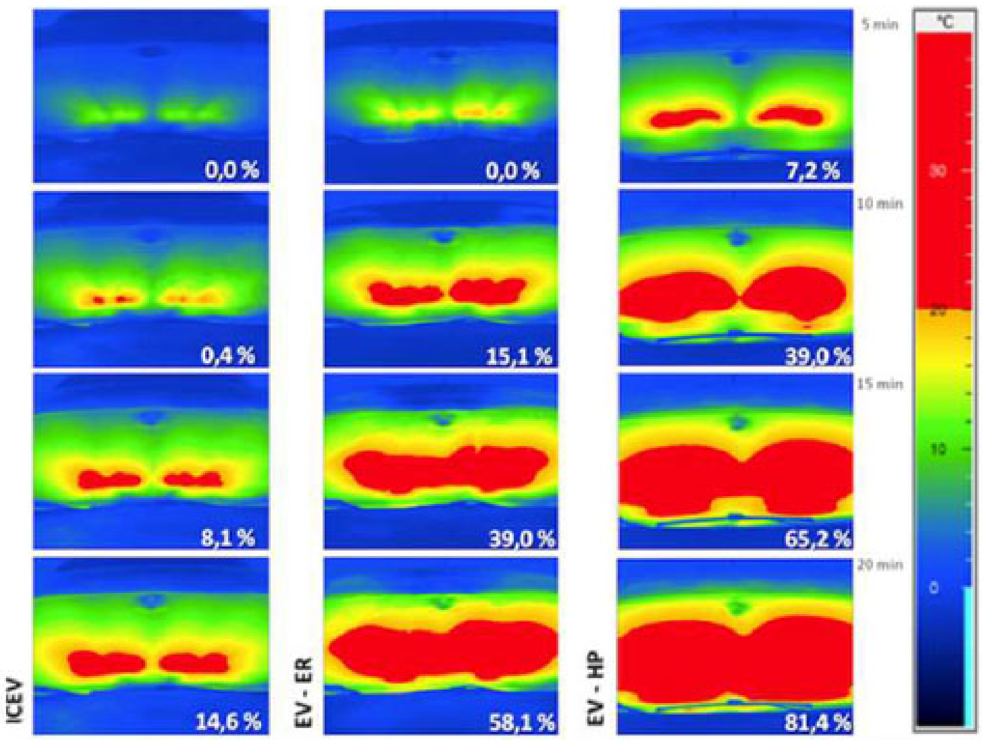


Figure 12: Thermography map on the windshield of the 3 models in time

5. CONCLUSIONS

IR Thermography demonstrates the relevance of using this medium as an analysis and validation tool in the homologation of the defrosting / demisting performance of vehicles for the EU (according to current EEC 87/318 Regulation)

The electric vehicles tested are more efficient in the demisting task than the thermal vehicle.

Of the 2 electric vehicles tested, the EV equipped with a heat pump is more efficient than the EV equipped with a PTC resistor.

The range (or Battery autonomy) lost in this test is of the order of 25% for the VE with PTC resistance and 20% for the VE with heat pump, this, taking GENERAL MEASUREMENT of the STARTING TEMPERATURE of the TEST: the average temperature is -2ºC: according to the European Regulation CEE78 / 317, which requires between -1ºC and -3ºC, taking into account the little autonomy that these cars already enjoy, making this point a great burden on the customer satisfaction.

In conclusion, the electric vehicle enjoys greater thermal comfort compared to its equivalent of combustion, but at the same time it demands a more demanding job in the "non-loss" of range or autonomy that we "sacrifice" in this comfort, with ample possibilities of tuning one with respect to the other.

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